# Soil physicochemical properties as indicators of chemical degradation in a mining-agricultural area of Samacá, Boyacá

## Propiedades fisicoquímicas del suelo como indicadores de degradación química en un área minero-agrícola de Samacá, Boyacá

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**ABSTRACT**

Soil is an essential natural resource that provides ecosystem services and supports productive activities such as agriculture and mining; however, it can be vulnerable to degradation due to both natural and anthropogenic causes. In Samacá (Boyacá department, Colombia), anthropogenic factors were identified that may trigger soil degradation, including irrigation with acidic waters, intensive agriculture, and improper disposal of mining waste. This study characterized variables associated with soil degradation in Samacá using databases from the project "Boyacá Adapts to Climate Change" (BSACC), field sampling, and laboratory analysis of associated variables. We applied the methodology proposed by IDEAM in the Protocol for the identification and evaluation of soil degradation by salinization, employing software tools such as ArcGIS, RStudio, and Python for cartographic analysis and data exploration. These soils were characterized by high sulfur concentrations and acidic pH. The results revealed that 92.72% (8,869.31 ha) of the study area is vulnerable to chemical degradation, with 6,402.05 ha at a medium level, 2,170.7 ha at a high level, and 40.67 ha at a very high level. Moreover, in areas of very high susceptibility, we observed elevated sulfur concentrations in soil and water as sulfates, which may acidify the environment, affecting nutrient availability and local biota. This allowed the validation of key indicators for monitoring this issue, highlighting pH, electrical conductivity (EC), and sulfur (S) content.

**Keywords:** soil acidity, food security, soil salinity, sulfur.

**RESUMEN**

El suelo es un recurso natural esencial que provee servicios ecosistémicos y sustenta actividades productivas como la agricultura y la minería, sin embargo, puede ser vulnerable a la degradación por causas naturales y antrópicas. En Samacá (departamento de Boyacá, Colombia), se identificaron factores antrópicos que pueden generar procesos de degradación edáfica como la irrigación con aguas ácidas, agricultura intensiva y la inadecuada disposición de residuos mineros. Esta investigación caracterizó las variables asociadas a procesos de degradación edáfica en Samacá, utilizando bases de datos del proyecto "Boyacá se Adapta al Cambio Climático" (BSACC), muestreos en campo y análisis en laboratorio de variables asociadas. Se empleó la metodología propuesta por IDEAM en el Protocolo para la identificación y evaluación de la degradación de suelos por salinización, aplicando herramientas de software como ArcGIS, RStudio y Python para el análisis cartográfico y exploración de datos. Estos suelos se caracterizaron por presentar altas concentraciones de azufre y pH ácido. Los resultados revelaron que el 92,72% (8.869,31 ha) de la zona de estudio es vulnerable a la degradación química, distribuyéndose en 6.402,05 ha en grado medio, 2.170,7 ha en alto y 40.67 ha en muy alto. Además, en la zona de muy alta susceptibilidad se observaron elevadas concentraciones de azufre en el suelo y agua en forma de sulfatos, lo cual puede acidificar el medio, afectando la disponibilidad de nutrientes y la biota local. Esto permitió validar los indicadores más importantes para el monitoreo de esta problemática, destacando el pH, la conductividad eléctrica (CE) y el contenido de azufre (S).

**Palabras clave:** acidez del suelo, seguridad alimentaria, salinidad del suelo, azufre.

## Introduction

Soil is a fundamental component for agricultural development and global food security. However, it is highly susceptible to anthropogenic chemical degradation, which compromises its productive capacity. In coal mining and farming zones, this degradation is primarily evidenced by processes such as acidification, salinization, and loss of fertility (FAO, 2024).

Key chemical variables for monitoring chemical soil degradation include pH and electrical conductivity (EC). A decrease in pH below 5.0 can increase the mobility of

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heavy metals, increasing their toxicity to crops (Rodríguez-Eugenio *et al*., 2019). Conversely, an increase in EC is associated with soil salinization, which disrupts water absorption by plants and can damage soil structure (Balasubramaniam *et al*., 2023; IDEAM, 2019). Soils undergoing simultaneous acidification and salinization are classified as Acid Sulfate Soils (ASS). These soils are rich in sulfur, often as sulfides, whose oxidation generates sulfuric acid and sulfates, creating a highly acidic and saline environment (IDEAM, 2017; Nyman *et al*., 2023). When acidity exceeds the soil's buffering capacity, pH can drop below 4.0 (Edén *et al*., 2024).

Under physical conditions such as compaction, the soil's susceptibility to chemical degradation increases. This occurs because compaction restricts subsurface drainage, promotes waterlogging, and leads to salt accumulation (Torres Guerrero *et al*., 2016; USDA, 2008). Bulk density (BD) values >1.5 g $cm^{-1}$ indicate compaction in fine soils such as clayey soils. This property is inversely related to porosity and is exacerbated in fine-textured soils, which can become nearly impermeable, directly determining water dynamics and degradation susceptibility (Bardet, 1997; IDEAM, 2017).

The municipality of Samacá (Boyacá department, Colombia) was the case study, facing high anthropogenic pressure from both mining and agriculture. Mining occurs in the Guaduas Formation, known for its bituminous, vitrinite-rich coals (51.4-87%), which form under reducing conditions (Gomez-Neita *et al*., 2016). In such environments, sulfate-reducing bacteria generate $H_2S$, which reacts with ferrous iron ($Fe^{2+}$) to form pyrite ($FeS_2$) (Chou, 2012). Mining overburden is a solid waste product of coal extraction and may contain pyrite. When exposed to weathering conditions, this mineral oxidizes and releases $H^+$, $Fe^{2+}/Fe^{3+}$, and $SO_4^{2-}$ ions, generating Acid Mine Drainage (AMD) (Ding *et al*., 2022; Mahanta *et al*., 2024). This process has contaminated local water sources with high concentrations of iron and lead (Agudelo-Calderón *et al*., 2016). Furthermore, practices such as incorporating mining waste into crops and using contaminated water for irrigation can alter soil chemistry, leading to acidification and increased salt content (Krechetov *et al*., 2019).

In Colombia, 45% of soils exhibit high susceptibility to chemical degradation caused by salinization (IDEAM, 2019). To address this issue, national authorities developed a protocol to identify and assess soil salinization (IDEAM, 2017). Given the intense anthropogenic pressure on land use in Samacá, this study characterized soil physicochemical properties to evaluate degradation in mining–agricultural zones. The methodology implemented the protocol for identifying degradation due to salinization, a zoning of susceptibility to chemical soil degradation that enabled identification of underlying factors contributing to this problem, and physicochemical characterization of soils and waters.

Soil degradation in Samacá compromises agricultural productivity and has direct socioeconomic impacts by reducing incomes and increasing production costs. To address this problem, a more detailed characterization is required through the monitoring of soil profiles and water sampling across different seasons. This approach is essential for effective resource planning and for advancing toward the objectives of the sustainable soil management policy (MADS, 2016).

## Materials and methods

### Study area

The study was conducted in the municipality of Samacá, Boyacá, within the cold and dry climatic unit, characterized by an average annual precipitation of 751.2 mm. The study area spanned 9,288.4 ha. This region comprises three soil cartographic units, as reported in the Soil Survey of Boyacá conducted by IGAC (2005), most notably the VMA unit corresponding to the valley area of the municipality (VMA is a designation specific to soil mapping developed by IGAC). This unit is characterized by fine textures, low permeability, susceptibility to waterlogging, and highly acidic soil reactions. Soil types found in this unit include Fluventic Haplustepts, Udertic Haplustepts, and Typic Dystrustepts. Conversely, the AHV unit corresponds to highland soils, which are shallow and limited by high aluminum concentrations. AHV is an internal code used by IGAC in its soil mapping to identify a specific cartographic unit associated with soils in high-altitude areas within the study area; this unit includes soil types Pachic Melanudands, Humic Distrudepts, and Typic Hapludands (IGAC, 2005). The hydrology of the study area consists of the upper, middle, and lower courses of the Gachaneca River, along with the irrigation canals of the ASUSA district.

The use of the BSACC database (112 points collected in 2021) and 40 field confirmation samples (2023) resulted in a total of 152 information points, ensuring data representativeness for characterization and cartographic analysis in accordance with the IGAC (2021a) guidelines. In this regard, the total number of observations was distributed among the zones as follows: Zone 5 comprised 4 observations, Zone 4 comprised 46, Zone 3 included 77, and Zone 2 contained 24 sampling points. The number of soil samples to be placed in each zone was determined based on the size of the polygons and the degree of soil susceptibility to degradation. This approach yielded an average sampling density of one sample per 61 ha.

Additionally, seven water sampling points were located along the Gachaneca River, considering the influence of this water body on the study area. The reference water variables considered in this study were selected from the set of water quality indicators proposed by IDEAM and INVEMAR (2021).

## Methodology

Our research employed the methodology outlined in the "Protocol for the identification and evaluation of soil degradation by salinization" (IDEAM, 2017), with specific adjustments tailored to the study area. The methodology is structured into the following three key stages.

### Pre-fieldwork stage

To identify homogeneous zones of soil degradation, we gathered secondary information from the "Boyacá adapts to climate change" (BSACC) study, IGAC cartographic sheets, IDEAM, the National Mining Agency, and the Land Use Plan of Samacá (2015). Using this data, the study area was delineated, and a zoning model was generated.

The Model Builder tool in ArcGIS 10.8 was used to construct the model. Input data were raster files from the BSACC project that contained chemical variables associated with salinization and acidification processes in Samacá. These raster files were reclassified into five categories, according to the criteria in Table 1, where 1 corresponds to the lowest susceptibility and 5 to the highest. Then, a weighted overlay was performed. The variable with the most significant influence was sulfur content, followed by pH, iron content, EC, organic matter content, and base content. Percentages were assigned to each variable to produce the zoning map, which used a traffic light color scheme for visualization.

The reclassification and weighting criteria were based on standard ranges for agricultural soils, the behavior of variables within the study area, and literature concerning the identification of ASS (Castro & Gomez, 2015). From the zoning process, 40 soil sampling points were distributed across the five zones (very low: 0, low: 4, medium: 21, high: 13, and very high: 2), considering the area of each zone; in other words, smaller zones had a lower density of sampling points.

For the study of soil physical properties, we collected 35 samples distributed across the zones with medium, high, and very high susceptibility. The objective was to observe how these parameters behaved in each zone and whether they showed any signs of alteration.

### Fieldwork stage

We collected soil samples in July 2023, during the second dry period of the year, using 50x50 cm pits, with approximately 1 kg of soil extracted from a depth of 20 cm for laboratory analysis (IGAC, 2021b). We also recorded in-field properties, including soil color, structure, and texture. We conducted laboratory analyses of the soil samples using the methodologies described in IGAC

**TABLE 1.** Criteria for constructing the preliminary zoning model.

| Weighting (%) | Var. | Units | Degree of soil susceptibility to chemical degradation | | | | |
|---|---|---|---|---|---|---|---|
| | | | Very low Zone 1 | Low Zone 2 | Medium Zone 3 | High Zone 4 | Very high Zone 5 |
| 20 | pH | | >5.5 | 5.5-5.25 | 5.25-5.0 | 5.0-4.5 | < 4.5 |
| 10 | EC | dS $m^{-1}$ | 0-0.2 | 0.2-0.4 | 0.4-0.6 | 0.6-0.8 | >0.8 |
| 35 | S | mg $kg^{-1}$ | <16 | 16-30 | 30-50 | 50-100 | >100 |
| 17 | Fe | mg $kg^{-1}$ | <100 | 100-120 | 120-150 | 150-200 | >200 |
| 10 | OM | % | >10.3 | 10.3-8.6 | 8.6-6.9 | 6.9-3.4 | <3.4 |
| 2 | Ca | cmol $kg^{-1}$ | <2.0 | 4.0-6.0 | 6.0-7.0 | 7.0-8.0 | >8.0 |
| 2 | Mg | cmol $kg^{-1}$ | <1.2 | 1.2-1.8 | 1.8-2.0 | 2.0-2.5 | >2.5 |
| 2 | K | cmol $kg^{-1}$ | <0.4 | 0.4-0.6 | 0.6-0.8 | 0.8-1.0 | >1.0 |
| 2 | Na | cmol $kg^{-1}$ | <0.1 | 0.1-0.2 | 0.2-0.25 | 0.25-0.3 | >0.3 |

* Var. = Variables, pH = hydrogen potential, EC = electrical conductivity, S = Sulfur, Fe = Iron, OM = soil organic matter, Ca = Calcium, Mg = Magnesium, K = Potassium, Na = Sodium.

(2006).: pH: potentiometry 1:1 soil-to-water ratio; EC: saturation extract; soil organic matter (OM): Walkley-Black method; exchangeable bases: ammonium acetate – atomic absorption; S: monocalcium phosphate method; texture: Bouyoucos method, BD: known volume cylinder; hydraulic conductivity: constant-head permeameter.

We established seven water sampling points along the upper, middle, and lower courses of the Gachaneca River. At each point, a one-liter integrated sample was collected from the river's cross-section (IDEAM & INVEMAR, 2021). Water samples were analyzed using specified methodologies: pH and EC (potentiometer); iron: colorimetric phenanthroline method; nitrates: (cadmium reduction method HACH 8039); and sulfates: colorimetry.

### Post-fieldwork stage

At this stage, we compiled a database to consolidate the analyzed variables, including data from BSACC soil properties and confirmation sampling points. We performed data cleaning and exploratory analysis, including the creation of distribution plots (histograms and boxplots). We conducted an exploratory study of soil-related variables using Python via the Anaconda interface and the Jupyter Notebook application, employing libraries such as *numpy, pandas, os, matplotlib,* and *seaborn*.

### Indicator selection

For selecting soil indicators, data from 40 field samples and information from the BSACC Project were used, totaling 152 sampling points. We adopted the methodology of Campitelli *et al.* (2010) to select soil chemical indicators based on three main criteria: 1) prioritizing parameters that are easy to measure for practical field application, 2) considering the statistical weight in explaining variability, expressed through the eigenvector value (Cp) associated with each soil variable, 3) analyzing positive and negative correlations between variables. This analysis was conducted for zones 2, 3, 4, and 5, which presented varying degrees of concern, using the variables listed in Table 1. The analysis was performed in RStudio, utilizing packages such as *ggcorrplot, factominer, factoextra,* and *ggplot2*, among others.

### Data analysis

We conducted descriptive statistical analysis in RStudio for soil and water variables, with results represented as boxplots. For the water variables analysis, the RStudio software, the summary package to obtain statistical data, and the ggplot2 package were employed to classify the results by areas.

## Results and discussion

### Zoning of soil susceptibility to chemical degradation

Chemical degradation processes in the study area are influenced by natural and anthropogenic factors. Key natural factors intensifying soil degradation in Samacá include cold, dry climate, valley geomorphology, and geology (IDEAM, 2017).

The Samacá's cold, dry climate defines the study zone. These conditions favor the accumulation of elements in the soil profile (IDEAM, 2017), as the lack of rainfall prevents the natural leaching of these compounds, while high evapotranspiration (loss of water from the soil) concentrates the salts. According to Shokri *et al.* (2024), the FAO indicates that this phenomenon affects more than two-thirds of the world's saline soils. Additionally, it represents a growing issue, as increases in evapotranspiration and changes in precipitation patterns are expected, especially in arid and semi-arid areas (Hassani *et al.*, 2021), because of climate change.

The model identified five zones with varying degrees of susceptibility to salinization and acidification. The zone with the largest area corresponded to medium susceptibility (6,402.05 ha), followed by high susceptibility (2,170 ha). However, the region most affected by this process, classified as "very high," covered 40.67 ha of the territory. This allowed for the identification and prioritization of areas that require the implementation of management strategies to mitigate this issue. In these predominantly agricultural and livestock-based regions, we observed irrigation with water from mining zones, the incorporation of mining overburden into crops, and the excessive use of agricultural fertilizers.

The presented map highlights affected areas in both the highland and valley zones, with the problem more pronounced in the latter ones (Fig.1). It is important to note that semi-intensive agriculture is practiced in both areas. In this way, the zone with the highest degree of susceptibility is located in the valley, in the lower course of the river, where sediment transport from mining areas and its deposition are predominant.

This suggests the influence of irrigation water on soil degradation processes caused by salinization and acidification. On the other hand, the geomorphology of the study area promotes the deposition of sulfurous materials in the valley; otherwise, the valley landscape collects and stores

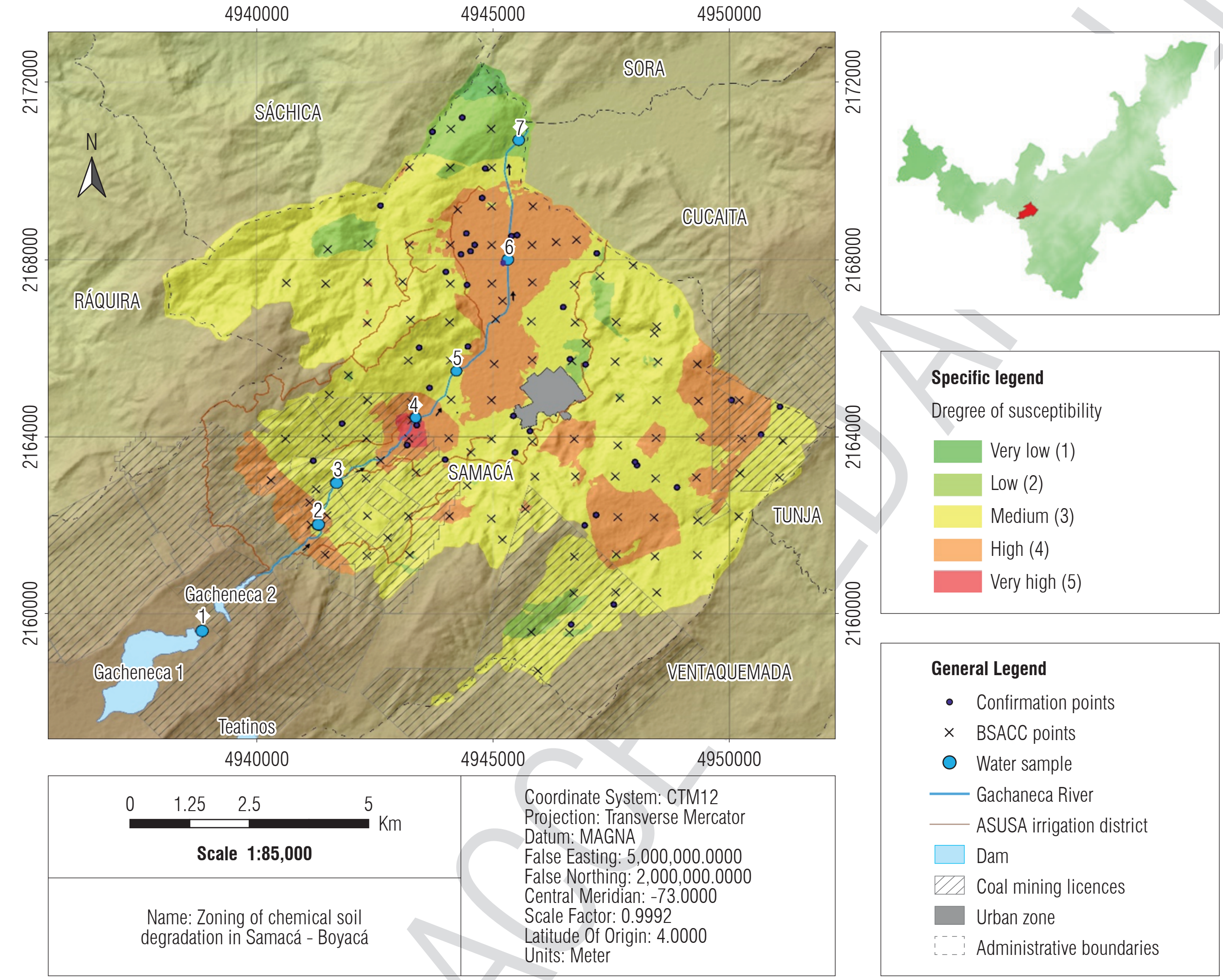


**FIGURE 1.** Preliminary map of zones of soil susceptibility to chemical degradation in Samacá.

compounds transported from higher elevations, where mining activities are concentrated. The Guaduas formation, which defines the area's geology, contains minerals such as pyrite and sulfur, found as thiols and sulfides (Gómez Rojas, 2015). Additionally, the high clay content in the soil profile (fine textures) traps these compounds (Liu *et al.*, 2024), altering the soil's physicochemical properties. Moreover, the high-susceptibility zone in the valley coincides with a contaminant plume along the Gachaneca River, indicating the key role of water in soil chemical degradation.

Furthermore, anthropogenic factors degrade soil in Samacá through contamination of water sources, use of sterile mines, and improper soil management. Mining coal activities and overloading landfills generate AMD, which contaminates water sources and reduces their quality for agriculture (Buitrago-Betancourt, 2020; Dinas Chinchilla & Prieto Ramírez, 2019). Irrigation water introduces sulfates and acidity into the ground, altering its properties. Figure 1 shows the relationship between the Gachaneca River and the high susceptibility areas, where a polluting plume migrates into the river, exacerbating the problem.

Besides, farmers incorporate mining waste into the soil to modify their superficial horizons and prepare it for crop planting. However, this waste usually has low organic matter content, limited water retention capacity, high density, and an acidic pH. It contains toxic heavy metals, including cadmium, iron, zinc, nickel, manganese, and chromium (Mazumder *et al.*, 2021). Improper soil management, such as excessive fertilizer application, acidifies the soil, raises salt and heavy metal levels, and increases soil bulk density (Hui *et al.*, 2022; Wang *et al.*, 2021). These modifications damage soil structure and quality, reducing agricultural productivity and long-term sustainability.

### Characterization of soil and water variables influencing chemical degradation

Chemical soil properties can change rapidly due to anthropogenic factors related to land use and management. In mining areas, the formation of ASS has been reported, with pH, EC, and sulfur content being affected. Given the potential AMD with irrigation water, the results of soil and water characterization in the study area are presented below.

### Water analysis

To analyze water properties, we collected seven sampling points along the Gachaneca River, from the Rabanal paramo to the municipal exit. The first three points, 1, 2, and 3, were located in the river's upper and middle courses, while points 4, 5, 6, and 7 were in the lower course as shown in Figure 1. Control point (1) was located downstream of the Gachaneca I dam, in the Rabanal páramo. this site was selected because the water in this area is minimally influenced by anthropogenic activities such as mining and agriculture. Figure 2 shows the behavior of the evaluated variables in the Gachaneca River.

EC increased significantly in Zone 5 (very high susceptibility), reaching a maximum value above 700 µS cm$^{-1}$, coinciding with the highest sulfate concentrations. In Zone 4 (high susceptibility), EC decreases to below 200 µS cm$^{-1.}$ However, at point 7, at the river's outlet, EC increases again to above 300 µS cm$^{-1}$, possibly due to the confluence of domestic wastewater from the municipality, which typically contains high nitrate levels. For this reason, the increase in EC in the very high-susceptibility zone is attributed to sulfate content. In contrast, in low-susceptibility areas, nitrates play a significant role.

This pattern is also observed by González Martínez (2017) in the Lenguazaque River. In this coal-mining-influenced area, EC of water ranged from 100 to 200 µS cm$^{-1}$ in the upper and middle courses and between 200 and 450 µS cm$^{-1}$ in the lower course. The findings aligned with this study, as the lower course of the Gachaneca River (Zone 5) exhibited the highest EC values, likely due to sediment accumulation from the upper and middle river courses.

Analyzing pH behavior from the dam outlet to point 4 of the Gachaneca River revealed a transition from neutral to acidic conditions, with a minimum pH value of 4.25. At points 5, 6, and 7, pH increased to a maximum of 6.73 (Fig. 2). Manrique Abril (2021) note that acidic pH values correlate with higher sulfate concentrations. For instance, at pH 4.0, sulfate levels reached 403 mg L$^{-1}$, and at pH 2.76, sulfate levels rose to 820 mg L$^{-1}$. In this study, a similar correlation was observed, with sulfate concentrations of 240 mg L$^{-1}$ at pH 4.25 (very high susceptibility zone) and 60 mg L$^{-1}$ at pH 6.5 (river outlet).

According to SOQUIMICH (2002), the water is not suitable for irrigation due to its high EC values exceeding 700 µS cm$^{-1}$. On the other hand, the classification established by MADS (2021) allows maximum EC values of up to 1,500 µS cm$^{-1}$. Under this limit set by MADS (2021), continuous monitoring by environmental authorities and water users becomes essential, since the response ranges for mitigating potential problems may become more complex in scenarios where EC values approach 1,500 µS cm$^{-1}$. Therefore, EC values around 700 µS cm$^{-1}$ could serve as early warning levels for monitoring potential issues in areas under mining influence.

Furthermore, Decree 1594 of 1984 (Colombia) specifies an acceptable pH range of 4.5 to 9.0 for agricultural water (MADR, 1984). The pH value of 4.25 recorded in the very high susceptibility zone does not meet this standard, indicating that it is unsuitable for agricultural use without management measures. The elevated concentrations of these elements may be associated with discharges from the Ancón channel, which originates in the mining zone.

During the formation of AMD, the oxidation of ferrous iron ($Fe^{2+}$) and the subsequent formation of ferric iron ($Fe^{3+}$) promote the precipitation of iron compounds and the release of hydrogen ions, thereby increasing water acidity (Chen *et al*., 2020). The highest iron concentration was recorded at point 4 (20.1 mg L$^{-1}$), which aligns with the most acidic pH reported along the river. These iron compounds were observed in the study area as mustard-yellow to orange-brown precipitates coating the riverbed.

### Soil analysis

Based on the physicochemical properties of the soil reported in the BSACC project for Samacá and given the high vulnerability to chemical degradation in mining-agricultural areas, this study focused on key variables such as pH, EC, and sulfur content in the form of sulfates (Fig. 3). These parameters are fundamental, as the oxidation of pyrite sulfides releases hydrogen ions, which cause acidity (low pH), and sulfate ions, which can increase soil salinity (EC) (Ding *et al*., 2022; Mahanta *et al*., 2024).

According to Krechetov *et al.* (2019), these properties exhibit significant heterogeneity in areas affected by mining waste deposition, with distribution varying according to

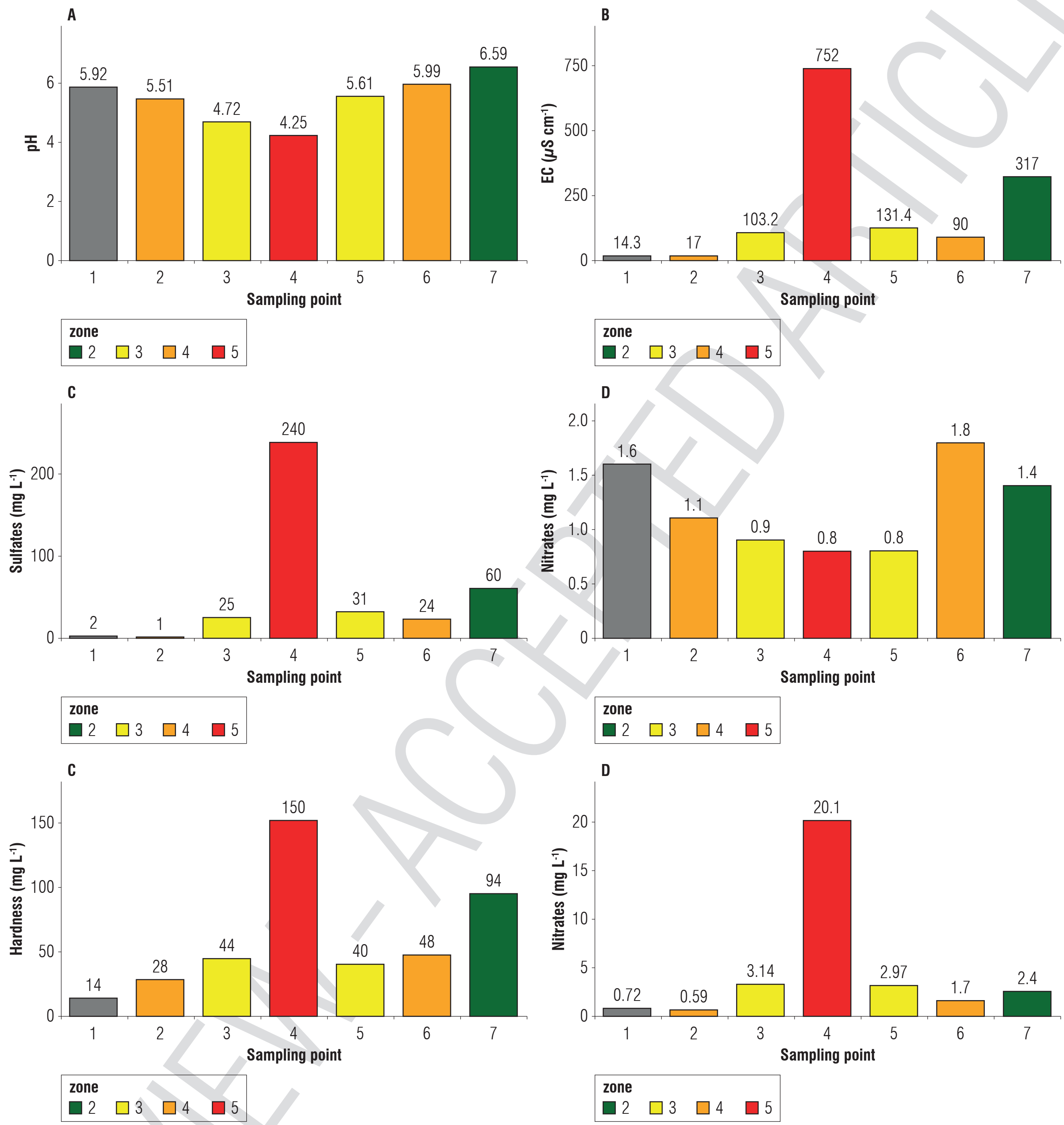


**FIGURE 2.** Mean values of variables evaluated in water samples. The gray bars indicate the control sample. Sampling points as in Figure 1.

the intensity of waste impacts, a pattern reflected in the study area. Similarly, IDEAM (2017) establishes specific criteria based on these same parameters for analyzing chemical soil degradation in regions with agricultural and mining activities.

The acidic conditions observed in irrigation water, associated with soils showing pH values below 4.5, may be a direct consequence of the oxidation kinetics of iron sulfides (Mahanta *et al.*, 2024). The pH showed an inverse relationship (r = -0.18) with susceptibility levels in zones 2, 3, and 4, decreasing as susceptibility increased. This trend towards acidification is attributed to the oxidation of pyrite, a mineral associated with coal, which releases $Fe^{2+}$, $SO_4^{2-}$, and $H^+$ ions, thereby acidifying the soil (Chaparro Leal, 2015).

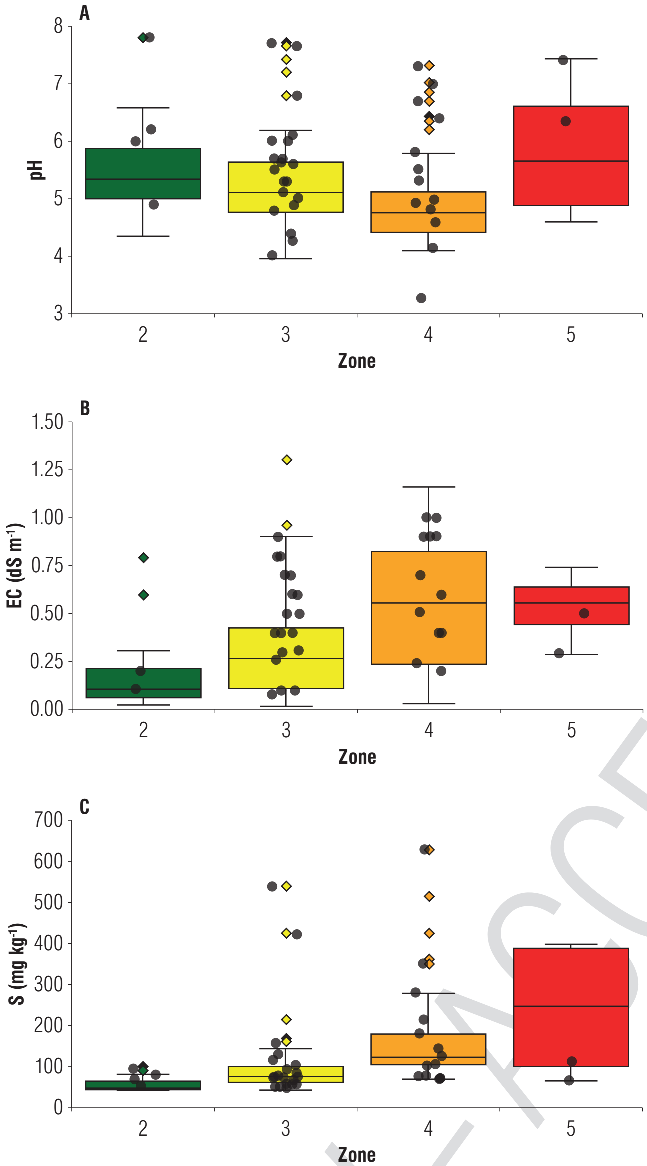


**FIGURE 3.** Chemical properties of soil in the study area: A) pH, B) electrical conductivity (EC), C) sulfur content. The black dots in each box plot refer to the confirmation points for each zone. Zones as in Figure 1.

However, this pattern was not observed in Zone 5, potentially due to the discharge of hard water (150 mg $L^{-1}$) rich in calcium and magnesium. This represents a key physicochemical interaction, in which Ca and Mg-bearing minerals (which neutralize acid drainage) temporarily counteract the acidity generated by the oxidation of $FeS_2$ (Castro & Gómez, 2015). The origin of this dynamic is attributed to geomorphological and geological characteristics; this zone is located in the valley and along the lower course of the Gachaneca River, which ensures the constant reception of surface water. Moreover, the area's geology is influenced by the Guaduas formation, characterized by pyrite in coal seams (Gómez Rojas, 2015). This formation is crossed by the Gachaneca River, which transports both acidifying agents derived from Acid Mine Drainage (AMD) and the buffering agents (Ca and Mg) from surface water into the valley. Additionally, the surrounding slopes contain mixed clastic sedimentary rocks in some sectors with calcium content (IGAC, 2005). These observations indicated that, in this environment, both natural and anthropogenic factors contribute to pH neutralization.

This represents a significant risk for Samacá soils. According to Castro and Gómez (2015), soils with pH levels below 5.5 have excesses of aluminum, iron, and manganese, alongside deficiencies of phosphorus and molybdenum due to fixation. Moreover, significant pH changes can reduce or inhibit mesophilic microbial activity in the soil.

The acidic conditions observed in irrigation water, associated with soils showing pH values below 4.5, may be a direct consequence of the oxidation kinetics of iron sulfides (Mahanta *et al.*, 2024). EC is a key parameter for assessing soil salinity. According to Ocampo (2013), soils with EC values exceeding 2.0 dS $m^{-1}$ are considered saline. In the study area, EC values did not reach these critical levels. However, differences were observed between high- and very high-susceptibility zones (up to 1.0 dS $m^{-1}$) and unaffected zones (Zones 2 and 3), which exhibited values ranging from 0.1 to 0.4 dS $m^{-1}$. This increase was noted near coal mining activities and watercourses, suggesting that improper disposal of mining residues (overburden and acid mine drainage) significantly contributes to soil salinity.

Furthermore, overfertilization of crops exacerbates the problem by causing nutritional imbalances and salt buildup (Castro & Agualimpia, 2024). Many farmers in Samacá omit soil analysis before planting and rely on commercial product recommendations without sound technical criteria or precise knowledge, which reduces agricultural yields.

In Samacá soils, sulfates are the predominant salts, with concentrations exceeding 500 mg $kg^{-1}$ in some soils and 240 mg $L^{-1}$ in water. Manrique Abril (2021) report that sulfur in the Guaduas formation coal-mining region is associated with coal-bearing rocks and mine waters. Mining activities in the area could represent a significant source of sulfur, EC, and acidity, transferred to the soil through mechanisms such as runoff, direct discharges, infiltration, and irrigation with contaminated water (Blanco-Zúñiga *et al.*, 2022). These findings indicate that the coincidence of these high concentrations suggests a strong influence of contaminated water inputs on soil sulfate content.

In mining regions, ASS can form due to sulfide oxidation, releasing acidity. Castro and Gómez (2015) characterize these soils by decreased pH, increased EC, and elevated sulfur content. They also classify Pseudo-Acid Sulfate Soils (PSSA) with pH levels above 4.5, typically associated with hard water rich in calcium and magnesium, as implemented in Samacá irrigation practices.

Based on data, it has been noted that Samacá may be experiencing the formation of ASS in Zones 3, 4, and 5 due to high sulfide content, increased EC, and low soil pH values. In these areas with high susceptibility to chemical degradation, high BD values (up to 1.7 g $cm^{-3}$) and low porosity (37%) were reported, which limit water movement (causing waterlogging) and reveal physical deterioration of the soil. Furthermore, decreases in pH and excessive fertilizers compromise biological health by inhibiting microbial activity (Castañeda García *et al*., 2024). Consequently, these areas are identified as the most affected by chemical, physical, and biological soil degradation.

This situation could have negative implications for soil health, agricultural productivity, and the region's food sovereignty. Therefore, understanding the distribution of this issue will enable proper territorial planning in the short and medium term, as well as the monitoring and implementation of management measures to mitigate soil degradation.

Considering that under physical conditions such as compaction, the soil's susceptibility to chemical degradation increases; physical parameters were analyzed exclusively in areas exhibiting significant chemical degradation, specifically areas 3, 4, and 5. Area 2 was excluded from this analysis due to its low susceptibility to degradation. The granulometric condition of the soils in the study area predominantly showed medium-fine and fine textures, such as clay loam (CL) and clay (C), characterized by a high proportion of micropores.

According to the results, the BD in Zone 3 averaged 1.4 g $cm^{-3}$, in Zone 4 it was 1.5 g $cm^{-3}$, and in Zone 5 it reached 1.7 g $cm^{-3}$, as shown in Figure 4. This indicates a higher degree of compaction in the area with the most significant susceptibility. However, all zones showed some level of resistance to root penetration. Porosity is inversely related to BD, as shown in the figure. The natural porosity of a soil is 50% (IGAC, 2014). The results indicate that porosity is below this value, especially in the area of highest susceptibility, where porosity was reported at 37%. This condition restricts water movement within the soil profile, promoting waterlogging and increasing susceptibility to chemical degradation through salinization and acidification (IDEAM, 2017). Therefore, management measures addressing this issue must consider modifying these physical conditions.

### Soil indicators for the assessment of chemical degradation

The soil indicators used in this study are presented in Table 2. The selection of these parameters was based on and statistically confirmed through Principal Component Analysis (PCA). This selection was derived from the dataset of variables considered in the zoning model (Tab. 1). The pH and EC values were prioritized across all zones due to their ease of field measurement. Furthermore, these factors were analyzed by principal component analysis in most zones. They showed significant correlations with the other evaluated properties. Consequently, they were selected as the primary indicators.

Furthermore, sulfur contents showed the highest positive and negative eigenvector values, indicating that this element could significantly explain the variability in other parameters, thus establishing itself as a crucial secondary

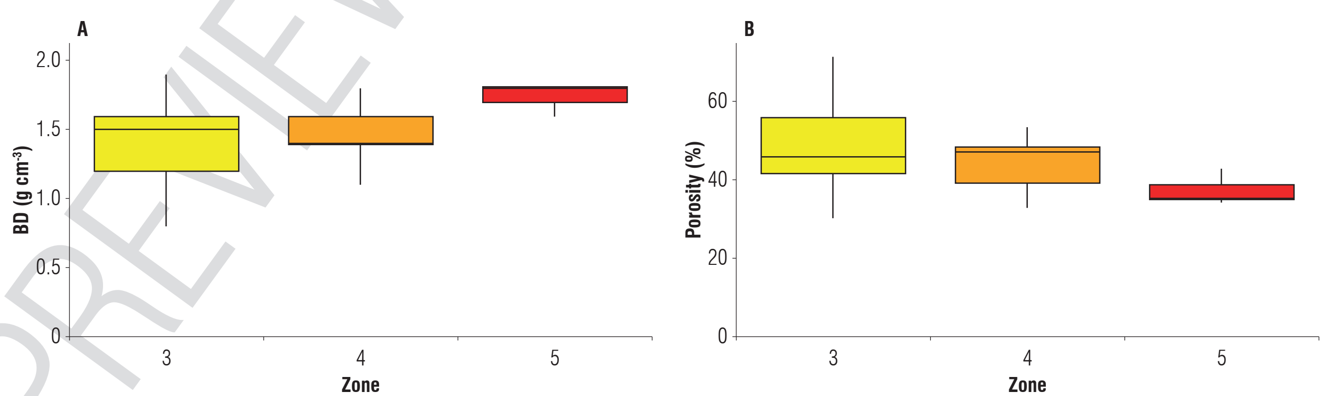


**FIGURE 4.** Physical properties of soils in the study area for zones of medium, high, and very high susceptibility: A) Bulk density (BD), B) Porosity. Zones as in Figure 1.

**TABLE 2.** Indicators for monitoring soil chemical degradation in Samacá.

| Zones | Indicador | Range | Units | Ease of measurement | Eigenvector value | |
|---|---|---|---|---|---|---|
| | | | | | PC1 | PC2 |
| 2 | pH | < 5.25 | - | High | 0.34 | 0.23 |
| | EC | > 0.4 | dS $m^{-1}$ | High | 0.32 | 0.29 |
| | S | > 30 | mg $kg^{-1}$ | Average | 0.43 | -0.27 |
| | OM | < 4.98 | % | Average | 0.27 | -0.58 |
| 3 | pH | < 5.0 | | High | 0.38 | 0.19 |
| | EC | > 0.6 | dS $m^{-1}$ | High | 0.48 | -0.17 |
| | S | > 50 | mg $kg^{-1}$ | Average | 0.25 | -0.51 |
| 4 | pH | < 4.75 | | High | 0.5 | 0.26 |
| | EC | > 0.8 | dS $m^{-1}$ | High | 0.37 | -0.26 |
| | S | > 100 | mg $kg^{-1}$ | Average | 0.07 | -0.47 |
| 5 | pH | < 4.5 | | High | 0.4 | 0.21 |
| | EC | > 1.0 | dS $m^{-1}$ | High | -0.38 | 0.28 |
| | S | > 200 | mg $kg^{-1}$ | Average | -0.42 | 0.08 |

* PC1 = Principal component 1, PC2 = Principal component 2, pH = hydrogen potential, EC = Electrical conductivity, S = Sulfur, OM = Soil organic matter.

indicator. Lastly, in zone 2, soil organic matter was proposed as a key indicator because its decline could increase soil vulnerability to degradation. Jamioy *et al*. (2015) emphasize the importance of pH, organic carbon content (OC), and calcium, magnesium, and iron content as indicators of soil quality. Moreover, IDEAM (2017) identifies EC as a reliable indicator for assessing soil chemical degradation caused by salinization.

In the study area, pH values below 4.5, EC levels exceeding 0.8 dS $m^{-1}$, and sulfur content exceeding 200 mg $kg^{-1}$ were identified as the primary indicators of increasing chemical degradation in Samacá soils, as shown in Table 2. Given their importance, the critical ranges (Tab. 2) serve as reference thresholds for land management, validated by this research and derived from the characterization of the areas with the highest susceptibility to chemical degradation.

## Conclusions

The research established that 92.72% (8,869.31 ha) of soils in the study area exhibited some degree of chemical degradation. This pattern could be explained by the complex interaction between natural factors such as geology, geomorphology, and a cold, dry climate, and anthropogenic activities, mainly associated with irrigation using acidic waters contaminated by AMD and the inadequate management of mining waste.

Furthermore, pH, EC, and sulfur content were identified and validated as the most relevant primary indicators for monitoring chemical degradation in the agromining zone. The results revealed that water in areas of very high susceptibility, with pH values of 4.25 and EC levels exceeding 750 µS $cm^{-1}$, served as an early warning indicator of environmental quality. In addition, the physical deterioration of the soil, evidenced by low porosity (37%) and high BD (1.7 g $cm^{-3}$), increased its vulnerability to salinization and acidification, therefore suggesting that management strategies should prioritize these physical constraints.

Overall, this research highlights the need for responsible management to mitigate the environmental, economic, and social impacts of mining. As a case study, it provides valuable insights to support land-use planning, environmental management, and the formulation of integrated public policies, which are essential for both local and national planning frameworks. Finally, it is recommended to increase the number of sampling points to design more targeted, site-specific management strategies tailored to each zone.

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### Conflict of interest statement

The authors declare that there is no conflict of interest regarding the publication of this article.

### Author's contributions

ARPM, LAMV, and ABG designed the conceptual approach and objectives; ARPM, LAMV, and ABG carried out the field and laboratory experiments and elaborated visual representations of the data and results; ARPM, LAMV, and ABG designed and developed the research methodology, including methods of data collection, equipment, and verified the accuracy and reliability of the research results through a validation process; ARPM, LAMV, and ABG wrote the initial draft. All authors participated in the critical review and approval of the final version of the manuscript.

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