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Facultad de Ciencias Agropecuarias

Universidad Nacional de Trujillo

RESEARCH ARTICLE

An integral soil quality index based on nematodes for mining-impacted Andean soils

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Received: 27 February 2026. Accepted: 19 October 2026. Published: 30 October 2026.

Abstract

Mining activities, while economically important, have caused significant soil degradation, affecting soil quality, ecosystem functioning, and sustainability in Andean ecosystems. This study developed an integral soil quality index based on physicochemical, microbiological, and nematode indicators to assess soil degradation in the Ollachea mining area, Peru. We collected soil samples from four land-use systems (natural pasture, *Zea mays* cultivation, *Ficus sp.* cultivation, and *Eucalyptus sp.* forest) during two dry and two rainy seasons. The proposed index integrates complementary indicators related to soil chemical properties, nutrient availability, metal contamination, microbial activity, and nematode community structure to characterize soil quality and detect ecological stress associated with mining disturbance. The results showed that the index effectively discriminated soil quality by land use and season, with *Eucalyptus sp.* forest soils showing the highest soil quality status, whereas cultivated and mining-impacted soils exhibited lower quality associated with greater environmental stress. The main contributors to soil stress were related to microbial and metal-associated indicators, particularly total actinomycetes (6.53), Al (1.87), and Fe (1.65), highlighting their relevance in mining-impacted soils. Furthermore, nematode-based biological responses increased the index's sensitivity to seasonal ecological changes. Compared with other soil quality indices, the proposed integral index performed better, showing strong correlations with soil quality patterns in both dry and rainy seasons (r = 0.97 and r = 0.95, respectively). Overall, this study shows that a nematode-enhanced integral soil quality index provides a robust, transferable approach for monitoring mining-impacted soils and supporting ecological restoration strategies in Andean ecosystems.

Keywords: Microbiological parameters; physicochemical parameters; soil ecosystems; soil quality indices; soil nematodes; stress gradient.

DOI: https://doi.org/10.17268/sci.agropecu.2025.063

Cite this article:

Niño-de-Guzman-Tito, M. O., Dominguez-Nuñez, J. A., & Lima-Medina, I. (2026). An integral soil quality index based on nematodes for mining-impacted Andean soils. *Scientia Agropecuaria, 17*(4), 963-977.

1. Introduction

Mining is a major global economic activity; however, it alters physical, chemical, and biological processes by changing soil structure, nutrient availability, microbial activity, and the accumulation of potentially toxic elements (Zenebe et al., 2026). These transformations can affect soil dynamics and modify the conditions that regulate the activity of associated biological communities (Nodirabonu & Zafarjon, 2025). Because mining disturbance does not affect isolated components but instead generates interconnected responses within the soil system, assessing soil quality requires approaches that consider multiple dimensions simultaneously (Huisa-Mamani et al., 2025).

The complexity of these responses has prompted the use of multiple indicators to characterize changes associated with mining activity (Garate-Quispe et al., 2026). Available evidence indicates that soil biological communities can provide relevant information about changes caused by pollutants and other environmental stressors, complementing interpretations from physicochemical variables (Afzal et al., 2025). In most assessments in mining environments, researchers have addressed changes in soil quality using physicochemical, microbiological, or biological indicators individually, thereby identifying responses associated with specific components of the soil system (Zhou et al., 2025). However, evaluating these indicators in

isolation can limit understanding of interactions among different soil dimensions during mining disturbance (Liu et al., 2026a). This limitation is especially relevant in Andean artisanal mining systems, where environmental conditions and the specific characteristics of soil disturbance require approaches that integrate multiple soil responses (Díaz-Rivera et al., 2025).

Integrating different soil components within a single assessment framework offers an alternative to overcome the limitations of independent variable analysis (Utge Perri et al., 2025). Comprehensive soil quality indices combine information on physicochemical properties, nutrient availability, contaminant presence, and biological responses, providing a more complete representation of soil condition (Rincon-Vasquez et al., 2025). These approaches have mainly been used to synthesize complex information and compare contrasting soil conditions; however, their interpretative capacity depends on the selection of indicators that adequately represent the type of disturbance being evaluated (Cavone et al., 2025). In soils influenced by mining, where changes can involve simultaneous chemical, microbiological, and biological modifications, including sensitive indicators, it is fundamental to strengthen a comprehensive assessment of soil quality (Mu et al., 2025).

Among the biological components that can strengthen this approach are nematode communities, which stand out for their ability to integrate information across trophic levels and respond to changes in soil environmental conditions (Wang et al., 2025). Their functional diversity, represented by groups with different feeding habits and life strategies, enables them to respond to changes in resource availability, alterations in biological structure, and soil stress conditions (Abatay et al., 2026). Additionally, their sensitivity to anthropogenic disturbances complements information from physicochemical and microbiological variables, offering a biological perspective on soil health (Konadu-Amoah et al., 2026). Despite these characteristics, the incorporation of nematode indicators into comprehensive soil quality indices for environments affected by artisanal mining in Andean ecosystems remains limited, particularly when integrating biological, microbiological, and physicochemical responses into a single assessment tool (Wang et al., 2025).

This limited integration presents an opportunity to develop methodologies that more comprehensively characterize soil responses to mining-related stress in Andean environments (Tumy-Gomez et al., 2025). In this regard, this study proposes an overall soil quality index based on nematological, physicochemical, and microbiological indicators to evaluate soils affected by mining in Ollachea, Peru; thus, this research develops a methodological approach aimed at integrating biological and edaphic responses for the assessment of soils impacted by artisanal mining in Andean ecosystems.

2. Methodology

The overall methodological framework for constructing the integral soil quality index is summarized in Figure 1.

2.1 Area of study

The study was carried out in the peripheral area of the artisanal mining community of Ollachea, in the province of Carabaya in the Puno region of Peru (13°47'-13°48' S, 70°29'-70°30' W) (Figure 2), at an altitude of 3041 meters above sea level (masl). The lithology of Ollachea is mainly composed of sandstone, shale, and limestone formations from the Paleozoic and Mesozoic (Díaz-Martínez et al., 2001). The physiography is mountainous, with altitudes ranging from 2800 to 4500 masl, characterized by rugged terrain with steep slopes and deep valleys. The vegetation is strongly influenced by mining waste, a product of the lack of adequate treatment of the waste generated by the mining community; agriculture, adapted to these conditions, focuses on crops such as *Solanum tuberosum* (potato), *Zea mays* (corn), and *Chenopodium quinoa* (quinoa) (Figueroa Pizarro et al., 2023; Salas-Mercado et al., 2022). According to the classification provided by the United States Department of Agriculture (USDA), the predominant soils are andisols and inceptisols, typical of volcanic and mountainous areas; Ollachea is located in the Andean bioclimatic region, specifically in the highland floor according to the Holdridge classification, characterized by a temperate and warm climate with an average annual temperature ranging between 6 and 18 °C and an average total annual rainfall ranging between 790 and 1000 mm.

2.2 Experimental design and soil sampling

Sampling was conducted during 4 seasonal periods: drought (2021-22 and 2022-23) and rainy (2021-22 and 2022-23) seasons. Sampling was carried out on 4 types of land use: natural pasture (13°48'8.38" S, 70°30'35.84" W), *Zea mays* cultivation (13°48'3.28" S, 70°29'50.46" W), *Ficus sp.* cultivation (13°47'56.44" S, 70°29'9.96" W), and *Eucalyptus sp.* Forest (13°48'8.22" S, 70°29'31.43" W). Soil collected soil samples from 100 m^2 sampling units, with three independent replicates for each

land-use type during each seasonal period, resulting in 48 composite soil samples across the two-year study. The 100 m^2 sampling area was selected to provide an adequate spatial scale to capture local soil heterogeneity associated with land-use conditions while keeping sampling units comparable across the evaluated systems (Darko et al., 2025). Three replicates per land-use type were appropriate for this study because they represented independent spatial units within each condition and allowed assessment of variability among land-use systems under similar mining influence (Afzal et al., 2025). Additionally, repeating sampling across four seasonal periods increased the design's robustness by incorporating temporal variability associated with seasonal changes (Mills et al., 2026). Using composite samples from multiple subsamples within each replicate further reduced microscale variability and improved the representativeness of soil properties, microbial characteristics, and nematode communities evaluated in each condition (Liu et al., 2026b).

In the natural pasture and *Zea mays* cultivation soils, sampling was carried out in a zigzag pattern; in *Ficus sp.* cultivation soils and *Eucalyptus sp.* forest soils, sampling was carried out in a star pattern; the soil samples were extracted with a 4 cm diameter auger up to 15 cm deep (for microbiological analysis) and up to 25 cm deep (for nematode and physicochemical analysis) (Wiesel et al., 2015). Composite samples were collected, each of 20 subsamples, for each type of soil; the composite samples were placed and labeled in black polyethylene bags; each soil sample was passed through a 2 mm sieve immediately after collection (Rumiani et al., 2021) and were immediately transported to the Entomology laboratory of the Faculty of Agrarian Sciences, of the National University of the Altiplano of Puno, Peru. The nematological and microbiological samples were stored at 4 °C, and the physicochemical samples at -20 °C, until processing (Knapp-Lawitzke et al., 2014). As a result, 48 composite soil samples were collected over 2 years.

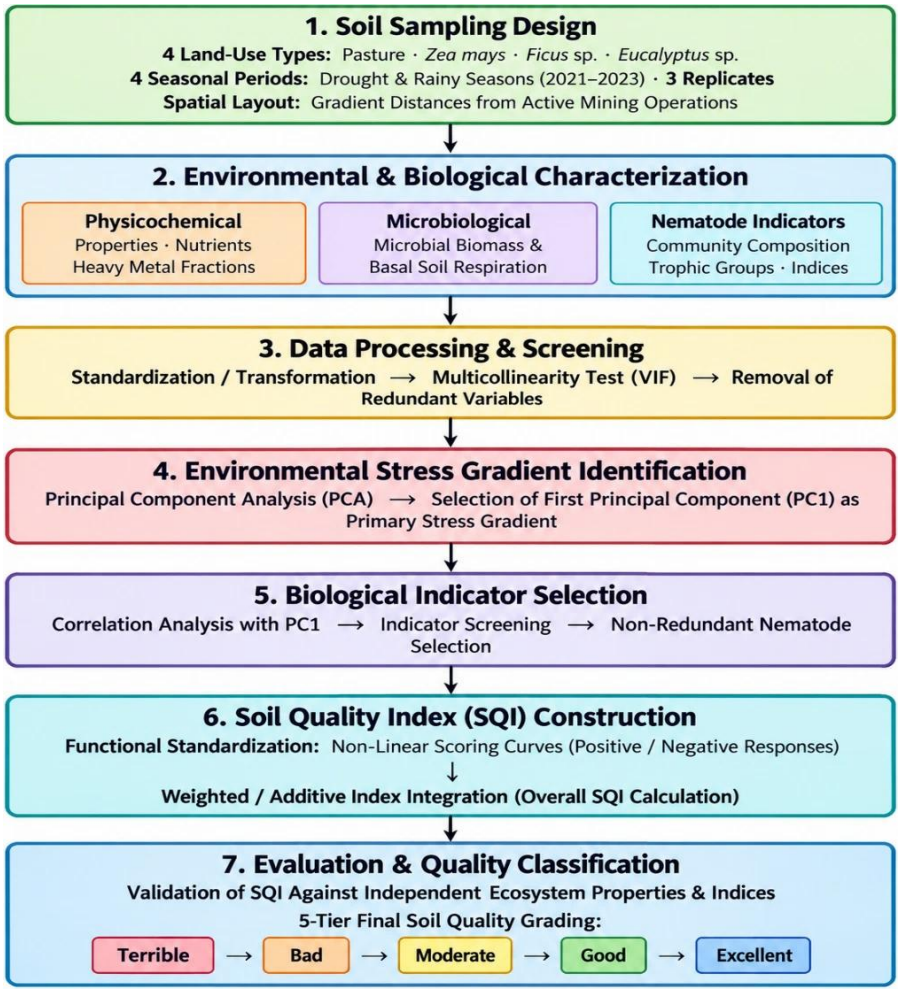


Figure 1. Methodological workflow for constructing the integral soil quality index.

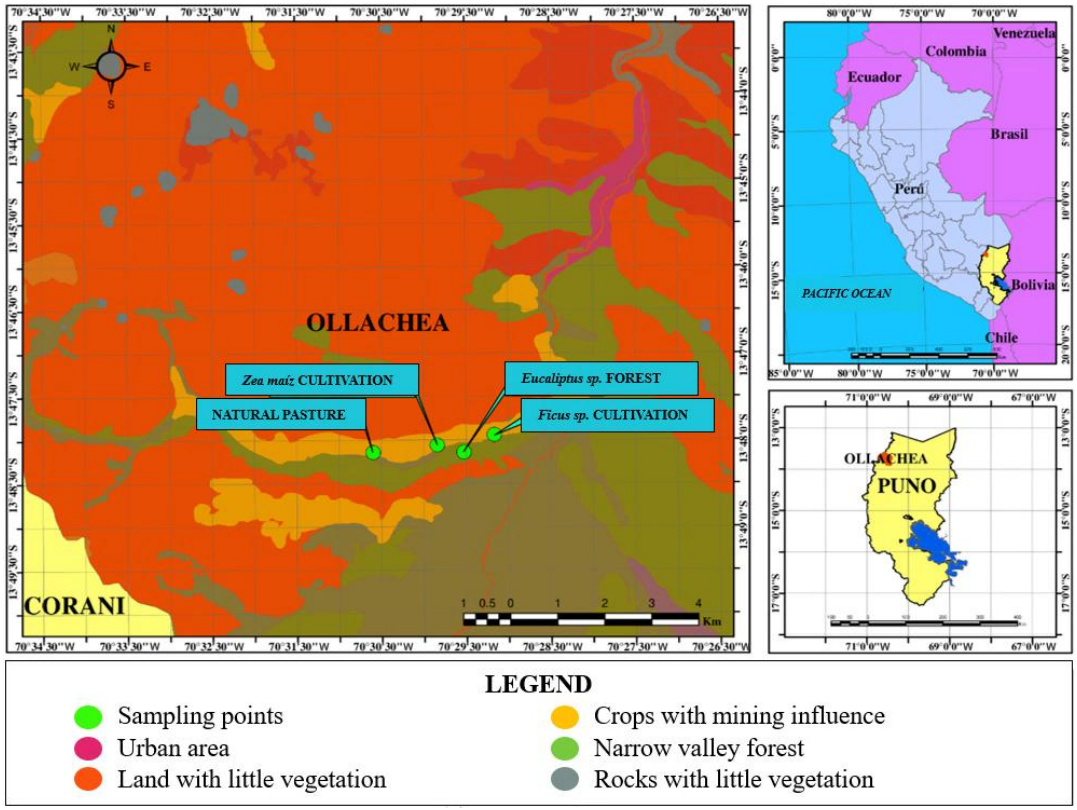


Figure 2. Geographic zoning of the sampling area, on the outskirts of the mining community of Ollachea, Puno, Peru.

2.3 Nematode community analysis

To improve the representativeness of the nematode community assessment, two complementary extraction methods were applied, thereby allowing a more comprehensive characterization of nematode abundance and community structure (Pashkovsky & Babych, 2026; Rybarczyk-Mydłowska et al., 2026). To achieve representativeness of mobile nematodes, the modified Whitehead tray method was used; for inactive or slow nematodes, the modified centrifugation-flotation method was used (Coleman et al., 2018).

After fixation in 4% formalin, the collected nematode suspensions were stored in 10-mL centrifuge tubes. All soil nematodes were counted using an Olympus ® stereoscope (4.5 X), and nematode abundance was expressed as the number of nematodes per 100 g of dry soil. At least 100 nematodes per sample were randomly selected and identified to genus level based on morphological characteristics (Young & Unc, 2023). When the total number per sample was less than 100, all individuals were identified. Soil nematodes were assigned by genus to the following trophic groups by genus: bacterivores, fungivores, herbivores, omnivores, and predators (Ribeiro et al., 2023).

To further analyze the structure of the soil nematode community, biological parameters such as metabolic fingerprints, trophic traits, and diversity indices (Table 1) were examined (Afzal et al., 2023; Liu et al., 2022; Rafael et al., 2023).

2.4 Soil physicochemical and microbiological analysis

Seven soil physicochemical parameters were evaluated, including cation exchange capacity (CEC), calcium carbonate ($CaCO_3$), electrical conductivity (EC), soil moisture, organic matter (OM), pH, and soil texture. These parameters were determined following standardized analytical procedures (Kabala & Jedrzejewski, 2024; Gargiulo et al., 2013; Deluz et al., 2024; Deviren Saygin et al., 2021).

Twelve nutritional parameters were analyzed, including aluminum (Al), boron (B), calcium (Ca), phosphorus (P), potassium (K), manganese (Mn), sodium (Na), zinc (Zn), magnesium (Mg), and their exchangeable fractions. These elements were quantified using standardized analytical extraction and spectrometric techniques (Benti Chalchissa & Kuris, 2024; S. Li et al., 2024; Cao et al., 2024).

Twenty-six heavy metals were analyzed, including antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), bismuth (Bi), cadmium (Cd), cerium (Ce), cobalt (Co), chromium (Cr), cesium (Cs), copper (Cu), tin (Sn), strontium (Sr), iron (Fe), lithium (Li), mercury (Hg), molybdenum (Mo), nickel (Ni), silver (Ag), lead (Pb), selenium (Se), silicon (Si), thallium

(Tl), titanium (Ti), uranium (U), and vanadium (V). Heavy metal concentrations were determined after acid digestion of soil samples and subsequent analysis by inductively coupled plasma mass spectrometry (ICP-MS) (Oyebamiji et al., 2024).

Finally, 7 microbiological parameters were analyzed: total actinomycetes, expressed as colony-forming units per gram of soil (CFU/g), quantified by the plate dilution method in actinomycete-specific medium, incubated at 28 °C for 7 days (Kim et al., 2024). Free-living nitrogen-fixing bacteria were quantified as CFU/g using Ashby's medium without a nitrogen source, and the plates were incubated at 28 °C for 7 days (Wang et al., 2024b). Nitrifying bacteria were quantified using the most probable number per gram of soil (MPN/g) method in a nitrifying-specific medium, incubated at 28 °C for 7 days. Total bacteria were expressed as CFU/g by plate dilution in a nutrient medium and incubated at 28 °C for 48 hours (Li et al., 2024). Microbial biomass was estimated as milligrams of carbon per kilogram of soil (mg C/kg) using the fumigation-extraction method, with microbial carbon extracted with potassium sulfate and organic carbon content measured by wet oxidation (B. Wang et al., 2024a). Total fungi were quantified as CFU/g by the plate dilution method on PDA medium, incubated at 28 °C for 5 days (Yu et al., 2024). Microbial respiration, expressed as milligrams of carbon dioxide released per gram of soil (mg CO_2/g), was measured by incubating soil samples in airtight jars and titrating the CO_2 evolved with a sodium hydroxide solution (Wang et al., 2024c).

2.4.1 Stress gradient

To elaborate on the integral index, it was essential to identify and select the environmental variables that best represented the stress imposed on the soil nematode community. A modification of the methodology proposed by Hertel et al. (2009) was applied. First, all variables were standardized using the Hellinger technique (Equation 1), where z_{ij} is the standardized value of variable j in sample I, and x_{ij} is the original value of variable j in sample i.

$$z_{iJ} = \frac{x_{iJ}}{\sqrt{\sum_{J=1}^{p} x_{iJ}^2}} \quad \text{... (Equation 1)}$$

This transformation enabled the data to be comparable and reduced differences in magnitude across variables, facilitating interpretation in multivariate analysis (O'brien, 2007). Subsequently, a Principal Component Analysis (PCA) was performed; before performing the PCA, uncorrelated variables were excluded using the Variance Inflation Factor (VIF ≤ 10), calculated as $VIF_j = 1/(1-R_j^2)$, where R_j^2 is the regression coefficient of variable j with all other variables. A high VIF (greater than 10) indicates high collinearity, and therefore, those variables are excluded from the analysis. The first PCA axis, which explains the highest percentage of the total variance, was selected as the stress gradient (Cheng et al., 2022). The variance explained by the first component was calculated used the Explained variance (Ev, Equation 2), where λ_1 is the eigenvalue of the first component, and λ_i are the eigenvalues of all components.

$$\mathrm{Ev} = \frac{\lambda_1}{\sum_{1=1}^{p} \lambda_i} \quad \text{... (Equation 2)}$$

This methodology allows a more accurate and robust assessment of the environmental impact on soil quality (Franco-Martinez et al., 2019).

2.4.2 Selection of biological parameters

To determine the biological parameters that were best correlated with the stress gradient, the methodology proposed by was used Syrbe et al. (2018) for this purpose, a Pearson correlation was performed between the stress gradient and the biological parameters, and those that presented a high correlation were selected (Pearson r ≥ ±0.6) (Wilson, 2017); in order to minimize redundancy and simplify the information obtained, a Pearson correlation was performed excluding those biological parameters that were highly correlated with each other (Pearson r ≥ ±0.8) (Gilioli et al., 2019).

Table 1
Main biological parameters analyzed, indicators of soil ecosystem quality

Biological parameter	Indicators of soil ecosystem quality
Metabolic footprint	Total metabolic footprint, enrichment footprint, structure footprint, herbivore metabolic footprint, fungivore metabolic footprint, bacterivore metabolic footprint, predator metabolic footprint, and omnivore metabolic footprint.
Trophic characteristics	Herbivores (%), free-living herbivores (%), fungivores (%), free-living fungivores (%), Bacterivores (%), free-living bacterivores (%), predators (%), free-living predators (%), Omnivores (%) and free-living omnivores (%).
Diversity	Simpson index, Shannon-Weiner index, evenness index, Brillouin index, Menhinick index, Margalef index, Pielou index, Fisher alpha index, Berger-Parker index, Hill number order 1 and Hill number order 2.

2.4.3 Integral index design soil quality

The values of the biological parameters were expressed in different units, so the data were standardized (Molina et al., 2022). In the case of the selected biological parameters in which there was a decrease against the stress gradient, the formula was used according to Esmaeili Ofogh et al. (2023) (Equation 3), where P_d is the score of the parameter with a decrease, v is the value of the measured parameter, v_{95} is the value of the 95th percentile of the measured parameter, and v_{min} is the minimum value of the measured parameter.

$$P_d = 100 \text{ x} \left(\frac{v}{v_{95} - v_{min}}\right) \text{ ... (Equation 3)}$$

For the selected biological parameters in which an increase against the stress gradient was expected, the formula was used, according to Carlson et al. (2023) (Equation 4), where P_i is the score of the parameter with increase, v_{max} is the maximum value of the measured parameter, v is the value of the measured parameter, and v_5 is the value of the 5th percentile of the measured parameter.

$$P_i = 100 \text{ x} \left(\frac{v_{max} - v}{v_{max} - v_5}\right) \text{ ... (Equation 4)}$$

To calculate the value of the integral index, it was averaged using the following Equation 5, where V_i is the value of the integral index, ΣP_d is the sum of the scores of the parameters with decrease, ΣP_i is the sum of the scores of the parameters with increase, and n_p is the total number of parameters used in the calculation (Labat & Usseglio-Polatera, 2023; Šidagytė-Copilas & Arbačiauskas, 2022).

$$V_i = \frac{\Sigma P_d + \Sigma P_i}{n_p} \text{ ... (Equation 5)}$$

Finally, using an adaptation of the methodology by Yadamsuren et al. (2024), the Integral index was assigned a quality rating based on the soil quality categories (Table 2) (Mukherjee & Lal, 2014), considering all biological parameters selected for both the drought and rainy seasons.

Table 2
Assignment of soil quality categories

Range	Quality
> 80th percentile	Excellent
> 60th percentile - ≤ 80th percentile	Good
> 40th percentile - ≤ 60th percentile	Moderate
> 20th percentile - ≤ 40th percentile	Bad
≤ 20th percentile	Terrible

2.5 Comparison of the integral index

The constructed integral index was compared with 7 soil quality indices: basal index (Ikoyi et al., 2023), structure index (Qing et al., 2022), enrichment index (Zhou et al., 2022), channel index (Du Preez et al., 2022), sigma maturity index, 2-5 maturity index, and maturity index (Maina et al., 2022). The stress gradient parameters and nematode indices were standardized to a range of 0 to 1 to ensure that all variables had equal weight in the analysis. Then, a Canonical Correlation Analysis (CCA) was applied to identify significant correlations between the environmental factors of the stress gradient and the indices (Hoy et al., 2008).

2.6 Data analysis

To determine the trophic abundance of nematodes, physicochemical (Table S1) and microbiological parameters (Table S2) were analyzed using PCA and CCA. All these statistical analyses were performed using RStudio® (version 4.0.2). Biological parameters, such as metabolic footprint, trophic traits, and diversity indices, were calculated using the free software NINJA (Sieriebriennikov et al., 2014) and the statistical program Past (version 3.17).

3. Results and discussion

3.1 Determination of the stress gradient

Fifty physicochemical and microbiological variables obtained a VIF ≥ 10; therefore, they were considered for PCA. The first principal component (PC1) explained 95.23% of the total variance, followed by PC2 (2.5%), PC3 (1.3%), and PC4 (0.6%), whereas the remaining components contributed less than 0.4% each. PC1 was mainly associated with aluminum (Al; r = 1.87), iron (Fe; r = 1.65), and total actinomycetes (r = 6.53), which showed positive loadings along this axis (Table S3; Figure 3). Increasing PC1 scores represented a unidirectional gradient of increasing soil disturbance associated with mining influence.

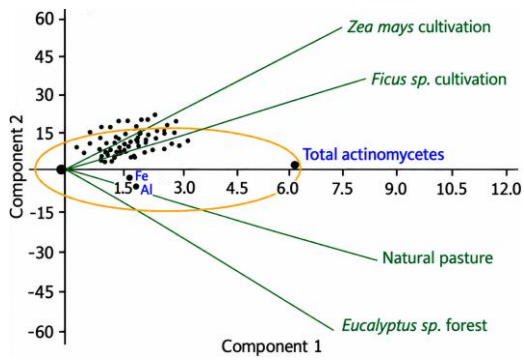


Figure 3. Spatial distribution of principal component analysis.

3.2 Selection of biological parameters

For the drought seasons, from a total of 29 biological parameters calculated for each of the sampling points, 5 were selected for the design of the integral index (Table S4), which presented a

Pearson correlation r > ±0.60 with the stress gradient; the parameters highly correlated with each other (r ≥ ±0.80) were also excluded; thus, the 5 selected parameters were: metabolic footprint of fungivores (r = -0.75), % free-living bacterivores (r = -0.62), % free-living predators (r = 0.73), % free-living omnivores (r = 0.77) and evenness index (r = 0.77).

For the rainy seasons, from a total of 29 biological parameters calculated for each of the sampling points, 7 were selected for the design of the integral index (Table S5), which presented a Pearson correlation r > ±0.60 with the stress gradient; the parameters highly correlated with each other (r ≥ ±0.80) were also excluded; the 7 selected parameters were: total metabolic footprint (r = -0.75), structure footprint (r = 0.78), metabolic footprint of predators (r = 0.76), metabolic footprint of omnivores (r = 0.79), % free-living fungivores (r = -0.64), evenness index (r = 0.69) and Berger-Parker index (r = 0.75).

3.3 Relationship of variables and biological parameters with the stress gradient

The stress gradient derived from PCA revealed an integrated response of soil chemical, microbial, and biological components to mining influence. The contribution of Al, Fe, and total actinomycetes to PC1 indicates that mining-related disturbance involves simultaneous changes in soil chemical conditions and microbial functioning (Zhou et al., 2026). The association of Al with the gradient may reflect alterations in soil chemical balance, as increased Al availability can interfere with nutrient dynamics and biological processes (Liang et al., 2022). Likewise, Fe contribution suggests modifications in elemental availability and microbial interactions under disturbed conditions (Ouyang et al., 2023). The contribution of actinomycetes suggests that microbial functional responses are also involved in the stress gradient, given their roles in organic matter transformation and nutrient cycling (Devassy et al., 2023; Oyedoh et al., 2023). Therefore, PC1 represents a multidimensional disturbance pattern that integrates chemical and biological responses rather than the effects of individual variables.

The relationship between the stress gradient and nematode indicators revealed a functional reorganization of the soil food web in response to mining-related disturbance. Trophic groups did not respond uniformly, reflecting differences in ecological strategies and resource dependence (Peñaloza-Bojacá et al., 2026). Predatory and omnivorous nematodes showed positive associations with the gradient, suggesting greater persistence of groups with broader trophic strategies under stressful conditions (Buch et al., 2025). Predators may benefit from changes in prey availability and trophic interactions under disturbance (Kanwar et al., 2021), while omnivores can maintain activity by exploiting diverse resources when environmental conditions become restrictive (Pen-Mouratov & Dayan, 2019). These responses were also reflected in their metabolic footprints, indicating adjustments in energy allocation and trophic functioning within the community (Kudrin et al., 2021; Tu et al., 2022).

In contrast, the negative associations observed for fungivorous and bacterivorous nematodes indicate reductions in microbial-based trophic pathways along the stress gradient. These responses are consistent with the dependence of these groups on fungal and bacterial resources, which may decrease under stressful conditions due to limitations in moisture availability and microbial activity (Yang et al., 2024). Reduced microbial activity under water-limited conditions can, in turn, affect the energy-transfer processes that support higher trophic levels (Xing et al., 2024). Thus, the contrasting responses among trophic groups indicate that environmental stress modifies specific functional pathways rather than producing a uniform decline of the nematode community (Ge et al., 2024).

Changes in community organization further supported structural adjustments along the stress gradient (Gattoni et al., 2026). The positive relationships observed for evenness, structural footprint, and Berger–Parker index suggest that disturbance modified dominance patterns and functional organization within the nematode community. Environmental stress can alter species abundance distributions by reducing the abundance of sensitive taxa and favoring organisms with greater tolerance to altered conditions (Gamito & Furtado, 2009; Ingram, 2008). Similar reorganizations have been reported in nematode communities exposed to environmental constraints, where changes in trophic structure and species distribution contribute to community adjustment (Diop et al., 2026).

3.4 Integral index design soil quality

For both the drought (Table 3) and rainy (Table 4) seasons, standardization formulas were developed for each selected biological index based on its response to the stress gradient. Additionally, a proposal of 5 soil quality ranges with their respective ratings was presented (Table 5).

Table 3
Standardization formula of the selected biological parameters according to their response to the stress gradient for the drought seasons

Parameters that increase with the stress gradient	5th percentile	Maximum value	Formula
Free-living predators (%)	0.2	36.9	100*((36.9-X)/36.7))
Free-living omnivores (%)	5.9	34.0	100*((34.0-X)/28.1))
Evenness index	0.6	0.9	100*((0.9-X)/0.3))
Parameters that decrease with the stress gradient	**95th percentile**	**Minimum value**	**Formula**
Metabolic footprint of fungivores	1.7	0.7	100*(X/1.0)
Free-living bacterivores (%)	72.2	23.7	100*(X/48.5)

X: value of the metric.

Table 4
Standardization formula of the selected biological parameters according to their response to the stress gradient for the rainy seasons

Parameters that increase with the stress gradient	5th percentile	Maximum value	Formula
Footprint of structure	42.1	164.2	100*((164.2-X)/122.1))
Metabolic footprint of predators	12.8	61.8	100*((61.8-X)/49.0))
Metabolic footprint of omnivores	29.2	102.4	100*((102.4-X)/73.2))
Evenness index	0.8	0.9	100*((0.9-X)/0.1))
Berger-Parker index	0.2	0.4	100*(0.4-X)/0.2))
Parameters that decrease with the stress gradient	**95th percentile**	**Minimum value**	**Formula, X=value of the metric**
Total metabolic footprint	740.0	216.8	100*(X/523.2)
Free-living fungivores (%)	18.3	9.6	100*(X/8.7)

X: value of the metric.

Table 5
Proposed soil quality rating for each range of values for the drought and rainy seasons

Drought season range	Rainy season range	Quality
≥ 97	≥ 70	Excellent
77 – 96	44 – 69	Good
24 – 76	32 – 43	Moderate
4 – 23	17 – 31	Bad
≤ 3	≤ 16	Terrible

3.5 Determination of soil quality using the integral index and comparison with other soil quality indices against the stress gradient

When calculating the integral index soil quality for the drought seasons, it was recorded that the 4 types of land use were distributed between 2 quality ranges; the integral index classified natural pasture and *Zea mays* cultivation in the "bad" soil quality category with values of 23 and 21 respectively; *Ficus sp.* cultivation and *Eucalyptus sp.* forest were classified in the "moderate" quality category with values of 60 and 73 respectively (Table 6).

When calculating the integral index for the rainy seasons, it was recorded that the 4 types of soil were distributed between 3 quality ranges; the integral index classified the natural pasture and *Zea mays* cultivation in the "good" soil quality category with values of 46 and 45 respectively; the *Ficus sp.* cultivation in the "moderate" quality category with a value of 40; and *Eucalyptus sp.* forest in the "excellent" quality category with a value of 86 (Table 6).

In the drought seasons, when comparing the integral index and 7 soil quality indices against the stress gradient, calculated for the 4 soil types, in the ACC (Figure 4), axis 1 explained 81.82% and axis 2, 18.18% of the data variability; between both, they explained 100.00%, therefore, they were the 2 axis considered for the analysis. The ACC showed that there are significant correlations between: the stress gradient with the integral index (r = 0.97), the maturity index 2 - 5 (r = 0.95), the maturity index (r = 0.85), and the sigma maturity index (r = 0.82); in the natural pasture, *Zea mays* cultivation, and *Ficus sp.* cultivation.

In the rainy seasons, when comparing the integral index and 7 soil quality indices against the stress gradient, calculated for the 4 soil types, in the ACC (Figure 5), axis 1 explained 69.72% and axis 2, 30.28% of the data variability; between both, they explained 100.00%, therefore, they were the 2 axis considered for the analysis. The ACC showed significant correlations between the stress gradient and the integral index (r = 0.95) and the structure index (r = 0.83) in the natural pasture, *Zea mays* cultivation, and *Ficus sp.* cultivation.

3.6 Soil quality using the integral index and comparison with other soil quality indices

Based on the integral index constructed in the present study, during dry seasons, natural grassland and *Zea mays* cultivation were classified as "bad"

quality; excluding the influence of soil moisture, this unfavorable classification can be attributed to various factors, such as high intensity of use, overgrazing on grasslands, and certain inappropriate agricultural practices, such as excessive use of chemical fertilizers, lack of crop rotation, and soil compaction due to heavy machinery (Perfanova et al., 2025). Serrano et al. (2024) have shown that soils under natural pastures can degrade due to overgrazing, thereby reducing their quality. In *Zea mays* cultivation, intensive agricultural practices and the use of agrochemicals can degrade soil structure and organic content, thereby decreasing soil quality (Huang et al., 2021). On the other hand, *Ficus sp.* cultivation and *Eucalyptus sp.* forest showed a "moderate" soil quality; this classification can be attributed to the capacity of these systems to improve or maintain soil quality through different mechanisms (Pazhavand & Sadeghi, 2020); in the case of *Ficus sp.* cultivation, being trees, they can contribute to the improvement of soil structure due to the larger size of their root systems, improve soil cover, and increase the contribution of OM through leaf fall and plant residues (Ferretti et al., 2024); in the same way, *Eucalyptus sp.* forests can also have a more positive effect on soil quality, although the results may vary depending on forest management and the specific species used (Hutapea et al., 2024), such as *Eucalyptus globulus* and *Eucalyptus camaldulensis*, which are distinguished by their rapid growth and ability to adapt to adverse conditions, contributing to soil structure improvement and the increase of OM content (Ferreira et al., 2019).

For the rainy seasons, it was observed that both natural pasture and *Zea mays* cultivation were rated as "good" quality, the opposite rating to the quality shown in the drought seasons; this is possibly related to the increase in soil moisture, facilitating microbial activity, decomposition of OM, and the release of essential nutrients (Karaca et al., 2021). In *Zea mays* cultivation, rainfall can also reduce water stress and improve fertilizer use efficiency, thereby contributing to better soil quality (Canning, 2026). *Ficus sp.* cultivation was classified in the "moderate" quality category, despite rainfall; soil quality in these systems may not improve as significantly as in other vegetation types due to factors such as plant density, competition for nutrients and water, or management practices (Shang et al., 2024). The soil in *Eucalyptus sp.* forest was rated as "excellent"; this result suggests that forest soil respond very positively to rainfall conditions, among other reasons, due to their ability to improve soil structure, increase water retention, and provide OM through leaf litter fall (Qin et al., 2024).

Table 6
Soil quality for drought and rainy seasons

Type of soil	Drought season value	Quality	Rainy season value	Quality
Natural pasture	23	Bad	46	Good
Zea mays cultivation cultivation	21	Bad	45	Good
Ficus sp. cultivation	60	Moderate	40	Moderate
Eucalyptus sp. forest	73	Moderate	86	Excellent

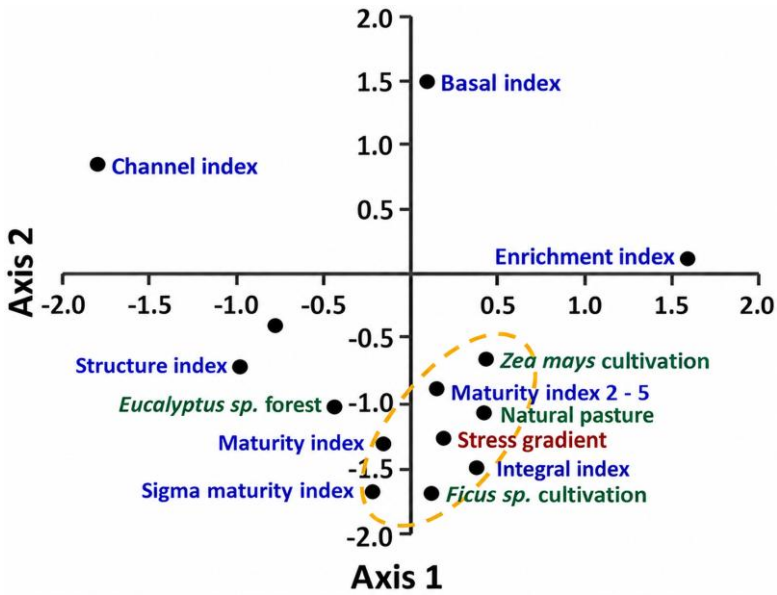


Figure 4. Relationship between soil quality indices and stress gradient for drought seasons.

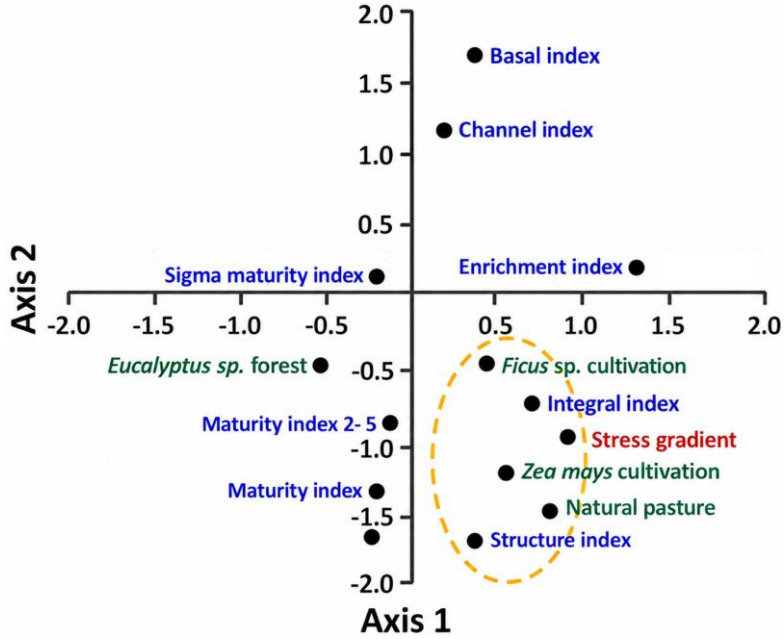


Figure 5. Relationship between soil quality indices and the stress gradient for the rainy seasons.

The integral index across the drought and rainy seasons highlights significant differences in soil quality among the cover types. During drought seasons, soil quality was observed to be bad in the natural pasture and *Zea mays* cultivation, which can be attributed to low water retention capacity and the lack of protective vegetation cover, factors that exacerbate OM loss and soil compaction under these conditions (Guo et al., 2025). In contrast, the *Ficus sp*. cultivation and the *Eucalyptus sp.* forest *exhibit*ed moderate soil quality, likely due to greater vegetation cover and deeper root systems, which improve soil structure and water retention capacity (Ferretti et al., 2024). In the rainy season, soil quality improved significantly in the natural pasture and the *Zea mays* cultivation, reaching good quality. This suggests that moisture and OM contribute to biological activity and soil structure under these conditions (Adebayo et al., 2026). The quality of the *Ficus sp*. cultivation and *the Eucalyptus sp.* forest was moderate, indicating that their responses to moisture conditions are less pronounced, probably due to their intrinsic capacity to adapt to different water conditions (Daly et al., 2023). Finally, the *Eucalyptus sp*. forest reached an excellent quality level, reflecting the high capacity of this system to maintain good soil structure, increase water infiltration, and promote soil biodiversity, even under conditions of greater water availability (Poudel et al., 2024). These findings emphasize the importance of cover type and management in preserving soil quality under different climatic conditions.

During drought seasons, when comparing the integral index and 7 soil quality indices against the stress gradient, the integral index and the maturity indices provided the best fit, suggesting that these indices are the most suitable for assessing soil quality under water-stress conditions (Saedi et al., 2016). Previous studies, such as those by Hu et al. (2024), have demonstrated that maturity indices, which reflect soil stability and resilience, are effective indicators of soil quality under drought conditions. And the integral index, by incorporating multiple nematological parameters, provides a holistic assessment of soil quality, which may explain its high performance under these conditions (Bajgai et al., 2026).

During rainy seasons, the integral index showed the highest correlation with the stress gradient, along with the structure index; these results indicate that the integral index is a good predictor of soil quality under mining influence, even under high humidity conditions (Wondmagegn & Mengistou, 2023). Furthermore, research such as that carried out by Vasu et al. (2024) has shown that these studies indicate that changes in the stress gradient, assessed by integral nematode indices, constitute an effective tool to analyze the evolution and condition of ecosystems, whether natural or agricultural, as evidenced by the patterns observed in natural pastures, *Zea mays*, and *Ficus sp.* cultivations in our research.

4. Conclusions

The integral soil quality index developed in this study demonstrated a robust capacity to assess mining-induced soil degradation by integrating physicochemical, microbiological, and nematode indicators into a comprehensive evaluation framework. The proposed index showed stronger relationships with the environmental stress gradient than traditional soil quality indices, presenting high correlations during both drought (r = 0.97) and rainy seasons (r = 0.95). These results highlight their ability to capture multidimensional soil responses associated with mining disturbance.

Soil quality was strongly influenced by land-use type and seasonal variability. During drought seasons, natural pasture and *Zea mays* cultivation showed bad soil quality conditions (values of 23 and 21, respectively), whereas *Ficus sp.* cultivation and *Eucalyptus sp.* forest maintained moderate quality levels (values of 60 and 73). During rainy seasons, soil quality improved in natural pasture and *Zea mays* cultivation, reaching good conditions (values of 46 and 45), while *Eucalyptus sp*. forest achieved the highest quality status (value of 86). These results demonstrate the importance of vegetation cover, land management, and seasonal dynamics in regulating soil quality in mining-affected ecosystems.

The integration of nematode-based biological responses with physicochemical and microbiological indicators provides a sensitive and comprehensive approach for monitoring soils affected by artisanal mining. The proposed index represents a useful tool for ecological assessment and restoration strategies in Andean mining landscapes, where multiple soil degradation processes occur simultaneously.

A limitation of this study is that the index was developed and validated under the specific environmental conditions of an Andean artisanal mining area. Future studies should evaluate its transferability across different mining regions and ecosystems, incorporating long-term monitoring approaches to strengthen its predictive capacity and broader applicability.

Data availability statement

The underlying data of this study are available as supplementary material attached to the article.

CRediT authorship contribution statement

M. O. Niño-de-Guzman-Tito: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Writing – review & editing. **J. A. Dominguez-Nuñez:** Writing – review & editing, Supervision, Methodology, Investigation, Data curation, Conceptualization, and Project administration. **I. Lima-Medina:** Writing – review, Data curation, Conceptualization.

Declaration of interests

The corresponding author declares that the Universidad Nacional de Moquegua has covered the costs associated with the Article Publishing Charges (APC) for the publication of this article.

Acknowledgement

The authors would like to thank the anonymous reviewers for their valuable comments and suggestions.

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