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Soil quality in the plains and piedmont areas of Valle del Cauca, Colombia: impact of heavy metal concentrations

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ABSTRACT

This study evaluated the quality of agricultural soils in Valle del Cauca, Colombia, through an integrated analysis of physicochemical properties and heavy metal concentrations. The research was conducted in the plains and piedmont areas of the region. The Soil Quality Index (SQI) ranges from 0 to 1, with values between 0.20–0.39 indicating low quality; 0.40–0.59, moderate; 0.60–0.79, high; and 0.80–1.00, very high. The results show that the evaluated agricultural soils exhibit moderate quality (SQI = 0.57), providing suitable conditions for agricultural productivity. Soil quality was positively influenced by saturated hydraulic conductivity, porosity, pH, and cation exchange capacity. The impact of heavy metals such as Cr, Ni, Pb, and Co on soil quality was moderate. Electrical conductivity contributed less to soil quality, mainly due to the established threshold values rather than actual salinity issues. It is recommended that agricultural practices that may alter soil properties and compromise its quality be avoided. The proposed soil quality index proved useful for monitoring soil conditions, ensuring sustainable agricultural productivity, and mitigating the effects of potentially toxic trace elements.

Keywords: heavy metals in soils, quality index, soil quality, soil properties.

Qualidade do solo nas áreas de planície e piedemonte do Valle del Cauca, Colômbia: impacto das concentrações de metais pesados

RESUMO

O objetivo deste estudo foi avaliar a qualidade dos solos agrícolas no Vale do Cauca, Colômbia, por meio de uma análise integrada das propriedades físico-químicas e das concentrações de metais pesados. A pesquisa foi realizada nas áreas de planície e piedemonte da região. O Índice de Qualidade do Solo (IQS) varia de 0 a 1, com valores entre 0,20–0,39 indicando baixa qualidade, 0,40–0,59 moderada, 0,60–0,79 alta e 0,80–1,00 muito alta. Os resultados mostram que os solos agrícolas avaliados apresentam moderada qualidade (IQS = 0,57), oferecendo condições adequadas para a produtividade agrícola. A qualidade do solo foi positivamente influenciada pela condutividade hidráulica saturada, porosidade, pH e

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capacidade de troca catiônica. O impacto de metais pesados como Cr, Ni, Pb e Co sobre a qualidade do solo foi moderado. A condutividade elétrica contribuiu menos para a qualidade do solo, principalmente devido aos valores de referência estabelecidos, e não por problemas reais de salinidade. Recomenda-se evitar práticas agrícolas que possam alterar as propriedades do solo e comprometer sua qualidade. O índice de qualidade do solo proposto mostrou-se útil para o monitoramento das condições do solo, garantindo a produtividade agrícola sustentável e mitigando os efeitos de elementos-traço potencialmente tóxicos.

Palavras-chave: índice de qualidade, metais pesados em solos, propriedades do solo, qualidade do solo.

1. INTRODUCTION

The concept of soil quality emerged in the 1990s, highlighting the need for tangible indicators to measure it (De *et al.*, 2022). The concept of soil quality includes the capacity of the soil to function efficiently in a healthy ecosystem based on the evaluation of its properties (Álvarez *et al.*, 2025). Soil quality is defined as the capacity of soils to function within ecological and management contexts, thereby supporting ecosystem services and biological productivity (De *et al.*, 2022). Preserving soil quality is therefore crucial, as it represents an essential resource for agricultural productivity and ensures the ability to meet the food demands of a continuously growing global population. However, the intensive use and management of agricultural soils have led to significant deterioration of their physical, chemical, and biological properties (Marion *et al.*, 2022).

Soil quality, influenced by trace elements such as heavy metals and metalloids, has a considerable impact on agricultural productivity. In China, for instance, grain cultivation in soils contaminated with these inorganic elements is widespread. It has been estimated that contamination affects 12 million tons of grain annually, resulting in economic losses of approximately US$2,570 million (Rodriguez Eugenio *et al.*, 2019).

According to the United States Natural Resources Conservation Service (USDA, 2015), soil quality is associated with its ability to perform essential functions for intended purposes. These functions include regulating the flow of water and solutes, providing biological support for diversity, activity, and productivity, filtering and buffering organic and inorganic compounds, storing and cycling nutrients and carbon, and offering physical stability and structural support.

In Colombia, the Ministry of Environment and Sustainable Development (Colombia, 2016) has adopted the concept of soil quality as a tool for monitoring soil conditions and guiding decision-making regarding preservation, restoration, and sustainable use. Specifically, soil quality refers to its ability to fully fulfill its function as a substrate for plant development productivity, in the environment for water regulation and distribution, acting as a buffer, and the physical, chemical, and biological properties, integrating them satisfactorily (Marion *et al.*, 2022).

This study aimed to establish a Soil Quality Index (SQI) for the plains and piedmont areas of Valle del Cauca. In both its simple and complex forms, the soil quality index is an instrument for diagnosing soil degradation (Meza Mori *et al.*, 2025). The SQI was developed based on the assessment of physical and chemical properties, as well as the concentrations of selected trace elements. Evaluation and monitoring through quality indicators will enable the implementation of preventive and protective measures for soil resources, supporting farmers and environmental authorities in ensuring sustainable soil management. Furthermore, studies conducted at the watershed level are regarded as an optimal scale for environmental monitoring. Hydrological processes, soil erosion, and land-use change at the watershed scale have been demonstrated by Zhang *et al.* (2020) to govern the migration, transport, and accumulation of potentially toxic elements (PTEs), including Cd, Pb, Cr, Cu, and Ni.

2. MATERIAL AND METHODS

2.1. Study area and sampling

The study was carried out in the plains and piedmont areas of Valle del Cauca (Figure 1), located between 3°30′ and 5°10′ north latitude and 75°42′ and 77°33′ west longitude (Marín-Pimentel *et al.*, 2023). 87.73% of the sampling points correspond to the flat area and the remainder to the piedmont. Simple Random Sampling was applied following the methodology proposed by Corral *et al.* (2015). Agricultural soil samples were collected across 13 watersheds in the region. To calculate the soil quality index, the surrounding areas of Arroyohondo, Yumbo, and the Zona Industrial (AYZ) were grouped together, which improved representativeness in the area by increasing the sample size (14) and reducing the total to 11 watersheds. A total of 489 sites were analyzed, of which 271 were classified as belonging to the Mollisols soil order, 128 to the Vertisols order, and 90 to the Inceptisols order.

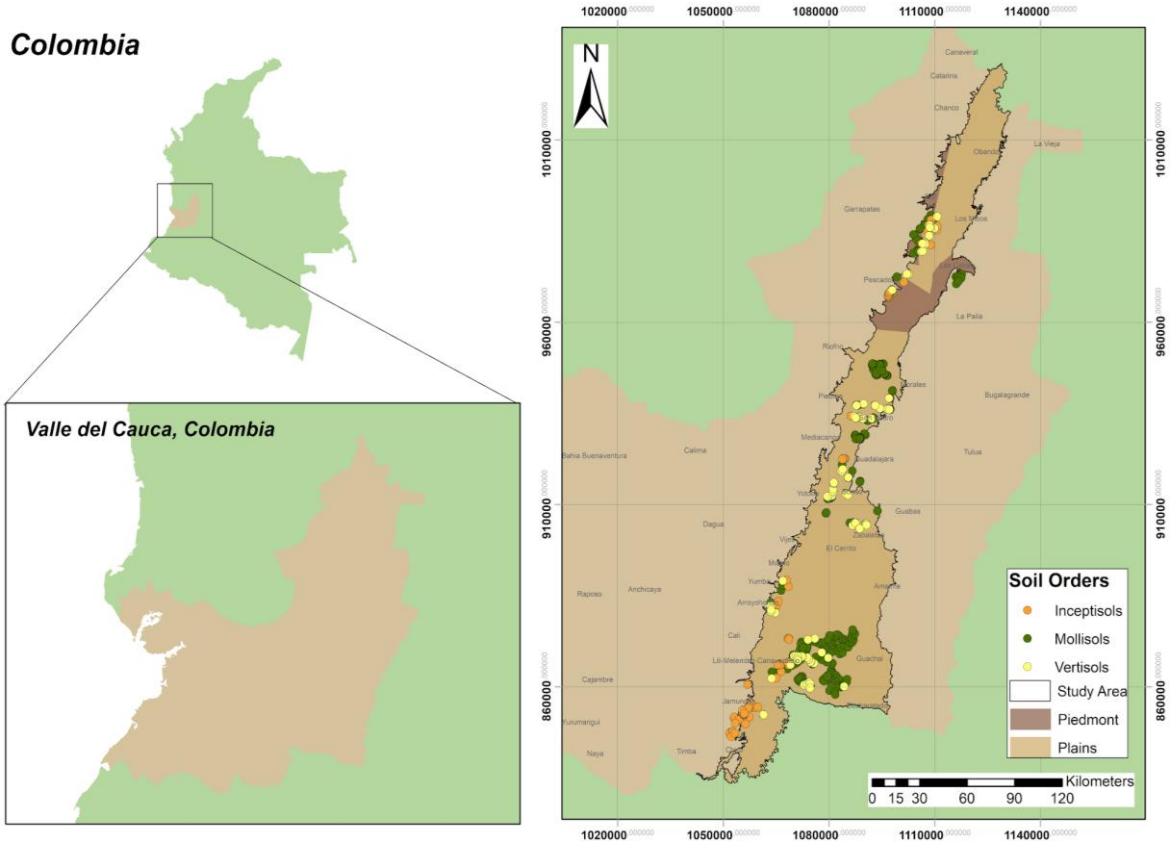


Figure 1. Geographic location of the study area in the plains and piedmont of Valle del Cauca (Colombia), and spatial distribution of the sampling sites.

2.2. Properties evaluated, methods, and techniques for their determination

The evaluated properties included both physical and chemical attributes of the soils. Physical properties comprised sand, silt, and clay fractions, texture, hydraulic conductivity, bulk density, saturated hydraulic conductivity, moisture retention, available water depth, and porosity. Chemical properties included pH, electrical conductivity, organic matter content, and cation exchange capacity. All analyses were conducted using standardized laboratory techniques (Marín-Pimentel *et al.,* 2023).

Analyses of the total concentrations of Hg, As, Cd, Ni, Pb, Cr, and Co were conducted using the wet mineralization technique (HNO_3–HCl) following method 3051A (USEPA, 2007a), with measurements obtained by graphite furnace atomic absorption spectroscopy (USEPA, 1994). For Co, the Colombian technical standard NTC 5526 was applied (ICONTEC,

2007). Detection limits for heavy metals were 0.02 mg·kg⁻¹ for Cd, 1.00 mg·kg⁻¹ for Cr and Ni, 0.75 mg·kg⁻¹ for Pb, and 0.10 mg·kg⁻¹ for Co. Determinations of As and Hg were performed using atomic absorption spectroscopy with the hydride generator technique, with detection limits of 0.10 mg·kg⁻¹ for both elements. All analyses were carried out at AGRILAB, a specialized laboratory for physicochemical analysis in the agricultural and environmental sector (Rueda-Saa *et al.* 2025).

AGRILAB is an ISO/IEC 17025 accredited laboratory providing agricultural and environmental testing services, adhering to international standard Quality Assurance and Quality Control (QA/QC) protocols recommended by the USEPA (2007b) (such as EPA Methods 3050B/3051A for digestion and EPA 6010D/7000B for heavy metals by ICP-OES or Atomic Absorption) and IDEAM Technical Guidelines. In its analytical batteries for determining total heavy metal concentrations, the analytical control methodology begins with processing a reagent blank (using the same acids and deionized/ultrapure water without sample) for each digestion batch (typically 1 blank per 10 to 20 samples). The same sample is digested and analyzed in duplicate within the same batch (minimum frequency of 10% per batch, or 1 duplicate per 10–20 samples). A known amount (spike) of a certified standard of Hg, Cd, Cr, Ni, Pb, and Co is added to a sample aliquot prior to the acid digestion step. Performance is evaluated through Control Charts using replicates of intermediate calibration standards and repeated analyses over time.

2.3. Methodological proposal to determine the soil quality index

This study proposes a SQI that integrates the impact of heavy metal concentrations with a comprehensive assessment of physicochemical properties. The evaluation was conducted on agricultural soils in the plains and piedmont regions of Valle del Cauca. The methodology applied represents an adaptation of the approach developed by Cantú *et al.* (2007). The SQI accounts for the combined effects of physicochemical properties and potentially toxic elements through the Kaiser–Meyer–Olkin (KMO) index and Bartlett's test of sphericity (Marín-Pimentel *et al.* 2026a). Results were weighted according to the surface area of the watersheds where samples were collected, yielding a single index value. The SQI was interpreted using the five categories proposed by Cantú *et al.* (2007; 2009), ranging from very low quality (0.00–0.19), low quality (0.20–0.39), moderate quality (0.40–0.59), high quality (0.60–0.79), and very high quality (0.80–1.00).

The selected indicators included pH, organic matter (OM), electrical conductivity (EC), cation exchange capacity (CEC), porosity (η), permanent wilting point (PWP), saturated hydraulic conductivity (Ks), bulk density (BD), and the heavy metals Cr, Ni, Pb, and Co. The Hg was excluded because mean soil concentrations were below the detection limit (AGRILAB, 2022). As noted by Prieto-Méndez *et al.* (2013), soil quality indicators are not universally applicable; while they may be used in diverse regions worldwide, their validity must be assessed within specific local contexts. It is therefore essential to consider the environmental and soil conditions of the region under study.

In this context, an integrated SQI was developed to reflect the environmental quality of soils, incorporating their physicochemical characteristics. To obtain a single value for each indicator, a weighted average was calculated as a function of the total area of each watershed (Equation 1) (Marín-Pimentel *et al.,* 2023).

$$Im = \sum_{i=1}^{n} \frac{Abi}{At} \text{ x } Mbi \quad (1)$$

Where:

Im = Indicator measure (respective units).

Abi: Area of watershed i (Km^2).

At: Total area (Km^2).

Mbi: Median of the indicator in watershed i.

Figure 2 illustrates the methodology employed for estimating the regional SQI. Maximum values (Imax) and minimum values (Imin) were determined for the normalization of soil quality indicators on a scale from 0 to 1. Minimum values were defined as the lowest statistical values of physicochemical properties and potentially toxic elements recorded in the sampled soils. Three criteria were established to define the maximum values: (1) an ideal condition for agricultural use reported in previous studies, (2) the limited availability of heavy metals in soils according to published research, and (3) a combination of criteria (1) and (2). For heavy metals, maximum values were set as reference concentrations that do not cause environmental deterioration or pose risks to human health. Additionally, values below the critical ranges reported in the literature were considered.

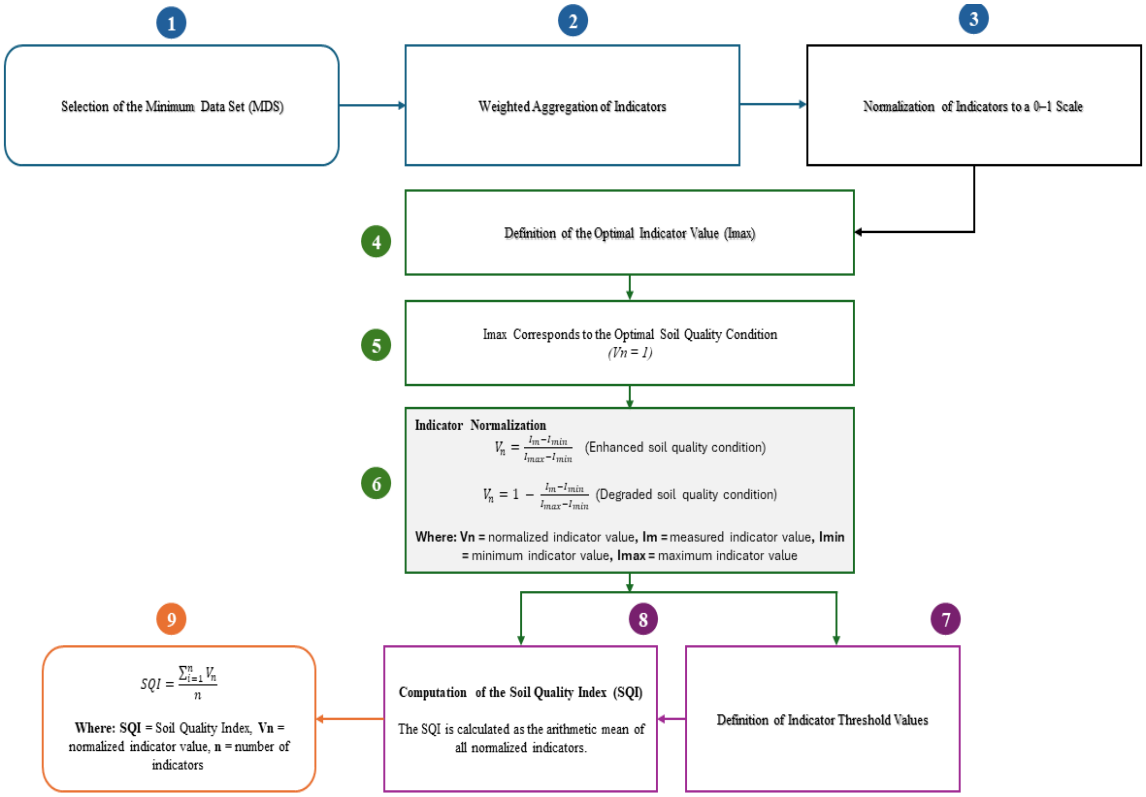


Figure 2. Methodology for estimating the regional soil quality index.

The soil properties electrical conductivity, bulk density, permanent wilting point, and the heavy metals Cr, Ni, Pb, and Co were calculated considering the worst soil quality condition, that is, when their values increase, the normalized value decreases. The other variables were determined based on the best soil condition, that is, when the variable's value increases, the normalized value increases.

2.4. Statistical analysis of the results.

To obtain the regional SQI, variables that were correlated were considered based on the Kaiser–Meyer–Olkin (KMO) index and Bartlett's test of sphericity (Marín-Pimentel *et al.,* 2026a). The degree of correlation between variables was assessed using Spearman's correlation analysis, since the data did not follow a normal distribution. Basic mathematical operations in Microsoft Excel were employed for the calculation of the SQI.

3. RESULTS AND DISCUSSION

3.1. Land use and management by soil type

Table 1 shows land use and management by soil order. The inputs or elements applied to the soil, mainly products resulting from agricultural activities, are indicated in general terms. The predominant crop is sugarcane, alongside other crops and practices such as livestock farming. In addition to agriculture, there are also swine and poultry farming activities.

Table 1. Land use and management in relation to soil type.

Soil order	Geomorphology (% of soil samples)	Crops (% of soil samples)	Sector (% of soil samples)	Inputs / Elements applied to soil (Generalities)	Other crops (other than sugarcane) – Other activities
Mollisols	Flat (87.45) Piedmont (12.55)	Sugarcane (50.50) Other crops (49.50)	Agricultural (87.82) Poultry (8.12) Cultivated pasture (0.74%) Swine (3.32)	Organic fertilizers Agrochemicals (Chemical fertilizers, ripeners, phytosanitary inputs) River water (Potential contamination) Wastewater	Fruit trees, Melon, Watermelon, Rice, Cilantro, Cacao, Corn, Pineapple, Passion fruit, Plantain, Guava, Papaya, Livestock
Inceptisols	Flat (73.33) Piedmont (26.67)	Sugarcane (24.44) Other crops (75.56)	Agricultural (70.00) Poultry (0.00) Cultivated pasture (28.89) Pasture (1.11) Swine (0.00)	Agrochemicals (Chemical fertilizers, phytosanitary inputs River water (Potential contamination)	Orange, Plantain
Vertisols	Flat (98.4) Piedmont (1.6)	Sugarcane (43.75) Other crops (56.25)	Agricultural (78.91) Poultry (12.50%) Cultivated pasture (0.00) Pasture (2.34) Swine (6.25%)	Agrochemicals (Chemical fertilizers, ripeners, phytosanitary inputs) Organic fertilizers Chemical substances (Detergents) River water (Potential contamination)	Corn, Boehmeria fodder, Ramie fodder, Lime, Avocado, Plantain, Grape, Citrus, Star grass, Livestock, Sheep grazing

3.2. Correlation between soil physicochemical properties and potentially toxic elements

The results of the KMO index and Bartlett's test of sphericity were used to examine the relationships among soil variables. Evidence was provided by a KMO index greater than 0.6

and a significance level below 5.00% in Bartlett's test (Garmendia, 2007). Montoya Suárez (2007) proposed that the KMO value should be greater than or equal to 0.50 (Table 2). Quantitative multivariate correlation analysis (factor analysis) was applied to reduce the number of variables, allowing the identification of a minimal set without loss of information. In addition, latent or non-observable variables were identified, with their existence inferred from the data (López-Aguado and Gutiérrez-Provecho, 2019). Soil characteristics with KMO values < 0.5 were excluded, specifically %sand (0.46), %silt (0.20), %clay (0.41), and field capacity (0.49). Trace elements excluded were As (0.37) and Cd (0.47). The exclusion of these variables improved the overall matrix sampling adequacy and ensured the statistical robustness of the retained components. Another exclusion criterion for As and Hg was that only 1.43% of the sampled sites had values above the detection limit (0.1 $mg.kg^{-1}$) for As, and only 1.02% in the case of Hg.

Table 2. Kaiser-Meyer-Olkin index (KMO) and Barttlett's test of sphericity for soil properties and heavy metals.

Variable	pH	OM	EC	CEC	η	PWP	Ks	BD	Hg	Cr	Ni	Pb	Co
Kaiser-Meyer-Olkin index (KMO)	0.72	0.76	0.70	0.82	0.62	0.84	0.80	0.62	0.80	0.83	0.76	0.77	0.84
Barttlett's test of sphericity	Chi-square									20954			
	Degrees of freedom									78			
	Significance level									p –value < 0.001			

OM (organic matter), EC (electrical conductivity), CEC (cation exchange capacity), η (porosity), permanent wilting point (PWP), Ks (saturated hydraulic conductivity), BD (bulk density).

According to Martínez *et al.* (2009), correlation analysis between soil physicochemical properties and heavy metals indicates that relationships may vary from weak to strong. In this study, the strongest correlations were observed between BD and η, PWP and Ks, and between Cr and Ni–Co (Figure 3). Weak positive correlations were identified between PWP and Cr and Ni, while moderate to strong direct correlations were observed with Co. Hooda (2010) reported that cations in the aqueous phase of soil are poorly soluble and their presence is limited. An inverse and weak correlation was established between Ks and the metallic elements Cr, Ni, and Co (Figure 3). This relationship may contribute to the leaching of heavy metals, since solute movement is conditioned by hydrodynamic dispersion and advection, which are largely controlled by Ks and dependent on soil texture (Hooda, 2010).

An unrotated principal component analysis (PCA) was performed on the standardized variables. The principal component analysis for soil properties and heavy metals retained the first four components, as they each had an eigenvalue greater than 1 and explained 63.60% of the total variance (Table 3). The variables that contributed most positively to the first component were PWP, Cr, and Co, explaining 27.40% of the total variance. For the second component, which explained 18.30% of the total variance, the highest-weighted variables were OM, η, and BD, with the first two showing negative contributions and the third a positive one. In this context, organic matter influences soils by increasing macropores (Jaramillo, 2002) and consequently decreasing bulk density.

For the third component, the highest contributions were from pH (positive) and Hg (negative), explaining 9.6% of the variance. Consequently, unlike various other trace metals, Hg mobility decreases in soils at pH < 3.00 and pH > 12.00, due to organic matter having a very high buffering capacity in acidic and alkaline media (Kabata-Pendias, 2011). Soil pH is one of the key factors to consider regarding Hg adsorption in soil, alongside its chemical form, the nature of organic and inorganic colloids, redox potential, and grain size and distribution

(Alloway, 2012). Finally, explaining 8.30% of the total variance, the fourth component grouped the variables EC, CEC, and Ks with positive contributions, and Pb with a negative contribution. In particular, a positive correlation exists between Pb and fine material distribution in mineral soils (Kabata-Pendias, 2011).

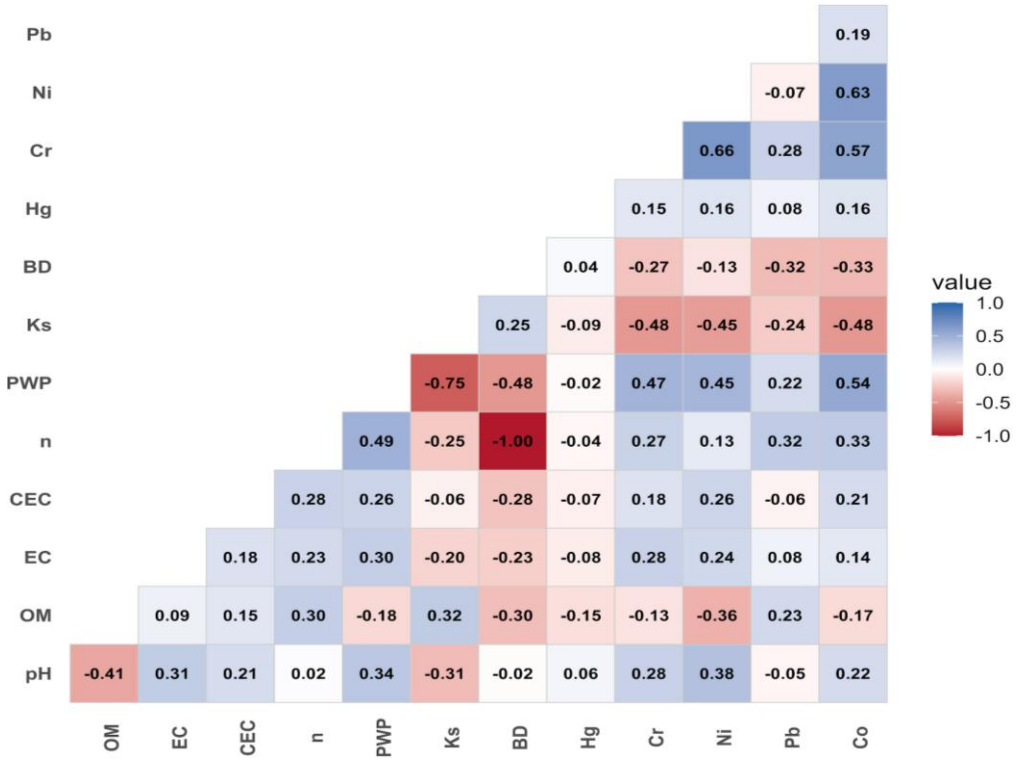


Figure 3. Spearman correlation for soil properties and heavy metals. OM (organic matter), EC (electrical conductivity), CEC (cation exchange capacity), η (porosity), permanent wilting point (PWP), Ks (saturated hydraulic conductivity), BD (bulk density).

Table 3. Principal component analysis for soil properties and statistically correlated heavy metals.

Variables	Principal Components			
	PC1	PC2	PC3	PC4
pH	0.21300444	0.26013047	0.486097232	-0.13627601
OM	-0.08915125	-0.48961317	-0.292589022	-0.07960848
EC	0.05526011	-0.18359909	-0.002219345	-0.47233832
CEC	0.16048924	-0.12816745	0.397615029	-0.43146937
η	0.33066200	-0.46124927	0.019259624	-0.03042967
PWP	0.41658342	-0.04251243	0.236061891	0.18605058
Ks	-0.32863535	-0.09677111	-0.120930192	-0.34725759
BD	-0.33066195	0.46124927	-0.019259717	0.03042980
Hg	0.09439294	0.15874854	-0.464484874	-0.35779227
Cr	0.38293500	0.16150801	-0.234648943	-0.06111289
Ni	0.32820228	0.32262600	-0.222977575	-0.15182787
Pb	0.13473862	-0.15336438	-0.194708215	0.50233001
Co	0.36909700	0.16403572	-0.300783475	-0.04037588
Standard deviation	1.8866793	1.5434865	1.1158782	1.04061258
Proportion of variance	27.4%	18.3%	9.6%	8.3%
Cumulative variance	27.4%	45.7%	55.3%	63.6%

3.3. Minimum and maximum values for the soil quality index

The minimum values for soil properties such as pH, OM, EC, CEC, PWP, η, and BD were adjusted according to the lowest statistical values calculated from the dataset. For Cr, Ni, Pb, and Co, minimum values were set below the detection limits for each element (AGRILAB, 2022) (Table 2).

The maximum value for pH was defined at the upper limit of the neutral condition (ICA, 1992), since heavy metals are less available under non-acidic conditions (Galán Huertos and Romero Baena, 2008; Rodríguez Eugenio *et al.*, 2019) (Table 2). According to López and Estrada (2015), the optimal pH value for agricultural soils is 6.5. For OM, the threshold at which the high-content category begins was assigned (ICA, 1992). Chelates formed between heavy metals and OM allow degradation of these elements by soil organisms (Galán Huertos and Romero Baena, 2008). The maximum EC value was established at the limit separating non-saline soils (Fernández Liná res *et al.*, 2006), as increased salinity may affect the retention or mobilization of metallic elements (Galán Huertos and Romero Baena , 2008).

The Imax for CEC was set at the upper limit of the suitable condition for soils classified as high (25.00 cmol(+).kg^{-1}) (ICA, 1992; López and Estrada, 2015). The maximum value for porosity (η) was determined as the optimal condition, corresponding to the lower limit of the "satisfactory" category, thereby avoiding compaction problems (Jaramillo, 2002). For PWP, the maximum value of the dataset plus a 10% safety margin was applied, preventing plants from being subjected to excessive suction forces during water extraction (Pachés, 2019). This criterion was considered under the assumption that loamy texture represents the ideal soil condition (López Díaz and Estrada Medina, 2015).

The maximum value for Ks was defined as the midpoint of the "Moderately High" category interval (Jaramillo, 2002). Solute movement in soil is influenced by Ks (Polo *et al.*, 2003), and metal desorption may be associated with water saturation under anaerobic conditions (Rodríguez Eugenio *et al.*, 2019). A maximum BD value was established between 1.10 and 1.40 g·cm^{-3}, depending on the predominant textures of the study area. This range prevents problems with root growth and water movement, and is preferable to low BD values (Corsi and Muminjanov, 2019). The application of this criterion avoids compaction issues, particularly when BD exceeds 1.6 g·cm^{-3} (Ramírez Carvajal, 1997). According to FAO (2023), bulk densities between 1.0 and 1.6 g·cm^{-3} may not significantly affect plant growth or soil processes.

The maximum levels of Cr, Ni, Pb, and Co were defined in accordance with the reference values proposed for the flat and piedmont areas of Valle del Cauca (Cr = 85, Ni = 45, Pb = 5.08, Co = 21 in mg.kg^{-1}) (Marín-Pimentel *et al.*, 2026b). These were calculated as the 75th percentile (CONAMA, 2009). The reference levels were obtained from background levels determined using the statistical method proposed by Dung *et al.* (2013). Nineteen percent (19.42%) of the sites presented critical chromium (Cr) values in agricultural soils exceeding the 100 mg.kg^{-1} threshold set by the FAO and the World Health Organization (WHO); 25.36% of the sites exceeded the maximum permissible limit for nickel (Ni) of 50 mg.kg^{-1}; no records exceeded the 100 mg.kg^{-1} threshold for lead (Pb); and 1.64% were above the 50 mg.kg^{-1} critical value for cobalt (Co) (FAO and WHO, 2001).

3.4. Determination of the soil quality index

An SQI value of 0.57 was obtained in this study, indicating that the soils of the study area are of moderate quality. The SQI values derived for soil properties and heavy metal concentrations (Table 4) were aligned with the definition of soil quality established by Wilson and Sasal (2017). This definition integrates the concepts of soil quality, crop growth, and dynamic quality mediated by the management and use of the edaphic environment.

Table 4. Definition of the percentage contribution to soil quality for each indicator from the measured values.

Watershed	% Area	Median values for each indicator											
		pH	OM	EC	CEC	η	PWP	Ks	BD	Cr	Ni	Pb	Co
		Units	%	$dS.m^{-1}$	$cmol_{(+)}kg^{-1}$	%	% $p.v^{-1}$	$cm.h^{-1}$	$g.cm^{-3}$	$mg.kg^{-1}$			
AYZ	0.0315	6.88	2.46	0.40	36.50	53.40	24.97	4.03	1.24	55.03	44.70	10.45	26.23
Guabas	0.0568	7.25	2.31	0.32	23.84	50.00	39.88	0.28	1.33	115.00	45.00	3.84	28.00
Guachal	0.2775	6.94	2.34	0.27	23.40	40.75	18.93	4.63	1.57	21.35	20.59	0.67	8.73
Guadalajara	0.0744	6.89	1.98	0.32	21.42	45.66	36.97	0.25	1.44	36.50	21.00	3.10	14.50
Jamundí	0.0824	5.66	4.78	0.24	9.56	50.75	21.00	4.15	1.31	31.39	11.35	7.91	16.70
Meléndez	0.0455	5.60	2.10	0.20	26.60	41.89	23.78	1.60	1.54	37.45	23.45	0.43	9.85
Pescador	0.0477	7.46	0.90	0.29	18.12	44.63	34.32	0.08	1.47	97.90	121.00	2.72	32.50
RUT	0.1041	7.31	1.45	0.42	22.61	48.72	41.92	0.06	1.36	65.10	46.50	8.94	18.10
San Pedro	0.0279	7.38	2.32	0.49	23.00	48.68	38.65	0.40	1.36	34.00	24.00	3.40	13.00
Sonso	0.0338	7.51	2.23	0.43	27.98	51.70	46.10	0.24	1.28	82.00	38.00	3.70	27.00
Tuluá	0.2184	7.13	2.00	0.46	20.77	45.28	34.41	0.31	1.45	108.00	57.00	1.28	17.00
% contribution to soil quality by indicator													
Indicator Measure (Im)		6.92	2.27	0.34	21.93	45.51	30.02	1.96	1.44	59.95	38.26	3.19	16.16
Imax		7.30	3.10	2.00	25.00	50.00	66.00	2.00	1.50	85.00	45.00	5.08	21.00
Imin		4.15	0.40	0.07	1.05	25.66	6.77	0.00	0.62	1.00	1.00	0.75	0.10
Normalized Value (Vn)		0.88	0.69	0.86	0.87	0.82	0.61	0.98	0.06	0.30	0.15	0.44	0.23
SQI regional		0.57											

AYZ (Arroyohondo-Yumbo-Zona Industrial), RUT (Roldanillo-Unión-Toro), Imax (Maximum value of the indicator), Imin (Minimum value of the indicator).

Ks was found to contribute significantly to the high soil quality, with an SQI value of 0.98 (Table 2). This property was identified as being related to soil drainage and strongly conditioned by moisture. The value of Ks could be substantially reduced if soil conditions shifted from saturation to the permanent wilting point (PWP). This behavior was influenced by other properties such as structure, texture, and clay mineralogy (Jaramillo, 2002). High Ks values were associated with accelerated transport of contaminants to the subsoil, thereby contributing to groundwater contamination (Marín-Pimentel *et al.*, 2023). In this study, the weighted average of Ks medians across watersheds was classified as moderately high (Jaramillo, 2002).

Bulk density (BD) was identified as a variable that impacted soil quality in the plains and foothills of the Valle del Cauca region. The weighted average BD (1.44 $g \cdot cm^{-3}$) was situated within the optimal range for root growth in soils with sandy-sandy clay loam and sandy-sandy-silty clay loam textures (Corsi and Muminjanov, 2019). This value was close to the ideal condition (1.33 $g \cdot cm^{-3}$), which corresponds to a pore space of 50% and a medium texture (USDA, 2008b).

CEC was determined to have a significant impact on soil quality (0.87), with a value of 21.93 $cmol(+).kg^{-1}$. This property was identified as reflecting the soil's capacity to bind cations, store nutrients for plants, and regulate pH. Sandy soils with low organic matter content were observed to have low CEC. In Colombia, organic matter or crop residues are rarely incorporated into soils to improve fertility, and 85% of soils present acidic and low fertility conditions, while only 15% exhibit medium to high fertility (Bueno Buelvas and Fernández Lizarazo, 2019).

pH was also found to contribute significantly to soil quality (0.88). This indicator was strongly correlated with the availability of heavy metals, which are absorbed to a lesser extent under acidic conditions (Galán Huertos and Romero Baena, 2008). According to Marín-Pimentel *et al.* (2023), pH plays a crucial role in nutrient availability for plants. The median pH value was 6.92, placing soils in the neutral to near-neutral category, with favorable nutrient availability for crops (ICA, 1992). A pH range of 5.5–7.5 was reported to favor nutrient availability (FAO, 2020).

Porosity (η) was identified as an important contributor to soil quality (0.82), with a weighted average of 45.41% across watersheds. This value placed soils in the low category (Jaramillo, 2002). Only 36.36% of watersheds exhibited satisfactory porosity, while 63.64% were classified as low. Increases in BD were associated with reduced porosity (Corsi and Muminjanov, 2019) and greater compaction (Giménez, 2013). Marín-Pimentel *et al.* (2023) reported that 19% of soils in the study area presented some degree of compaction. Porosity was considered a fundamental variable for soil quality, as it regulates water retention and biological and physicochemical exchange (González-Barrios *et al.*, 2011). Porosity is associated with texture; in clay soils, microporosity predominates, which negatively affects plants with low tolerance to excess moisture. This can be improved by adding organic matter, which balances the pore size. In sandy soils, which have low organic matter content, there is a deficiency of retained water and leaching of nutrients due to the abundance of macropores (Avila Pedraza, 2025).

Ni concentration was found to negatively contribute to soil quality (0.15). Median values across watersheds were below the proposed reference level (45.00 $mg \cdot kg^{-1}$), with only 27.27% exceeding this threshold. Due to human activities, sources of Ni in the environment originate mainly from steel manufacturing, fossil fuel combustion, mining, smelting, petroleum refining, motor vehicles, and sewage sludge (Selinus *et al.*, 2013). Most Ni was immobilized by clay minerals and organic matter. Adsorption–desorption processes were influenced by pH, with low pH favoring adsorption at low concentrations, while high pH and elevated Ni concentrations promoted precipitation–desorption (Gómez-Puentes *et al.*, 2020). The geochemical classification of Ni places it as a siderophile trace element (TE) that frequently presents geochemical associations with ultramafic igneous rocks, ferromagnesian minerals, Fe and Mn

oxides, and black shales (Selinus *et al.*, 2013). Representative geological sources of Ni, from highest to lowest concentration, are ranked as ultramafic rocks (2000 mg.kg^{-1}), black / bituminous shales (< 300 mg.kg^{-1}), and gabbro-basalts (130 mg.kg^{-1}) (Alloway, 2012)."

Low contributions to soil quality were observed from Co (0.23), Cr (0.30), and Pb (0.44), while OM made a moderate contribution (0.69). OM is essential for the incorporation of N, P, S, and other minor elements, while also improving physical properties, increasing CEC, and contributing to buffering capacity. Furthermore, OM adsorbs heavy metals, particularly within the humus fraction (Rodríguez Eugenio *et al.*, 2019). Mean Co values indicated that 36.36% of watersheds exceeded the reference level proposed for the study area (21.00 mg·kg^{-1}). Human activities related to the presence of Co in the biosphere are associated with fossil fuel combustion, mining, and smelting (Selinus *et al.*, 2013). Co was reported to be strongly adsorbed by Fe and Mn oxides and carbonates, and to form chelates with organic matter. According to Mendoza-Escalona *et al.* (2021), Co exhibits low risk of translocation and mobility to plants under basic soil conditions. In its geochemical classification, Co is considered a siderophile element and shows associations with ultramafic igneous rocks, ferromagnesian minerals, and Fe and Mn oxides (Selinus *et al.*, 2013). The primary geological sources of cobalt are found in ultramafic rocks (110 mg.kg^{-1}), black / bituminous shales (67 mg.kg^{-1}), gabbro-basalts (45 mg.kg^{-1}), and schists (20 mg.kg^{-1}) (Alloway, 2012).

For Cr, the reference level of 85.00 mg·kg^{-1} was exceeded in only 27.27% of watersheds. Depending on the natural composition of sediments and rocks, Cr concentration in soils can vary significantly; its levels primarily increase due to anthropogenic atmospheric deposition or as a result of solid or liquid discharges of chromium by-products, such as chrome plating baths or ferrochrome slag (Dwivedi *et al.*, 2023) Total soil Cr concentration shows little correlation with the concentration in plant leaves, whereas evidence suggests a correlation with easily extractable Cr, and soil-to-plant concentration ratios are associated with soil properties such as organic matter (OM), pH, or oxidation-reduction potential, as well as plant species (Hooda, 2010).

In industry—for example, in leather finishing and tanning, plastic coatings, corrosion resistance in metal electroplating, and in wood preservatives and pigments—chromium (Cr) is a widely used element (Pabón Guerrero *et al.*, 2020). Classified as a lithophile, Cr typically occurs in silicate-type minerals and is found in association with ultramafic igneous rocks (Selinus *et al.*, 2013). The approximate abundance of Cr in soils follows the order: high clay content > low clay content > medium clay/silt content (Kabata-Pendias and Mukherjee, 2007). There is variation in the Cr content in phosphorus fertilizers (66–245 mg·kg^{-1}), nitrogen fertilizers (3.2–19 mg·kg^{-1}), manure (1.1–55 mg·kg^{-1}), and sewage sludge (8–41,000 mg·kg^{-1}) (Selinus *et al.*, 2013).

Pb exhibited the same percentage of exceedances as Cr, relative to the recommended reference level of 5.08 mg·kg^{-1}. According to Selinus *et al.* (2013), concentrations in the biosphere resulting from human activities are related to fossil fuel combustion, mining, smelting, motor vehicles, sewage sludge, and pesticides. Pb accumulation at the soil surface was considered ecologically significant due to its strong impact on biological activity (Kabata-Pendias, 2011). Lead (Pb) is released into the environment through devices designed to shield against X-rays, battery manufacturing, metal products, ammunition, the mining industry, and the burning of fossil fuels (Pabón Guerrero *et al.*, 2020). Selinus *et al.* (2013) report concentration ranges for Pb in phosphorus fertilizers (4–1000 mg·kg^{-1}), nitrogen fertilizers (2–27 mg·kg^{-1}), manure (11–27 mg·kg^{-1}), and sewage sludge (30–3600 mg·kg^{-1}). Alloway (2012) specifies different global Pb concentration ranges in phosphorus fertilizers (7–225 mg·kg^{-1}), nitrogen fertilizers (2–1450 mg·kg^{-1}), liming materials (20–1250 mg·kg^{-1}), and manure (6.6–350 mg·kg^{-1}).

Indicators of low contribution to soil quality included PWP (0.39). High PWP values were

associated with compaction, where water was retained more strongly in compressed pores (USDA, 2008a). The median PWP value across watersheds was 30.02%. EC also exhibited a low contribution (0.14), with a weighted average of 0.34 $dS \cdot m^{-1}$, a value that does not represent salinity problems or affect crop development (ICA, 1992). The low contribution of EC was attributed to the large difference between assigned Imax and measured Imin. Mixtures of Ca, Na, Mg, and K cations with Cl^- and sulfate anions were commonly found in soils, and increases in these concentrations were reported to cause degradation of plants and soil environments (FAO, 2020).

Based on the soil quality index (moderate quality), it is recommended that agricultural activities in the region be maintained by monitoring pH and applying liming when necessary, maintaining the pH within the range of 6.5 to 7.2. The use of agricultural or dolomitic lime increases the negative charge of clays and organic matter, reducing the bioavailability and mobility of potentially toxic elements (Kabata-Pendias, 2011). Optimize the CEC by adding mature compost or biochar to the soil to increase cation exchange sites, which immobilizes nutrients and stabilizes metals within the solid matrix (Bolan *et al.*, 2014). Manage bulk density and porosity by implementing minimum or no-till practices to reduce compaction, enhance infiltration, and maintain adequate aeration (FAO, 2024). Finally, increase organic matter through the addition of stabilized organic residues to optimize the permanent wilting point (increasing available water retention) without raising the risk of phytotoxicity (Lal, 2020).

4. CONCLUSIONS

An integrated analysis of physicochemical properties and heavy metal concentrations was carried out, and a Soil Quality Index (SQI) value of 0.57 was obtained. This result indicated that the agricultural soils of the plains and piedmont areas of Valle del Cauca were classified as moderate quality, with pH, CEC, η, and Ks identified as the most influential properties.

Moderate impacts on soil quality were attributed to the concentrations of Cr, Ni, Pb, and Co. It was recommended that the SQI be adjusted to local and regional conditions by incorporating potentially toxic trace elements and evidence of anthropogenic accumulation, thereby strengthening its applicability for sustainable soil management.

Overall, this study can improve knowledge about the state of soil quality in the Valle del Cauca over an extended period of time and provide significant information for the management and reduction of actions that reduce the agricultural potential of the region by periodically evaluating the physical and chemical properties and total concentration of PTEs.

5. DATA AVAILABILITY STATEMENT

Data availability not informed.

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