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Geospatial distribution of cadmium in soil profiles of cacao (*Theobroma cacao* L.) plantations in the Peruvian Amazon basin

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Introduction: Cacao plants can translocate heavy metals from the soil to vegetative tissues, potentially leading to concentrations that exceed maximum permissible limits. This study aimed to analyze the geospatial distribution of cadmium (Cd) in soil profiles of cacao (*Theobroma cacao* L.) plantations in the Amazon basin of Peru.

Methods: The research was conducted in the localities of Jeberillos, Arahuate, and Luz del Oriente, within the department of Loreto. In each locality, 10 plots of 100 m² were selected, totaling 30 plots. Cd concentrations and physicochemical soil parameters were evaluated.

Results: In cacao soils from Luz del Oriente at 0–30 cm depth, Cd concentrations averaged 1.11 ± 0.26 mg.kg⁻¹, representing the highest values; whereas the lowest average was recorded in Arahuate at the same depth, with 0.61 ± 0.15 mg.kg⁻¹. Cd levels in Luz del Oriente cacao soils (0–30 cm) were above the average among all localities, while Jeberillos and Arahuate soils showed comparatively lower Cd levels.

Discussion: Overall, Cd in cacao soils was found to be strongly associated with edaphic factors such as pH, texture, effective cation exchange capacity (CEC), and cation composition. The maps represented the spatial distribution of the metal and guided the identification of potential accumulation zones. These findings provide essential insights for guiding agricultural management decision-making, environmental monitoring, and metal contamination risk assessment in cacao-growing areas and other agrarian systems in the Peruvian Amazon basin.

KEYWORDS

agricultural management, edaphic factors, heavy metals, physicochemical properties, soil contamination

1 Introduction

The high global demand for cocoa positions this crop as an agrifood product of great economic value, recognized for its superior sensory and nutritional qualities (Villegas et al., 2024). In Peru, cacao is extensively cultivated by more than 100,000 farmers across >180,000 ha, yielding approximately 74,712.48 t annually with an average market

price of USD\$ 7.56 per kg. Production is concentrated mainly in the regions of Tumbes, Piura, Amazonas, Cajamarca, San Martín, Ucayali, Huánuco, Pasco, Junín, and Cusco (MIDAGRI-Ministerio de Desarrollo Agrario y Riego, 2023). Peru is also among the world's leading exporters of cocoa, a sector that directly sustains the livelihoods of millions of smallholder farmers worldwide (Rojas-Briceño et al., 2022). In recent years, the expansion of cacao cultivation has accelerated, driven by the sharp increase in international prices, which has significantly improved cocoa farmers' household incomes. Yields are estimated to average 840 kg·ha⁻¹, with cocoa typically grown in both conventional and organic agroforestry systems (Charry et al., 2025) in Colombia, Ecuador and Peru. Nevertheless, one of the major concerns threatening the sustainability of this sector is the presence of cadmium (Cd) in Amazonian soils.

Cd not only poses serious risks to human health but also exerts toxic effects on key physiological processes involved in plant growth and development, significantly affecting seed germination rates, transpiration rates, chlorophyll content, and biomass accumulation (Zhang et al., 2024). In crop plants, Cd toxicity impairs nutrient and water uptake and translocation, enhances oxidative damage, disrupts metabolic pathways, and inhibits both morphological and physiological functions (Haider et al., 2021). The toxic effects of Cd extend from early developmental stages, such as seed germination, to yield suppression at maturity. Plant physiological functions, including water interactions, mineral nutrient uptake, and photosynthesis, are particularly affected by Cd. Moreover, Cd exposure induces metabolic alterations, either by directly affecting enzymes and metabolites or by promoting the production of reactive oxygen species, which in turn trigger oxidative stress. Beyond its biological impacts, Cd is also a major environmental pollutant, mainly due to its widespread industrial use and persistent contamination of soils and water, becoming a common, recent issue and activities and industrial wastewater (Oladimeji et al., 2024). Consequently, heavy metals such as Cd can severely constrain plant growth, reduce crop yields, and compromise the nutritional quality of food produced (Madhav et al., 2024; Goel et al., 2024).

Research on strategies to reduce cadmium (Cd) accumulation in cocoa beans is currently limited by an incomplete understanding of Cd transfer pathways within the cocoa tree (Blommaert et al., 2022). This study provides an analysis of total cadmium concentrations in soils in relation to key edaphic variables, including pH, cation exchange capacity (CEC), carbon content, magnesium, among other. This knowledge is expected to have a significant impact on cocoa development and traceability, as it may help prevent the establishment of new plantations in areas where soil Cd levels approach maximum permissible limits. Accordingly, total soil Cd concentration, soil pH, and leaf Cd content have been identified as the best predictors of Cd accumulation in cocoa beans (Wade et al., 2022). Moreover, elucidating the dominant factors governing heavy metal accumulation and their spatial heterogeneity in soils is essential for the implementation of science-based environmental management protocols. Collectively, these findings clarify the key drivers and spatial distribution patterns of Cd in the study area, providing a scientific basis for the targeted identification of contamination sources and the design of precise control strategies (Wang et al., 2025). In addition, total soil Cd content

decreased with increasing soil depth, consistent with the findings of Li et al. (2022), who reported a decline in total soil Cd from 0.377 to 0.196 mg kg⁻¹ with increasing soil depth.

Several studies have shown that cacao plants can translocate soil heavy metals to their vegetative tissues, often resulting in concentrations that exceed the maximum permissible limits (Scaccabarozzi et al., 2020; Oliva et al., 2020; Vallejos-Torres et al., 2022). This is particularly critical for cadmium, which not only impairs plant organ function but can also be lethal to humans and animals (Vanderschueren et al., 2021). In Peru, Cd concentrations in soils under cacao cultivation vary across geographic regions. Reported maximum values include 0.50, 0.53, 1.46, 0.10, 0.82, and 0.86 mg·kg⁻¹ in the departments of Tumbes, Piura, Amazonas, Junín, Huánuco, and Ucayali, respectively (Nelino, 2021). In contrast, Cd contents in San Martín remain below the permissible threshold of 1.4 mg·kg⁻¹ established by the Ministry of the Environment (MINAM-Ministerio del Ambiente, 2017), with values of 0.39 mg·kg⁻¹ detected in cacao agroforestry systems. These lower concentrations are likely associated with the higher tree density typical of agroforestry systems compared to monoculture systems or the presence of arbuscular mycorrhizae (*Rhizoglosum cacao*) found in the Peruvian jungle (Corazon-Guivín et al., 2022).

The departments with the highest average cacao yields are Junín (1,192 kg·ha⁻¹), followed by La Libertad (1,161 kg·ha⁻¹), Tumbes (1,039 kg·ha⁻¹), Loreto (989 kg·ha⁻¹), and San Martín (950 kg·ha⁻¹) (MINAGRI, 2019). Although Loreto shows considerable potential for cacao production, no studies have yet been conducted to determine Cd concentrations in its soils. In this context, it is particularly relevant to analyze the geospatial distribution of Cd in cacao-cultivated soils of the Amazon basin in Peru, with special attention to edaphic zones and soil profile characteristics.

2 Materials and methods

2.1 Study area

The study was conducted in three localities within the Loreto department between May and December 2024. Loreto covers an area of 368,852 km² and is characterized by a humid tropical climate, with minimal seasonal temperature variation (average 27 °C; range 20 °C–33 °C), high annual rainfall (2,500–3,000 mm), and consistently elevated relative humidity (87%–90%) throughout the year (Dourojeanni, 2021). The three study sites included Arahuate (Arhant), located in the district of Lagunas, and Jeberillos (Jbrllos) and Luz del Oriente (Lhze), both situated in the district of Yurimaguas; all belong to the province of Alto Amazonas (Figure 1). The districts of Lagunas and Yurimaguas share the typical topography of the Amazonian lowlands, with flat to gently undulating relief and elevations ranging from 80 to 180 m.a.s.l. In Lagunas, the landscape is dominated by low terraces, *tahuampas* (seasonally flooded forests), and *restingas* (elevated levees), while Yurimaguas is characterized by medium terraces, fluvial deposits, and ancient river channels disconnected from the main river, which form seasonal lagoons. Both areas are underlain by poorly drained soils prone to temporary waterlogging

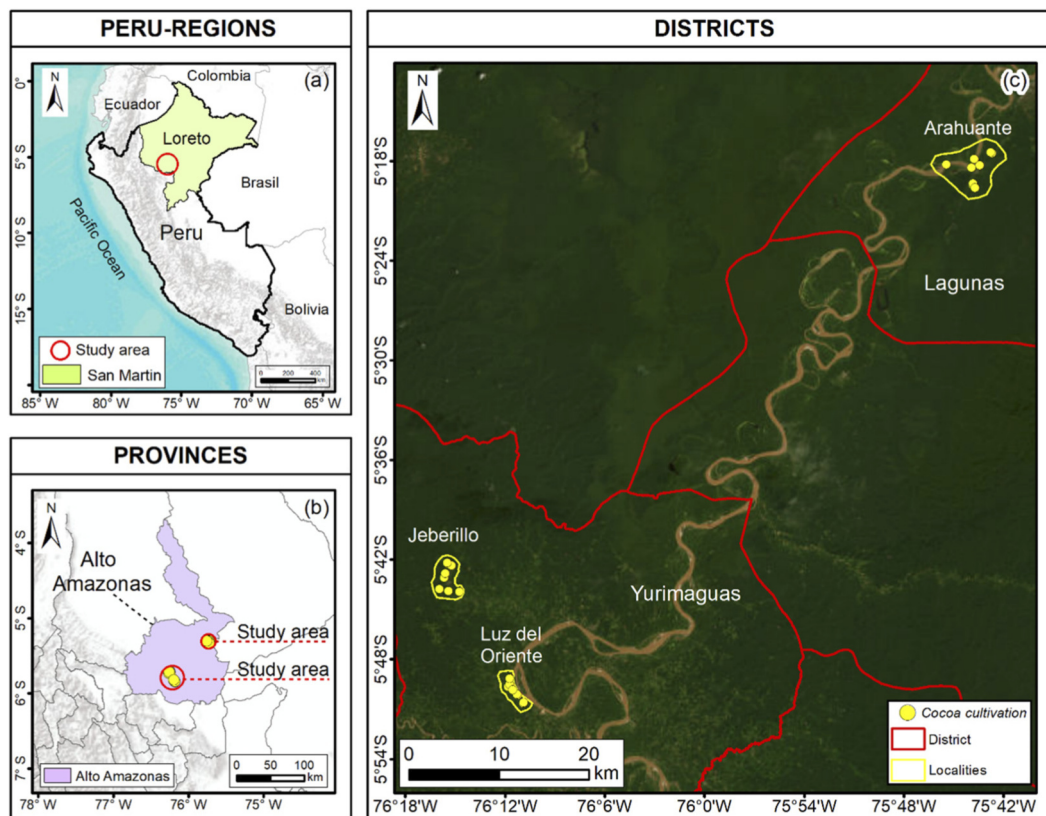


FIGURE 1
Location of the study area in the Loreto department, Peru. (a) Country and regional setting; (b) Provincial boundaries; (c) District boundaries, localities, and sampling points.

(MINAM-Ministerio del Ambiente, 2015; SINIA-Sistema Nacional de Informacion Ambiental, 2021).

2.2 Sampling design

In this study, 10 plots of 100 m² (10 m × 10 m) were established in each locality, for a total of 30 plots, following the methodology of Yu et al. (2019). Soil sampling was conducted by excavating pits measuring 1 × 1 m. Prior to excavation, the sites were cleared of weeds and litter, and samples were collected using a shovel and a metal bar. One sample was taken from each soil profile at depths of 0–30 cm and 30–60 cm, as several previous studies (Li et al., 2022; Ding et al., 2021; Wang et al., 2024) have reported significant variations in Cd stocks within similar soil depths. In total, 60 soil samples were obtained across the two soil profiles for subsequent analyses of cadmium concentrations and physicochemical soil properties. The soils in Yurimaguas (Alto Amazonas, Loreto) are predominantly alluvial, ranging from sandy loam to clayey textures, and belong mainly to the Ultisol order (Buol et al., 1982). In other cases, Vertisols are present, such as those found in Luz del Oriente, which exhibit well-defined physical and chemical characteristics and a reddish-yellow coloration. Due to intensive productive pressure and management practices, many areas are severely degraded.

2.3 Determination of soil edaphic and nutritional parameters

Soil samples were collected using a shovel from different points within each plot, including the four corners and the center, and then homogenized to form a composite sample weighing approximately 1 kg. The samples were analyzed at the accredited laboratory of the National Institute of Agrarian Innovation (INIA), Tarapoto, Peru. Soil texture was determined using the hydrometer texture method; pH was measured potentiometrically in a 1:2.5 soil-to-water suspension following Davey and Conyers (1988); and soil organic matter (SOM) was quantified following the NOM-021-RECNAT-2002 (2002) method.

Aluminum was measured by atomic absorption spectrophotometry using an air–nitrous oxide flame. Calcium and magnesium were determined following the Mexican Official Standard NOM-021-RECNAT-2000. Cation exchange capacity (CEC) was determined according to the Manual de Procedimientos de los Análisis de Suelos y Aguas con Fines de Riego (Bazán, 2017).

Available potassium (K) according to NOM-021-RECNAT-2002 (2002).

2.4 Determination of cadmium concentrations in soils

For Cd analysis, soil samples were collected, one from each subplot, following the Technical Sampling Guide developed by the Ministry of the Environment of Peru ([Ministerio del Ambiente, 2014](#)). Total Cd in soil was determined using the EPA 3051A method ([Link et al., 1998](#)), which employs microwave-assisted acid digestion with nitric acid (HNO₃) to simulate conventional heating-based extraction. After digestion, the concentration of Cd of soil was measured by flame atomic absorption spectrophotometry (direct aspiration) following EPA 700B:2007, using a standard solution prepared by dissolving 1 g of metallic cadmium in 20 mL of HNO₃ (1:1) and diluting to 1 L with deionized water. The method detection limit was 0.2 mg·kg⁻¹ ([EPA, 2007](#)).

The Cd analysis was performed using inductively coupled plasma mass spectrometry (ICP-MS), following the quality assurance and quality control (QA/QC) procedures established in the US EPA methods [US EPA \(1996\)](#) and [US EPA \(1994\)](#). Each analytical batch included a method blank to check for potential contamination, a fortified duplicate sample (5%) to assess precision and bias, and a laboratory control sample (LCS) with known concentrations to verify accuracy. Analytical performance was validated using standard reference materials (SRMs) from NIST, ensuring the reliability and traceability of the results.

The balances used in the preparation of this CRM are regularly calibrated with traceability to NIST standards. All volumetric dilutions are performed using calibrated Class A volumetric glassware. The certified concentration and its associated uncertainty were determined using the “high-performance ICP-OES” protocol developed by NIST, and both the certified concentration and uncertainty values are traceable to NIST SRM 3108, lot No. 130116. The uncertainty associated with the certified concentration represents the expanded uncertainty at a 95% confidence level, using a coverage factor of $k = 2$.

2.5 Statistical analyses

Statistical analyses were performed using the R software version 4.3.2 ([R Core Team, 2024](#)) through specialized packages such as *ggplot2*, *corrplot*, *GGally*, *ph heatmap*, *dplyr*, *readxl*, and *RColorBrewer* ([Wickham, 2016](#)), which facilitated the processing, visualization, and comprehensive exploration of soil data collected from three localities in the Loreto department, Peru. A principal component analysis (PCA) was conducted with the *factoextra* package to reduce dimensionality and assess the joint variation of soil physicochemical variables. The results were displayed in a biplot, which enabled the visualization of the distribution of soil physicochemical parameters by locality and soil profile (0–30 and 30–60 cm), as well as the identification of variables that best explain the observed variability in the dataset. Subsequently, a geostatistical analysis of soil Cd was carried out using the Smart Map plugin in the QGIS software (version 3.34.14–Prizren) to fit theoretical variogram models, apply ordinary kriging interpolation, and evaluate the spatial dependence of the data. This approach supported the generation of thematic maps and the identification of Cd accumulation in soils. A cross-correlation matrix based on

Pearson’s coefficient ($p < 0.05$) was then generated and visualized with the *corrplot* package to identify significant associations among variables. In addition, a heatmap was generated through the *ph heatmap* package to examine clustering patterns among samples, while scatterplot matrices (*GGally* package) were employed to explore correlations between numerical variables, color-coded by locality. Bar plots were also used to illustrate Cd distribution by locality and soil texture, aiding the interpretation of visual trends. Finally, analysis of variance (ANOVA) followed by Tukey’s *post hoc* test ($p < 0.05$) was applied to determine statistically significant differences among the mean values of soil physicochemical variables according to soil profile, thus providing inferential validation of the observed patterns.

3 Results and discussion

3.1 Physicochemical properties of soils across profiles in three localities

The highest cadmium content ([Table 1](#)) was recorded in cacao soils from Lhze at 0–30 cm depth, with an average of 1.11 ± 0.26 mg·kg⁻¹, followed by Arhant soils at 30–60 cm depth with an average of 0.81 ± 0.11 mg·kg⁻¹. No significant differences were observed between these two localities or soil profiles. The lowest Cd concentration was found in Arhant at 0–30 cm depth, averaging 0.61 ± 0.15 mg·kg⁻¹. Soil pH varied across localities: Arhant showed an average of 3.58 ± 1.25 at 0–30 cm depth, along with a high sand content averaging $46.89\% \pm 7.29\%$. In contrast, Lhze presented the highest pH values, with an average of 6.30 ± 0.35 . Regarding exchangeable cations, including potassium (K⁺), calcium (Ca²⁺), and magnesium (Mg²⁺), the highest values were observed in Arhant soils at 0–30 cm depth.

Cacao soils in Arhant at 0–30 cm depth showed the lowest Cd content, characterized by low cation exchange capacity (CEC), high sand content, and low levels of Ca and Mg. These findings provide a basis for mitigation strategies through the application of soil amendments aimed at modifying soil properties and reducing Cd bioavailability in soil ([Zhuang et al., 2023](#)). In Lhze, the average soil pH was 6.17, while [Du et al. \(2018\)](#) and [Liu et al. \(2023\)](#) emphasized that soil pH plays a critical role in regulating Cd bioavailability, noting that Cd availability in soil increases markedly when pH falls below 6.5. The elevated Cd content observed in Lhze at 0–30 cm depth may be associated with root activity and microbial processes ([Huang et al., 2021](#)), as further supported by [Ma et al. \(2024\)](#).

Cadmium concentrations were higher, particularly in samples from Lhze at the 0–30 cm depth. However, Cd levels tended to decrease with increasing soil depth, consistent with the findings of [Li et al. \(2022\)](#). The elevated Cd content in surface soil profiles of cacao plantations might primarily result from high fertilizer inputs, atmospheric deposition (mainly from rainfall), and parent material, which affect the fractions present in the topsoil ([Li et al., 2019](#); [Li et al., 2022](#)). In a recent study of Colombian cacao soils, an average Cd concentration of 1.43 mg·kg⁻¹ was reported across 1,837 soil samples, well above the natural background levels typically observed in soils worldwide ([Bravo D. et al., 2021](#)).

TABLE 1 Analysis of variance and Tukey's post hoc test of soil physicochemical parameters across two soil profiles in three localities of the Loreto region.

Physicochemical parameters	Tukey test by locality						Analysis of variance	
	Jbrllos		Arhant		Lhze		F	P-value
	0–30	30–60	0–30	30–60	0–30	30–60		
pH	5.55 ± 1.21 ab	5.11 ± 1.16 b	3.58 ± 1.25 c	4.13 ± 0.21 c	6.30 ± 0.35 a	6.04 ± 1.24 a	61.76	<0.0001***
K	83.43 ± 11.41 b	78.91 ± 13.23 bc	41.44 ± 14.25 cd	8.88 ± 5.88 d	164.50 ± 32.73 a	145.25 ± 32.52 a	96.54	<0.0001***
CEC	16.93 ± 4.05 bc	20.48 ± 5.07 ab	5.56 ± 1.65 cd	3.62 ± 1.05 d	28.99 ± 6.57 a	29.26 ± 8.65 a	37.8	<0.0001***
Cd	0.77 ± 0.21 b	0.73 ± 0.32 b	0.61 ± 0.15 b	0.81 ± 0.11 b	1.11 ± 0.26 a	0.75 ± 0.25 b	9.31	0.0003***
Sand	47.74 ± 11.25 a	41.32 ± 7.50 ab	46.89 ± 7.29 a	47.69 ± 8.96 a	31.45 ± 7.60 bc	23.63 ± 6.69 c	26.85	<0.0001***
Clay	24.62 ± 5.29 d	34.94 ± 8.38 bc	25.92 ± 6.32 cd	36.65 ± 9.29 b	40.16 ± 8.68 b	49.48 ± 10.23 a	32.04	<0.0001***
Ca	14.78 ± 3.86 a	13.87 ± 4.79 a	0.86 ± 0.90 b	0.44 ± 0.6 b	24.72 ± 5.23 a	24.31 ± 6.90 a	35.05	<0.0001***
Mg	1.60 ± 0.52 b	1.13 ± 0.41 bc	0.3 ± 0.2 cd	0.12 ± 0.2 d	3.64 ± 0.81 a	3.26 ± 0.72 a	95.92	<0.0001***

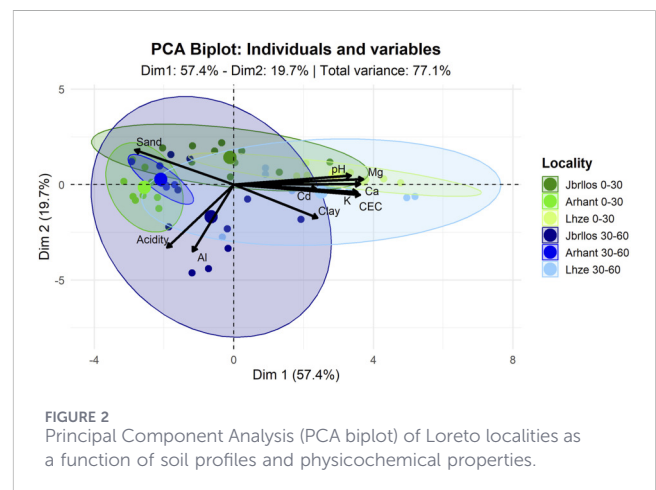
Different letters within each physicochemical parameter indicate statistically significant differences among locations at $p < 0.05$, as determined by Tukey's test. ns: not significant; *statistically significant; ***highly statistically significant.

3.2 Analysis of soil properties across profiles in Loreto localities

The biplot (Figure 2) shows a clear separation among sample groups from different localities and soil profiles (0–30 cm and 30–60 cm), indicating that soil properties vary both spatially and across profiles. The PCA accounted for 77.1% of the total variability in the data through its first two principal components (Table 2). These dimensions are sufficient to capture and visualize the majority of the data structure. Samples from Lhze at both 0–30 cm and 30–60 cm depths cluster on the right side of the plot, in the quadrant where the arrows for pH, CEC, Mg, Ca, clay, and K are also projected, indicating that these variables exert greater influence in this locality and soil profile. In contrast, samples from Arhant at 0–30 cm and 30–60 cm depth are positioned to the left, in the same direction as the arrows for acidity, sand, and aluminum (Al), suggesting higher concentrations of these variables in those soils. These results demonstrate that soil properties vary not only across localities but also along soil profiles.

The Cd vector points in the opposite direction to that of pH, indicating a negative association; that is, higher pH is associated with lower Cd concentrations, whereas lower pH (more acidic conditions) corresponds to higher Cd levels. This behavior is consistent with the greater mobility of Cd in acidic soils. Likewise, the Cd vector also points in the opposite direction to that of CEC, indicating a negative correlation; soils with higher CEC tend to exhibit lower levels of available Cd, likely due to a greater adsorption capacity associated with colloidal complexes. Consequently, soils with low CEC show a stronger association with Cd (Figure 2).

The variable of interest, Cd, shows a partial correlation with CEC, Ca, and Mg, while also displaying a certain degree of independence from the dominant PCA patterns. This interpretation is supported by the factor loading values presented



in Table 3. Cd has a loading of 0.2517 on PC1 and -0.039 on PC2, indicating that its variance is explained mainly by the first component and to a lesser extent by the second. Furthermore, the uniqueness value for Cd is 0.01526, the lowest among all variables analyzed. This means that 98.5% of Cd variance is well explained by the principal components, which is a highly favorable result. Table 3 further reinforces this interpretation by showing the factor loadings of each variable on the first four components. Variables such as Mg (0.395), CEC (0.385), Ca (0.385), pH (0.357), and K (0.377) exhibit high loadings on PC1, indicating that they are the main contributors to the variance explained along this axis. Meanwhile, the uniqueness values of each variable reveal the extent to which their variance lies outside the PCA model.

Previous studies have demonstrated that soil CEC and the balance of exchangeable cations (Ca^{2+} , Mg^{2+} , and K^{+}) are key factors influencing plant growth and development (Yang et al.,

TABLE 2 PCA variance analysis in the study localities.

Component	Sum of Squared Loadings	Percent_Variance	Cumulative_Percent
1	5.74	57.4	57.4
2	1.97	19.7	77.1
3	0.92	9.2	86.3
4	0.68	6.8	93.2

TABLE 3 Vector analysis of the principal components (PCA) in the study localities.

Variable	PC1	PC2	PC3	PC4	Uniqueness
Cd	0.2517	-0.039	0.0431	-0.9581	0.01526
pH	0.3572	0.0856	-0.3859	0.0651	0.71189
CEC	0.3853	-0.0983	-0.3003	0.129	0.73508
K	0.3772	-0.0724	-0.0644	0.0005	0.84835
Sand	-0.3019	0.3305	-0.4165	-0.1416	0.6061
Clay	0.2551	-0.3161	0.5862	0.1094	0.47938
Ca	0.3855	0.005	-0.304	0.1424	0.73865
Mg	0.3954	0.053	0.072	0.0771	0.82973
Al	-0.1254	-0.6358	-0.3164	-0.0422	0.47812
Acidity	-0.2036	-0.6	-0.2001	-0.0325	0.55744

2024), which may be promoting cacao growth in the Lhze locality. The dynamics of the dispersive behavior of clay, in turn, determine soil characteristics such as permeability and aggregate stability, and consequently crop productivity (Zhu et al., 2020). Magnesium is an essential nutrient for cultivated plants, directly involved in photosynthesis and numerous metabolic processes; its deficiency negatively affects crop yield and quality, either directly or by impairing the utilization of other plant nutrients (Ahmed et al., 2023). Soil pH is another critical parameter that influences a wide range of soil properties and processes, including nutrient cycling, microbial activity, inorganic carbon, and metal speciation (Mosley et al., 2024). It strongly affects the nutrient availability cycle and soil fertility (Robinson et al., 2017).

Figure 3 presents a clustered heatmap with hierarchical grouping, which enables the visualization of multivariate patterns and similarities among study localities and soil depths. This tool is useful for identifying groups of samples with similar profiles of physicochemical variables and highlighting which localities are associated with higher or lower concentrations of specific elements. Each cell in the heatmap represents a standardized value (z-score), indicating whether a sample shows a value above or below the mean for each variable. Regarding cadmium (Cd), standardized positive values are mainly observed in Lhze samples at 0–30 cm, indicating concentrations above the overall mean across localities. In contrast, samples such as Jbrllos (30–60 cm) and Arhant (0–30 cm) show negative Cd values, reflecting lower levels of this metal.

This pattern suggests that the Lhze locality, particularly in the surface layer, contains soils with higher cadmium accumulation,

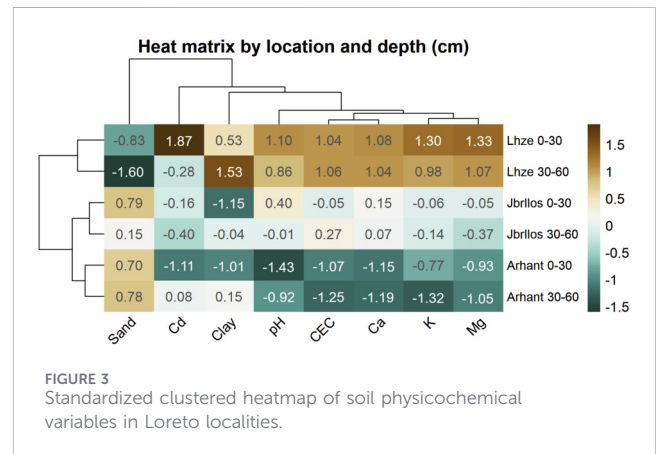


FIGURE 3 Standardized clustered heatmap of soil physicochemical variables in Loreto localities.

which is relevant for environmental and agricultural monitoring given the potential risk of bioaccumulation. Beyond cadmium behavior, the heatmap also highlights contrasting patterns in other soil variables across the evaluated localities. Clay shows elevated standardized values in Lhze samples at 30–60 cm, reflecting greater accumulation of fine particles in these soils, typically associated with higher nutrient retention capacity. Conversely, sand exhibits predominantly negative values in the same samples, confirming a finer soil texture. Exchangeable bases such as Ca and Mg tend to be more abundant in Lhze soils at 0–60 cm depths, suggesting lower leaching in this area. Similarly, K and effective cation exchange capacity show their highest values in Lhze soils at 0–60 cm, which may reflect surface layer accumulation processes or greater relative fertility at these depths.

In contrast, both soil layers from Arhant samples exhibit a clear tendency toward negative values for most variables, indicating a more degraded soil profile with lower nutrient availability. Soil pH also varies across localities, with higher values (less acidic) in Lhze, while more acidic soils are evident in Arhant and Jbrllos, a relevant pattern given its influence on the mobility of metals such as cadmium. Overall, these results demonstrate a clear differentiation among localities based on their physicochemical properties, which are further modulated by soil depth.

The higher Cd concentrations in the upper soil layers (first 30 cm sampled) may be partly attributed to the long-term accumulation of the metal in fallen leaves and husks. In cocoa farms of central Colombia, cocoa litter has been found to contain higher Cd concentrations than both cocoa beans and green leaves, with an average concentration of 85.5 mg·kg⁻¹, indicating an intense cadmium cycling process (Gramlich et al., 2018; Albarracín et al.,

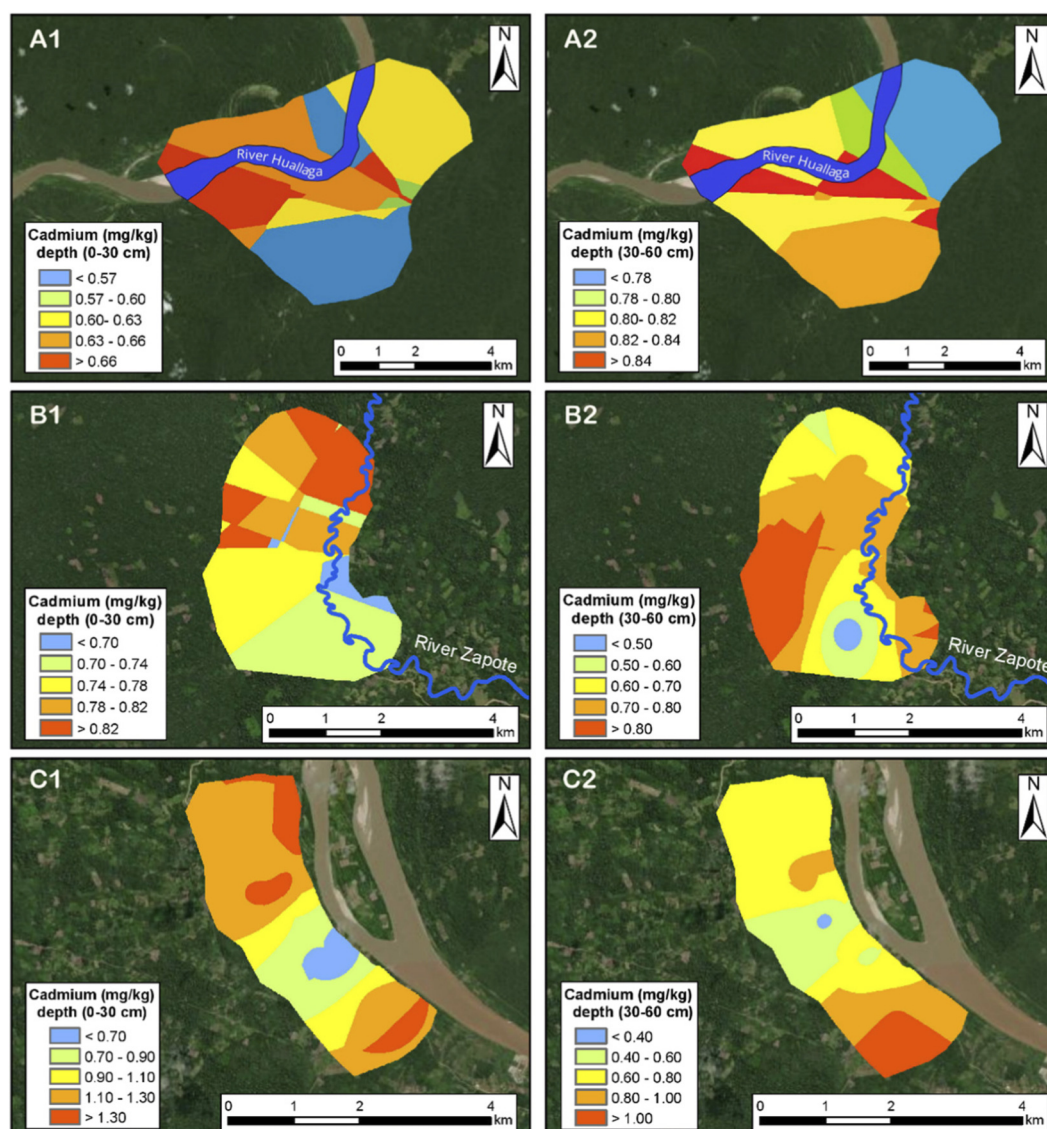


FIGURE 4 Spatial distribution maps of cadmium ($\text{mg}\cdot\text{kg}^{-1}$) in soils at 0–30 cm and 30–60 cm in the localities of Arhant (A1, A2), Jbrllos (B1, B2), and Lhze (C1, C2), generated by ordinary kriging interpolation. Colors represent different concentration ranges.

2019). This is further supported by studies suggesting that tree litter use as an organic amendment can indeed act as an additional source of Cd in soils (Barraza et al., 2019). Several soil factors influence Cd phytoavailability, including the total Cd concentration in soil, pH, organic matter content, clay mineralogy, and soil solution cations, present in the Lhze locality (Loganathan et al., 2012; Young, 2013).

3.3 Spatial distribution of soil cadmium at two depths across study localities in the Loreto region

In the surface soil layer (0–30 cm), Cd distribution in Lhze soils exhibited significant spatial autocorrelation (Moran's Index = 0.744; $p < 0.05$) and the best model's cross-validation performance between observed and predicted values (RMSE = 0.24 and $R^2 = 0.50$). These results indicate a moderate level of spatial predictability, enabling

the identification of Cd distribution and accumulation patterns (Figures 4C1). In contrast, the Arhant (Figures 4A1) and Jbrllos (Figures 4B1) localities showed low spatial autocorrelation (Moran's Index < 0.3 ; $p > 0.05$) and limited predictive capacity ($R^2 < 0.30$). At greater depths (30–60 cm), all three localities (Figures 4A2–C2) exhibited weak spatial structuring of Cd, with Moran's Index values < 0.2 ($p > 0.05$) and low coefficients of determination ($R^2 < 0.31$). This suggests a more heterogeneous distribution, as no consistent spatial pattern of Cd distribution with respect to distance was observed.

In the surface layer (0–30 cm), the Lhze locality exhibited moderate predictive capacity ($R^2 \approx 0.50$), whereas Arhant and Jbrllos showed low values ($R^2 < 0.30$). In the deeper layer (30–60 cm), all localities displayed low spatial autocorrelation and reduced predictive capacity, which can be attributed to the high small-scale variability of Cd concentrations. This variability is

likely influenced by soil heterogeneity, differences in agricultural practices, and environmental processes that generate irregular distributions of the metal, thereby hindering the identification of a well-defined spatial pattern. Similar findings have been reported in cacao-producing regions of northern Peru ($R^2 = 0.22$; Pulgar-Vásquez et al., 2023), Colombia ($R^2 = 0.28$; Bravo F. et al., 2021), and Costa Rica ($R^2 = 0.26$; Carrillo et al., 2023), confirming that the spatial heterogeneity of Cd constrains the predictive capacity of geostatistical models in cacao systems.

Figure 4 presents the spatial distribution maps of Cd ($\text{mg}\cdot\text{kg}^{-1}$) in soils at 0–30 cm and 30–60 cm in Arhant, Lhze, and Jbrllos, generated through ordinary kriging. The maps effectively represented the spatial distribution of the metal and guided the identification of potential accumulation zones.

These findings highlight the importance of focusing attention on areas with higher Cd concentrations, as even relatively reduced cultivated areas may exceed Cd permissible limits for agricultural soils ($1\text{--}3\text{ mg}\cdot\text{kg}^{-1}$; Kubier et al., 2019). In this study, only the Lhze locality surpassed the threshold of $1\text{ mg}\cdot\text{kg}^{-1}$ (though without reaching the maximum permissible limit of $1.4\text{ mg}\cdot\text{kg}^{-1}$), representing a potential risk in markets with stricter regulatory standards. This reinforces the need for continuous monitoring and management practices aimed at preventing Cd accumulation in the root zone and its subsequent transfer to cacao beans. The statistical evidence supports the presence of edaphic hotspots, induced by localized microenvironmental and geochemical processes such as selective adsorption in specific soil fractions or the influence of point-source contamination (Xu et al., 2025). These findings suggest that soil characteristics may directly or indirectly modulate the spatial distribution of Cd (Solórzano et al., 2025). Overall, this study demonstrates that total cadmium (Cd) content in cacao-cultivated soils of Loreto, Peru, exhibits a highly heterogeneous spatial distribution. Concentrations exceeding $1\text{ mg}\cdot\text{kg}^{-1}$ cannot be attributed to random variability but rather to the systematic influence of edaphic and profile-related factors (Pan et al., 2022). Since metals can accumulate in agricultural soils and pose serious risks to human health, assessing soil quality is crucial to prevent potential harm associated with future contamination (Wdowczyk et al., 2023).

The pathways through which cadmium is absorbed and loaded into cocoa beans have not yet been fully elucidated. Previous studies have suggested that Cd loading into cocoa beans may occur via direct uptake through the xylem rather than through phloem-mediated redistribution from leaves (Vanderschueren et al., 2023). Regions of South and Central America host cocoa-growing areas, where the highest Cd concentrations in cocoa beans have been reported compared with other parts of the world, with values ranging from 0.6 to 0.8 mg kg^{-1} (Chavez et al., 2015). Likewise, Vallejos-Torres et al. (2023) reported average soil Cd concentrations of 0.39 mg kg^{-1} in Peruvian Amazon soils; in the same sites, mean Cd concentrations in leaves ranged from 1.12 to 1.28 mg kg^{-1} , whereas bean concentrations averaged 0.35 and 0.34 mg kg^{-1} . Additionally, Blommaert et al. (2022) indicated that the combined effects of soil properties and cultivar resulted in high Cd concentrations in cocoa beans, exceeding the typical commercial limit of 0.6 mg Cd kg^{-1} .

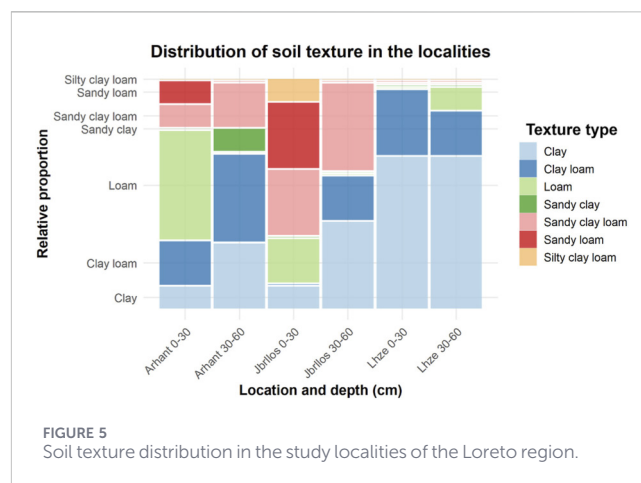


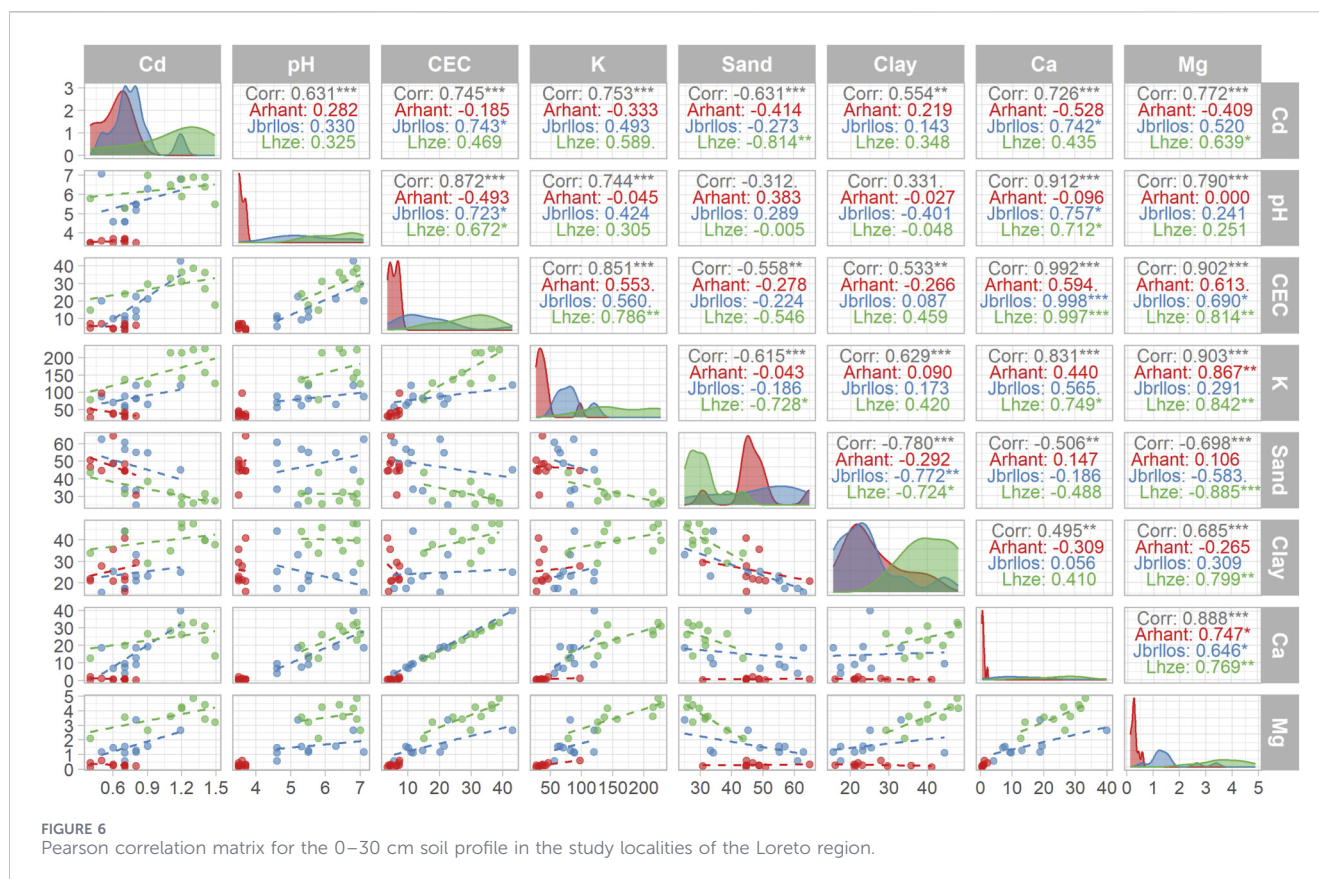
FIGURE 5
Soil texture distribution in the study localities of the Loreto region.

To obtain more precise and site-specific results on the translocation of Cd from soil to cocoa beans, further research more specifically focused on these processes is warranted.

3.4 Soil texture distribution in the study localities of the Loreto region

Figure 5 reveals that, contrary to the expected general homogeneity, soil textures vary markedly across localities and depths. In Lhze, clay and clay loam textures dominate both at 0–30 cm and 30–60 cm, consistent with the high values of CEC, Ca, and Mg observed in the heatmap, properties typically associated with finer-textured soils. In contrast, Jbrllos exhibits a greater proportion of coarser textures, such as sandy clay loam, in both profiles, which aligns with its lower levels of Mg, K, and CEC. Meanwhile, Arhant shows a heterogeneous mix in the 0–30 cm layer, with a notable proportion of clay and clay loam, which becomes sandier and more variable at 30–60 cm, reinforcing the heatmap results that indicated lower nutrient accumulation. This complementarity between soil texture and chemical elements underscores the importance of considering granulometry as a key structural factor directly influencing soil fertility and the dynamics of heavy metals such as cadmium.

In the cacao soils of Lhze, both at 0–30 cm and 30–60 cm, clay and clay loam textures predominate, with higher cadmium concentrations compared to the other sites. These soils also present elevated Ca and Mg contents, reflecting a positive correlation between exchangeable Ca and clay minerals (Shabtai et al., 2023). Clay minerals are key soil components that often coexist with organic matter, forming mineral–organic associations that regulate the speciation, mobility, and bioavailability of heavy metals (Xu et al., 2022). Chen et al. (2025) demonstrated that the silt–clay aggregate ($<0.053\text{ mm}$) exhibited the highest Cd enrichment across all soils tested, consistent with the findings of Shen et al. (2022). Cd preferentially binds to fine aggregates such as clay. Furthermore, fine-sized aggregates generally exhibit narrower pore diameters and higher clay content, which collectively reduce water conductivity and limit the physical mobility of Cd (Lu et al., 2024). Consequently, these aggregates enhance Cd retention, explaining its consistently higher enrichment observed in the silt–clay aggregate. In addition, Cd sorption is strengthened by



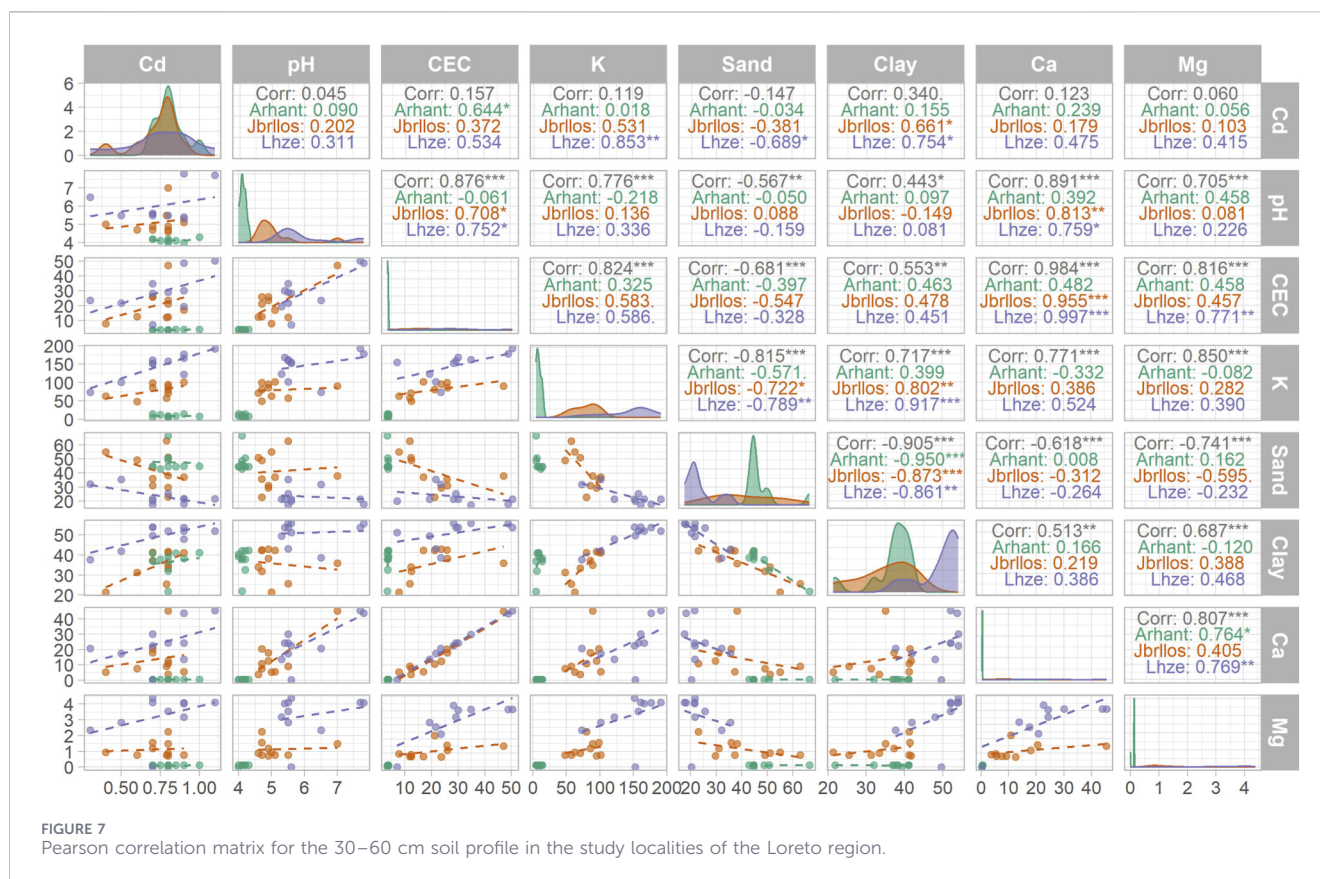
the presence of abundant hydrated oxides, clay minerals, and organic matter, while its mobility is further influenced by soil pH (Kubier et al., 2019). By contrast, the cacao soils of Jbrillos and Arhant, where sandy textures are more prevalent, showed lower Cd contents. These results are consistent with the observations of Scaccabarozzi et al. (2020), who also reported lower Cd levels in sandy soils.

In the 0–30 cm profile (Figure 6), strong positive correlations were observed between Cd and Ca ($r = 0.72$), Cd and Mg ($r = 0.77$), and Cd and CEC ($r = 0.74$), suggesting that cadmium content is strongly influenced by cation exchange capacity and the presence of basic cations. An inverse relationship between Cd and sand content ($r = -0.63$) was also noted, consistent with the fact that sandy soils tend to retain fewer heavy metals. Among the study sites, Lhze most closely reflected these conditions, exhibiting high correlations with cations (Ca, Mg, and K), which were particularly associated with higher CEC values. In the 30–60 cm profile (Figure 7), the correlations were generally stronger, especially in Lhze, where Cd showed a strong association with K ($r = 0.85$) and with CEC ($r = 0.53$). This pattern may be attributed to greater stabilization of Cd in less mobile forms at deeper soil profiles.

In Figure 6, pH shows a positive but weak relationship with Cd across all soils; meanwhile, cation exchange capacity (CEC) emerges as the most influential factor, particularly in Jbrillos and Lhze. This indicates that Cd behavior in the 0–30 cm soil layer is more strongly dependent on soil type than on any single chemical factor. Figure 7 shows that in Arhant, Cd is clearly associated with higher CEC, even at greater depths, whereas in Jbrillos and Lhze the relationship is

moderate but less consistent. Therefore, unlike the surface layer, in the 30–60 cm depth interval CEC remains more explanatory than pH, although with lower intensity. In addition, a significant and positive correlation between clay content and Ca and Mg was observed, with correlation coefficients of 0.496 and 0.685, respectively.

Calcium exhibits specific resistance mechanisms when plants are exposed to Cd stress and serves as an effective means of controlling Cd translocation from soil to rice grains (Liu et al., 2023). In this study, Cd showed positive correlations with Ca, Mg, and CEC, indicating that these elements contribute to Cd immobilization in the soil by retaining this metal and preventing its transfer into cacao tissues and beans. Consequently, calcium (Ca^{2+}) reduces Cd mobility within plants, thereby limiting its translocation from roots to shoots and decreasing overall toxicity (Argüello et al., 2022). Similarly, Adarme-Durán et al. (2024) reported positive correlations between Cd with Ca, Mg, and K in cacao farms, consistent with our results. These correlations were particularly strong in Lhze, where Cd stabilization in less mobile forms was more evident at deeper soil profiles. An inverse relationship was also observed between Cd and sand content, consistent with the fact that sandy soils tend to retain fewer heavy metals. Under such conditions, Cd is highly mobilized and leached into depths between 0 and 30 cm (Kruszewski et al., 2018; Villalaz-Pérez et al., 2024). In contrast, our study shows greater Cd stabilization in less mobile forms within deeper profiles (30–60 cm). Therefore, sand content has a significant negative correlation with Cd retention parameters (Marković et al., 2019).



4 Conclusion

The Lhze locality exhibited a higher cadmium content. This result underscores the susceptibility of this locality to Cd accumulation, likely due to its combination of clayey texture, high Ca and Mg contents, high CEC, and slightly acidic pH, conditions that favor metal adsorption. Other variables also differed significantly. For instance, pH was more acidic in Arhant and closer to neutral in Lhze, which can affect Cd bioavailability, as its mobility tends to increase in more acidic soils. Similarly, CEC, Ca, and Mg values were significantly higher in Lhze, reflecting a greater cation retention capacity of the soil. Regarding the spatial distribution of Cd, in the surface profile (0–30 cm), Lhze exhibited significant spatial autocorrelation and moderate predictive capacity, whereas Arhant and Jbrllos showed low autocorrelation and limited predictability. At deeper layers (30–60 cm), all three localities displayed weak spatial autocorrelation and poor model predictability, indicating a heterogeneous distribution of Cd without a defined spatial pattern. Overall, the spatial distribution of Cd in cacao soils revealed, in most localities and depths, low autocorrelation and limited predictive capacity, attributable to high local variability. The maps represented the spatial distribution of the metal and guided the identification of potential accumulation zones. Such analyses are essential to guide agricultural management decision-making, environmental monitoring, and risk assessment of heavy metal contamination in cacao-producing areas and other crops in the Peruvian Amazon basin. These findings provide essential insights for guiding agricultural management decision-making,

environmental monitoring, and metal contamination risk assessment in cacao-growing areas and other agrarian systems in the Peruvian Amazon basin. Furthermore, to promote the immobilization of cadmium from soil to plants, it is necessary to apply well-matured compost derived from cocoa residues and simultaneously establish leguminous cover crops to enhance cation exchange capacity (CEC) and soil structural stability. Through these practices, overall soil quality could be improved.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

GV-T: Formal Analysis, Methodology, Validation, Writing – original draft, Investigation. RC-R: Software, Formal Analysis, Visualization, Data curation, Writing – review and editing. NG-J: Data curation, Formal Analysis, Software, Visualization, Writing – review and editing. CM: Conceptualization, Supervision, Validation, Visualization, Writing – review and editing. JC: Formal Analysis, Funding acquisition, Investigation, Project administration, Supervision, Writing – original draft. RS: Conceptualization, Formal Analysis, Investigation, Methodology, Project administration, Resources, Visualization, Writing – original draft.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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