Agrociencia

PHYSICAL, CHEMICAL, AND BIOLOGICAL CHARACTERIZATION OF SOIL FROM THREE SHADE-GROWN COFFEE FARMS IN JILOTEPEC, VERACRUZ, MEXICO

Yadeneyro **de la Cruz-Elizondo**[1], Evelin Zugey **Segura-Saavedra**[1], Rosa María **Arias-Mota**[2], Juan Carlos **Moreno-Seceña**[3*]

[1]Universidad Veracruzana Campus Xalapa. Facultad de Biología. Circuito Gonzalo Aguirre Beltrán s/n, Zona Universitaria, Xalapa, Veracruz, Mexico. C. P. 91000.
[2]Instituto de Ecología, A.C. Antigua Carretera a Coatepec km 2.5, Congregación el Haya, Xalapa, Veracruz, Mexico. C. P. 91073.
[3]Colegio de Postgraduados Campus Montecillo. Carretera México-Texcoco km 36.5, Montecillo, Texcoco, State of Mexico, Mexico. C. P. 56264.
* Author for correspondence: rosa.arias@inecol.mx

ABSTRACT

The soil of shaded coffee plantations in Veracruz, Mexico, provides environmental services such as water regulation, carbon storage, and support for soil biodiversity. However, it has traditionally been treated solely as a physical support for crops, resulting in the overuse of agrochemicals and deterioration of functionality. In light of this problem, this study had the objective of characterizing the physical, chemical, and biological properties of the soil in coffee plantations in the municipality of Jilotepec, Veracruz, to generate useful information for monitoring and promoting sustainable management. Three farms were evaluated: La Barranca, Los Bambús, and San Isidro. La Barranca showed the highest organic matter content (11.87 %), mulch accumulation (57.74 g m^{-2}), and microbial activity (705.7 μg C-CO_2 kg^{-1} d^{-1}), but also had the lowest earthworm density (9.2 individuals m^{-2}), possibly limited by its acidic pH (4.81) and low phosphorus availability (2.04 mg kg^{-1}). Los Bambús farm had a pH value of 5.24, a loamy-clay texture, high microbial respiration (700 μg C-CO_2 kg^{-1} d^{-1}), and the highest earthworm density (17.6 individuals m^{-2}), despite containing a low organic matter content (6.38 %). San Isidro, with a clay texture, had low microbial activity (645 μg C-CO_2 kg^{-1} d^{-1}) and intermediate earthworm density (15.2 individuals m^{-2}), which could be related to its strongly acidic pH (4.09) and low available phosphorus (4.98 mg kg^{-1}). The results reflect the complexity of the edaphic system and the need to consider multiple indicators for integrated soil management that take into account its physical, chemical, and biological properties to improve the sustainability and resilience of coffee systems.

Key words: edaphology, indicators, coffee, management, agroecology.

Citation: de la Cruz-Elizondo Yadeneyro, Segura- Saavedra Evelyn Zugey, Arias-Mota Rosa María, Moreno- Seceña Juan Carlos. 2025. Physical, chemical, and biological characterization of soil from three shade-grown coffee farms in Jilotepec, Veracruz, Mexico. **Agrociencia.** https://doi.org/ 10.47163/agrociencia.v59i7.3469

Editor in Chief:
Dr. Fernando C. Gómez Merino

Received: April 09, 2025.
Approved: October 01, 2025.
Published in Agrociencia:
October 13, 2025.

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INTRODUCTION

In Mexico, coffee cultivation (*Coffea arabica* L.) is of great economic importance due to the foreign exchange it generates, as a significant part of production is destined for foreign trade. However, this crop has undergone substantial changes since the implementation of new technologies promoted by the Green Revolution, which, in many cases, have proved ineffective due to inadequate agronomic practices. These conditions have led to growing interest in biodiversity conservation in agriculture, highlighting the role of agroforestry systems in coffee plantations. By incorporating a tree structure that emulates the forest ecosystems where coffee has historically been grown, these systems contribute significantly to the preservation of such environments (Manson *et al*., 2008).

Mexico ranks eleventh in global coffee production, with 710 361 ha destined for this crop (SADER, 2023). Although it is not part of the basic food basket, coffee represents 0.66 % of the national gross domestic product and generates approximately 700 000 direct and indirect jobs. The main producing states are Chiapas, Veracruz, and Oaxaca. In Jilotepec, Veracruz, coffee has been internationally recognized for its high quality, ranking first in the Cup of Excellence competitions in 2017 and 2023. However, there are still few studies focused on soil characterization and the analysis of production practices associated with this crop.

Coffee growers in Jilotepec have faced severe economic losses due to the incidence of pests such as coffee berry borer and rust, which have significantly compromised crop productivity. In response, the use of agrochemicals has increased, which is detrimental to soil health. The soil is a key component of the coffee agroecosystem, providing water and nutrients essential for plant growth through a complex edaphic trophic network (Burbano-Orjuela, 2016; Lavelle, 2021). Understanding the physical, chemical, and biological characteristics of the soil is essential for evaluating its overall functioning. The joint analysis of these properties allows for the diagnosis of its condition, the identification of limiting factors, and the design of appropriate management practices. From this perspective, the objective of this study was to characterize the physical, chemical, and biological properties of the soil in coffee plantations in the municipality of Jilotepec, Veracruz.

MATERIALS AND METHODS

Area of study

The study area is located in the municipality of Jilotepec, in the central mountainous region of the state of Veracruz, Mexico (19° 36′ N and 96° 55′ W), at an altitude between 860 and 1900 m. It borders Naolinco to the north, Banderilla to the south, Rafael Lucio to the southwest, and Tlacolula to the west (Figure 1). The climate is temperate, subhumid, with rainfall in the summer (Cw). Its average annual temperature ranges between 16 and 22 °C, with an annual accumulated precipitation between 1400 and

Figure 1. Location of the study area and sampled farms in the municipality of Jilotepec, Veracruz, Mexico.

1600 mm (INEGI, 2023). The soil is mainly andosol, characterized by volcanic ash and grayish tones (INAFED, 2013).

The area is characterized by a rugged landscape with steep slopes ranging from 10 to 45 % in most of the territory where coffee farming is located (INEGI, 2023). In the municipality of Jilotepec, mesophilic mountain forests, oak forests, and tropical deciduous forests predominate. The main species of flora include *Persea schiedeana* Nees, *Quercus xalapensis* Bonpl., *Fraxinus uhdei* (Wenz.) Lingelsh., *Populus mexicana* Wesm., *Salix humboldtiana* Willd., *Inga vera* Willd., and various ferns, orchids, and bromeliads (Rivera-Hernández *et al*., 2019).

For this study, three coffee farms established more than 25 years ago were selected, all of which are cultivated using the shade-grown system (Figure 2). Coffee plants

Figure 2. Selected coffee farms in the municipality of Jilotepec, Veracruz, Mexico. A: San Isidro; B: Los Bambús; C: La Barranca.

of different varieties are intermingled on the farms, with densities greater than 2500 plants per hectare. The farms are managed using conventional agronomic practices, with the application of agrochemicals for fertilization and control of weeds, pests, and diseases such as rust and coffee berry borer, although some farms also incorporate organic amendments. The geographical location, altitude, variety, and density of the coffee plants, as well as other characteristics of the agroecosystem, are described in more detail (Table 1).

Table 1. Geographic location, size, and characteristics of the study sites in the municipality of Jilotepec, Veracruz, Mexico.

Sites	Latitude Longitude	Size (ha)	Characteristics
San Isidro	19° 36′ 12.15′′ 96° 54′ 44.91′′	2	The dominant coffee variety is 'Costa Rica', followed by 'Mundo Novo' and 'Sachimor' in smaller proportions. Plant density is approximately 2500 plants per hectare. The system includes around 160 shade trees, mainly *Inga* spp. and *Ficus* spp. Management is conventional: horse manure and coffee compost are applied, along with chemical fertilizers once a year. Weed control is performed three to four times annually by mowing, and biological control of the coffee berry borer is implemented. The slope exceeds 30 %.
Los Bambús	19° 36′ 42.7′′ 96° 65′ 16.01′′	1.5	The coffee varieties cultivated are 'Costa Rica' and 'Sarchimor'. Plant density is approximately 2857 plants per hectare. The system includes about 100 shade trees, primarily *Inga* spp., *Citrus* spp., and *Musa paradisiaca* L. Management practices are conventional: chemical fertilizers are applied once a year, and weed control is performed three to four times annually by mowing. The slope of the area exceeds 30 %.
La Barranca	19° 36′ 38.07′′ 96° 55′ 40.57′′	2	The coffee varieties cultivated are 'Costa Rica', 'Typica', 'Mundo Novo', and 'Sarchimor'. Plant density is approximately 2,857 plants per hectare. The system includes about 100 shade trees, mainly *Inga* spp., *Trema micrantha* (Roem. and Schult.) Blume, and *Citrus* spp. Management is conventional: chemical fertilizers are applied once a year, and both compost and leaf mulch are incorporated into the soil. The slope of the area is less than 10 %.

Sampling

Considering that the farms have an approximate area of 2 ha each, according to the Tropical Soil Biology and Fertility (TSBF) method (Anderson and Ingram, 1993), a transect of five monoliths separated by 5 m was delimited. At these points, biological properties were determined from soil samples obtained at a depth of 0 to 30 cm. The collected soil was dried in the shade at room temperature (25–28 °C). Physical and chemical analyses were performed in the laboratory of the Institute of Ecology (INECOL A.C.), following the guidelines established by NOM-021-SEMARNAT-2000 (DOF, 2002).

Physical analysis

For physical analyses of bulk density and texture (Bouyoucos), NOM-021-SEMARNAT-2000 (DOF, 2002) and the Tropical Soils Manual (Moreira *et al*., 2012) were followed. Field capacity was measured using the gravimetric method. Soil samples were saturated in running water and then drained for 24 h. The calculation was performed using the formula:

$$\text{Moisture content} = \frac{\text{Wet weight - Dry weight}}{\text{Dry weight}}$$

Five samples were analyzed at each farm. Tests to determine structure were carried out following the guidelines for visual assessment of soil quality (Noellemeyer *et al*., 2021).

Chemical analysis

Chemical tests included determining organic matter using the Walkley and Black (1934) method and analyzing available phosphorus (P) using the Bray and Kurtz (1945) method. pH and electrical conductivity were measured with a potentiometer in a supernatant suspension of a soil-water mixture (1:2). Electrical conductivity results are expressed in decisiemens per meter (dS m^{-1}). Five samples were analyzed for each farm.

Biological analysis

Biological evaluations included litter weight and earthworm counts, both conducted using the TSBF method (Moreira *et al*., 2012). Soil microbial respiration was measured according to Isermeyer (1952). Earthworm abundance was expressed as the number of individuals per square meter (individuals m^{-2}). Five samples were collected from each farm for evaluation.

Statistical analysis

The assumptions of normality and homogeneity were verified using the Kolmogorov-Smirnov and Bartlett tests, respectively. The data were subjected to a one-way analysis of variance (ANOVA). In cases where significant effects were detected ($p < 0.05$), means were compared using Tukey's test (HSD), using the STATISTICA statistical package version 7.0.

RESULTS AND DISCUSSION

Physical characterization of the soil

In this study, differences in soil texture classes were observed among the three farms sampled: clayey in San Isidro, loamy-clayey in Los Bambús, and loamy-clayey-sandy in La Barranca (Table 2). The percentage composition of soil particles determines soil texture (Porta-Casanellas, 2008), which in turn can significantly influence coffee plant growth and development.

Table 2. Values of physical, chemical, and biological parameters obtained in the farms sampled in the municipality of Jilotepec, Veracruz, Mexico.

Parameters	San Isidro	Los Bambús	La Barranca
	Physical		
Texture	Clay	Clay loam	Sandy clay loam
Clay (%)	44.36 ± 1.10 a	32.36 ± 1.63 b	26.36 ± 1.60 c
Silt (%)	20.0 ± 1.25 b	26.0 ± 1.73 a	20.0 ± 1.39 b
Sand (%)	35.64 ± 2.33 c	41.64 ± 3.45 b	53.60 ± 2.63 a
Bulk density (g cm^{-3})	1.45 ± 0.18 a	1.6 ± 0.08 a	1.32 ± 0.25 a
Structure	Good	Moderate	Good
Field capacity (%)	31.72 ± 1.91 a	22.69 ± 2.15 b	21.62 ± 3.12 b
	Chemical		
Organic matter (%)	9.13 ± 3.1 ab (Medium)	6.38 ± 2.10 b (Medium)	11.87 ± 2.50 a (High)
Available phosphorus (mg kg^{-1})	4.98 ± 0.88 a (Low)	2.67 ± 0.89 b (Low)	2.04 ± 0.82 b (Low)
pH	4.09 ± 0.45 b	5.24 ± 0.70 a	4.81 ± 0.43 ab
Electrical conductivity (mS m^{-1})	0.20 ± 0.05 a	0.09 ± 0.05 b	0.11 ± 0.03 b
	Biologic		
Earthworms	15.2 ± 6.94 ab (Poor)	17.6 ± 5.17 a (Poor)	9.2 ± 4.20 b (Poor)
Mulch (g m^{-2})	46.89 ± 23.83 ab	27.02 ± 10.53 b	57.74 ± 22.43 a
Microbial respiration (µg C-CO_2 kg^{-1} d^{-1})	645.0 ± 4.94 b	700.0 ± 4.94 a	705.7 ± 4.94 a

The data correspond to the average of five repetitions ± standard deviation. Different letters represent significant differences ($p < 0.05$).

The optimal texture for coffee development corresponds to loamy soils, characterized by an adequate balance between sand, silt, and clay (Rosas-Arellano *et al.*, 2008). This type of soil allows for good water and nutrient retention while promoting drainage and aeration. The soils in this region are of volcanic origin and have an approximate clay content of 40 %, which gives them a high phosphorus retention capacity, thus reducing its loss through leaching (Sadeghian, 2008). In this context, Los Bambús and La Barranca have textures suitable for coffee cultivation, while San Isidro has a less favorable texture due to its high clay content. This condition can cause drainage and aeration problems, limit root system development, and encourage the proliferation of pathogenic microorganisms (Márquez-de la Cruz *et al.*, 2022).

In this study, bulk density was similar between farms ($p < 0.05$), with values ranging from 0.88 to 0.9 g cm^{-3} (Table 2), which is within the optimal range suggested for coffee cultivation (0.8 to 1 g cm^{-3}) by Sadeghian *et al.* (2019). The physical conditions of the soil on the farms are favorable for root development and water infiltration, given that bulk density reflects the mass of soil solids and their pore space in relation to the total volume of undisturbed dry soil (Porta-Casanellas, 2008). This indicator is essential for assessing compaction, porosity, and water retention capacity, which directly affect plant growth and microbial activity in the soil (Salamanca-Jiménez *et al*., 2018).

According to Lince-Salazar (2021), maintaining this bulk density, mainly in the surface strata (0–20 cm), is crucial in areas with steep slopes, such as those in this region, as it promotes adequate rainwater infiltration and helps minimize soil erosion. On the other hand, the results coincide with those reported by Geissert and Ibáñez (2008), who recorded values of 0.8 to 1.4 g cm^{-3} in coffee plantations in Coatepec-Huatusco, Veracruz, showing variations associated with management and topographic characteristics.

The results of soil structure on the San Isidro and La Barranca farms indicate good condition, while Los Bambús was classified as moderate according to Noellemeyer *et al*. (2021) (Table 2). These data are consistent with Geissert and Ibáñez (2008) in a study carried out in the central area of Veracruz (Coatepec-Huatusco), where they observed that forest and coffee plantation soils have a porous and light structure, derived from the three-dimensional arrangement of solid particles and porous spaces that form between them. The authors highlight that the development of this porous structure is the main cause of the low bulk density observed in the volcanic soil characteristic of this region.

Field capacity was significantly higher ($p < 0.05$) at San Isidro (31.72 %) than La Barranca (21.62 %) and Los Bambús (22.69 %) (Table 2). This difference is related to the higher clay content in San Isidro (44.36 %), which favors greater water retention (Lince-Salazar, 2021). Field capacity corresponds to the water content that the soil retains after heavy rainfall or irrigation, once gravitational drainage has ended (24–48 h) and water potential stabilized (FAO, 2024). This is a key indicator of water availability for crops. The values in San Isidro are close to the optimal range of 30–35 % reported by Geissert and Ibáñez (2008) for coffee plantations on volcanic soils in Coatepec-Huatusco, Veracruz, indicating good water availability in the surface profile.

Soil chemical characterization

Organic matter content was 9.13 % in San Isidro, 6.38 % in Los Bambús, and 11.87 % in La Barranca (Table 2). According to NOM-021-SEMARNAT-2000 (DOF, 2002), these values are in the medium to high range. However, according to Sadeghian *et al*. (2019), for coffee cultivation, values below 8 % are considered low, between 8 and 16 % are medium, and above 16 % are high. Therefore, San Isidro and La Barranca have medium levels, while Los Bambús has low content. The variation in organic matter between sites can be attributed to differences in agricultural management, vegetation cover, and soil conservation practices.

The results are consistent with studies in the coffee-growing region of Veracruz. For example, in Tlapacoyan, organic matter contents ranging from 3.74 to 10.09 % were reported. In Colombia, González-Osorio (2019) found organic matter levels ranging from 4 to 7 %, depending on management and geographic location. Adequate organic matter content in the soil plays a crucial role in pH stabilization, as it acts as a mixture of weak acids and allows pH regulation (Sadeghian, 2016). Moreover, it influences soil texture and structure by improving aeration in clay soils and increasing water retention and adhesion in sandy soils, which in turn affects nutrient content and availability (Palma-López *et al*., 2015).

The levels of available phosphorus in the farms evaluated were 4.98 mg kg^{-1} in San Isidro, 2.67 mg kg^{-1} in Los Bambús, and 2.04 mg kg^{-1} in La Barranca (Table 2). According to the classification proposed by Sadeghian *et al*. (2019), values below 10 mg kg^{-1} are considered low, between 10 and 20 mg kg^{-1} are medium, and above 20 mg kg^{-1} are high. Therefore, all three sites have low levels of available phosphorus. In Tlapacoyan, Veracruz, Márquez-de la Cruz *et al*. (2022) reported phosphorus levels in coffee soils ranging from 3.74 to 10.09 mg kg^{-1}, indicating limited availability of this nutrient. In Colombia, González-Osorio (2019) found phosphorus contents ranging from 4 to 7 mg kg^{-1}, also in the low range.

The soils of the three farms showed a pH classified as strongly acidic to moderately acidic (4.09–5.24) (Table 2) according to NOM-021-RECNAT-2000 (DOF, 2002). The ideal pH range for coffee growth is between 5 and 5.5 (Sadeghian, 2016); values outside this range are limiting, either due to acidity (pH <5) or alkalinity (pH >5.5). Acidity restricts the availability of nutrients such as phosphorus and calcium, and when exchangeable aluminum contents exceed 1 cmolc kg^{-1}, toxicity increases, affecting biological activity and crop development.

The electrical conductivity (CE) values in the soils evaluated were 0.2 mS cm^{-1} for San Isidro, 0.09 mS cm^{-1} for Los Bambús, and 0.11 mS cm^{-1} for La Barranca (Table 2). According to FAO (2005), soils with CE values below 0.4 mS cm^{-1} are considered non-saline, a condition that favors coffee growth by preventing salt stress. According to NOM-021-SEMARNAT-2000 (DOF, 2002), the effects of salinity were negligible, with values less than one. Márquez-de la Cruz *et al*. (2022) reported EC values below 0.3 mS cm^{-1}, confirming low salinity. Similarly, González-Osorio (2019) documented similar values in Colombian coffee plantations, highlighting the importance of maintaining low salt levels to preserve soil health and productivity.

Soil biological characterization

The mulch values recorded in this study (27.02 to 57.4 g m^{-2}) (Table 2) are considerably low compared to other coffee systems in Latin America. In Costa Rica, Magaña *et al*. (2004) found that in full sun exposure, the mulch layer stored 240 g m^{-2}, while under shade with *Eucalyptus,* it reached values of 840 g m^{-2}. Although specific literature on mulch biomass in coffee plantations is limited in Mexico, research on agroforestry systems in Veracruz and Chiapas recognizes mulch as an essential component in soil protection and fertility (Paz-Pellat *et al*., 2022), with a key role in carbon and moisture conservation.

The low accumulation of mulch could be due to low tree cover, intensive cleaning practices that remove leaf litter, the use of herbicides, or limited plant biomass production. This deficit has significant ecological implications, as mulch acts as a protective barrier against erosion, regulates soil temperature and moisture, and is a source of resources for edaphic fauna that degrade it and incorporate it into the soil matrix. In this context, the results indicate low functionality of the edaphic system in terms of surface organic cover.

The results obtained from the farms show a very low density of earthworms, with average values between 9.2 and 17.6 individuals m^{-2} (Table 2), well below the value proposed by Geissert *et al*. (2013), who establish that a population is considered rich when it exceeds 900 individuals m^{-2} in coffee soils. This low abundance reflects severe biological impoverishment and could indicate unfavorable soil conditions, such as low mulch production, soil acidification, compaction, or intensive use of agrochemicals.

In a comparative study between coffee plantations and forests in Colombia, Rueda-Ramírez and Varela (2016) found earthworm densities of between 147.2 and 281.6 individuals m^{-2}, suggesting moderate biological activity, but still limited compared to more conserved agroforestry systems, where values close to 900 individuals m^{-2} are reported. This difference suggests that, although other groups of macroinvertebrates may persist, earthworms are particularly sensitive to disturbances in the system, especially native species. In a shade-grown coffee plantation in Cuba, Ferrás-Negrín and Rusindo-Hernández (2025) found an average density of 354 individuals m^{-2} and a biomass of 80.25 g m^{-2}, dominated almost exclusively by the exotic species *Pontoscolex corethrurus*, which is known for its tolerance to disturbed environments. These values far exceed those of this study, highlighting the magnitude of the biological impact on the farms assessed.

Microbial respiration values differed between farms ($p < 0.05$); the highest value was detected in La Barranca (705.7 μg C-CO_2 g^{-1} d^{-1}) and Los Bambús (700 μg C-CO_2 g^{-1} d^{-1}), while in San Isidro, the values were significantly lower (645 μg C-CO_2 g^{-1} d^{-1}) (Table 2). These respiration values indicate high microbial activity, comparable to or higher than those reported in other coffee systems in Latin America. For example, Durango *et al*. (2015) reported values of 580 μg C-CO_2 g^{-1} d^{-1} in coffee plantations in Costa Rica, while Chavarría-Bolaños *et al*. (2012) found 640 μg C-CO_2 g^{-1} d^{-1} in forest systems and 440 μg C-CO_2 g^{-1} d^{-1} in unshaded coffee, indicating that more complex systems with greater vegetation cover promote greater biological activity in the soil.

In contrast, Paolini-Gómez *et al*. (2008) reported considerably lower soil respiration values (15.5–26 mg C-CO_2 kg^{-1} d^{-1}) in traditionally managed Venezuelan coffee plantations established on acidic soils. Although subsequent research (Paolini-Gómez, 2017) recorded increases of up to 76.2 mg C-CO_2 kg^{-1} d^{-1} in organically managed systems, these values are still lower than those observed in the present study. Similarly, Azevedo-Junior *et al*. (2017) reported rates of between 60 and 70 mg C-CO_2 kg^{-1} d^{-1} in Brazilian organic coffee plantations, while Pardo-Plaza *et al*. (2019) documented a range of 18.5 to 37 mg C-CO_2 kg^{-1} d^{-1}.

The data obtained from the three farms studied suggests that La Barranca, with the highest organic matter content (11.87 %), also showed the highest microbial activity (705.7 μg C-CO_2 kg^{-1} d^{-1}) and the highest mulch accumulation (57.74 g m^{-2}). However, it had the lowest earthworm density (9.2 individuals m^{-2}), indicating that resource availability does not necessarily translate into greater earthworm abundance but rather into other conditions, such as acidic pH (4.81) or low phosphorus availability (2.04 mg kg^{-1}), which are limiting factors.

In contrast, Los Bambús, with high microbial respiration (700 μg C-CO_2 kg^{-1} d^{-1}) and moderate mulch (27.02 g m^{-2}), had the highest earthworm density (17.6 individuals m^{-2}). This farm has the highest pH (5.24) and a loamy-clay texture, which may suggest more stable and favorable soil conditions for earthworms, despite its lower organic matter content (6.38 %). On the other hand, San Isidro, with a clay texture and good structure, had lower microbial activity (645 μg C-CO_2 kg^{-1} d^{-1}) and an intermediate earthworm density (15.2 individuals m^{-2}), despite having a high organic matter content (9.13 %). The strongly acidic pH (4.09) and low phosphorus availability (4.98 mg kg^{-1}) could be limiting microbial activity.

CONCLUSIONS

A comprehensive analysis of the soils on all three farms revealed significant differences in physical, chemical, and biological properties. In physical terms, textures ranged from clayey to sandy loam, with good or moderate structures and bulk densities within acceptable ranges, although with differences in field capacity that may affect water retention. Chemically, variable organic matter and carbon contents were identified, as well as generally acidic pH and low phosphorus availability, conditions that may limit biological activity and nutrient availability. Biologically, the soils showed low earthworm density and low humus values, while microbial respiration values were high.

ACKNOWLEDGEMENTS

This research was funded by the COVEICYDET 131627 project, "Development of a fungal bioinoculant that solubilizes soil phosphorus and promotes the growth and productivity of coffee plants (*Coffea arabica* var. Costa Rica) in Jilotepec, Veracruz." Authors thanks to coffee producers for supporting our investigation.

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