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PHYSICOCHEMICAL CHARACTERISTICS OF SOILS AND THEIR IMPACT ON THE PRODUCTIVITY OF COFFEE FARMS ON THE COAST OF OAXACA

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Abstract: The present study consisted of the characterization of soils in the coffee-growing areas of the Oaxaca coast, with the objective of generating useful information to improve the productivity of coffee plantations. Soil samples were analyzed from the horizons identified in four soil profiles in the municipalities of San Pedro Pochutla, Candelaria Loxicha and Pluma Hidalgo. In all profiles, medium to coarse textures and high apparent densities were found, particularly in the subsurface horizons. The pH found was strongly to moderately acidic. In the surface horizons, high values of Organic Carbon, Organic Matter, Total Nitrogen, Phosphorus and Potassium were found. On the contrary, the contents of the aforementioned elements decrease drastically in the subsurface horizons. When estimating the amount of inorganic Nitrogen in the surface horizons, quantities were found that varied from 303.8 kg ha^{-1} (25 cm of Depth); 313.2 kg ha^{-1} (24 cm of Depth); 256.2 kg ha^{-1} (26 cm of Depth) y 668.8 kg ha^{-1} (45 cm depth). When soil samples are taken in the surface stratum, generally from 0 to 30 cm, an inaccurate impression is obtained that the nutrients are present in adequate quantities for the crop (Rosas et al., 2008; Correa-Pérez, et al., (2014) because the subsurface horizons are not explored as occurs when soil samples are taken from horizons identified in soil profiles.

Keywords: soil horizon, coffee-growing areas, inorganic nitrogen, Oaxaca Coast.

INTRODUCTION

Coffee production is a very important economic activity in Mexico due to the area planted in 2023 of 700 thousand hectares, mainly with Arabica coffee, which is only surpassed by corn, pastures and meadows, sorghum, beans and sugar cane (SIAP, 2024). Its importance also lies in the number of producers who are dedicated to this activity since only in the state of Oaxaca in 2014 a total of 101,272 producers were dedicated to this crop on 128,801 ha (UACh, 2014). According to figures from SIAP (2024), in 2023 coffee production in Mexico was carried out mainly in the states of Chiapas (34.9%), Veracruz (20.4%), Oaxaca (19.0%) and Puebla (10.3%) which concentrate 84.6% of the planted area and 88.6% of the production volume. The rest of the production takes place in the states of Guerrero, Hidalgo, San Luis Potosí, Jalisco, Nayarit, Colima, Tabasco, State of Mexico, Querétaro and Morelos.

In 151 municipalities of the state of Oaxaca, coffee production was reported in 139,819 ha in 2023 with an average yield of 0.76 t ha-1 and a production volume of 66,451 tons of cherry coffee (SIAP, 2024). The production system consists of coffee plantations under natural vegetation shade. Although coffee production is carried out on a greater or lesser scale in all regions of Oaxaca, this activity began in the Costa region (Gonzalez, 2012) where thirteen municipalities concentrate 85% of the 41,0370 ha that were reported planted in 34 municipalities in 2023 (SIAP, 2024). The coffee-growing area is located between the mountains and the coast, with altitudes between 900 and 1200 meters above sea level, and temperature and rainfall conditions suitable for the plant. Due to the existing topographic conditions, most of the plantations are established on ground slopes that exceed 30%.

Coffee yields in Oaxaca are low compared to other producing states such as Puebla, Veracruz and Chiapas, where yields of 3.3,1.8 and 1.6 t ha^{-1} of cherry coffee, are achieved, respectively (SIAP, 2024). Various factors contribute to this low productivity, particularly old plantations that are more than 30 years old. According to López et al (2013), a coffee plantation begins its productive stage between four and five years after being established and this stage lasts approximately eight years, to subsequently gradually decrease its production, according to the management given to the plantation during its pre-productive and productive stages. Based on the above, plantations that are twelve or more years old require good management so that the reduction in yield is not so impactful on income. Other aspects that affect low productivity are inadequate climate and soil conditions (height, slope and depth), poor agronomic management (varieties, population density, pruning, shade management, harvest), inadequate management of plant nutrition due to lack of updated recommendations and incidence of orange rust. (*Hemileia vastatrix*).

According to Carvajal (1984), C. arabica grows adequately in highlands with altitudes greater than 600 masl and up to 2000 masl, where the average annual temperature is between 17 and 23 °C, while the average adequate annual rainfall is considered to be between 1,600 and 1,800 mm. Schapira et al., (1982) indicate that in Colombia the ideal altitude conditions for the production of high quality coffee are between 610 and 1,830 masl. Castillo et al., (1996) point out that quality production in Mexico takes place in an altitude range of 900 to 1,300 masl; an annual rainfall of 1,800 to 2,000 mm with a dry period of two to three months; average monthly temperatures between 19 and 22 °C and deep soils, with good drainage and pH values between 4.5 and 5.5. On the other hand,—Regalado (1996) considers that the optimal conditions for coffee production in Mexico consist of altitudes between 900 and 1,200 masl; temperature between 18 and 22 °C; annual rainfall between 1,400 and 2,300 and deep soils with a loamy texture with more than 7% of Organic Matter and a pH between 4.5 and 5.5. Ruiz et al., (2013) mention that *C. arábica* L. develops in temperatures between 5 to 30°C and thrives at altitudes between 1,000 to 2,800 meters above sea level; with an optimal rainfall of 1900 mm for *C. arábica* L. and from 1900 to 2500 mm for *C robusta.*

Regarding the soils suitable for cultivation, Carvajal (1984) points out that these have a depth of more than one meter and loamy textures with a slightly acidic pH between 6.0 and 6.5, since lower values inhibit the availability of nutrients. Regalado (1996) reports a classification of the fertility of coffee soils based on their chemical properties indicating that values greater than: 7% of Organic Matter; 0.57 % of total Nitrogen; 12 ppm of Phosphorus; 0.51 meq $100g^{-1}$ of Potassium; 6.1 meq 100 g^{-1} of Calcium and 3.1 meq 100 g^{-1} of Magnesium indicate a soil with adequate conditions for coffee production. Zetina et al., (2013) indicate that for caturra coffee the adequate proportion of nutrients $N:P_2O_5:K_2O$ is 6:1:8 and in organic production systems the production of 800 kg ha^{-1} of green coffee requires the extraction of 51.5, 10.66 and 37.5 kg of N, P_2O_5 y K_2O, respectively.

In a study carried out in coffee-growing areas of Chiapas, Veracruz, Oaxaca, Puebla and Guerrero, Rosas et al., (2008) found high contents of total Nitrogen, Organic Matter, iron and Phosphorus; medium levels of Calcium, copper and manganese and low levels of Potassium, Magnesium and zinc. In the samples taken in soils of the state of Oaxaca, high contents of total Nitrogen (0.41%) and low values of Phosphorus (0.19%) were found. (4.44 mg kg^{-1}) as well as high potassium contents (7.78 cmol kg^{-1}). Based on studies carried out in San Pedro Cafetitlan, Oaxaca, Correa-Pérez, et al., (2014) found that the soils are suitable for coffee production, with a neutral pH and water retention capacity of an average of 70%, high Organic Matter content and sandy loam texture. Based on the above, it was concluded that the physicochemical properties are suitable for growing coffee on hills and that the low production of coffee plantations is not due to soil fertility conditions.

The objective of this study was to characterize the physical and chemical properties of soils in horizons identified in soil profiles and their impact on the productivity of coffee plantations in the producing areas of the coast of Oaxaca.

METHODOLOGY

The study was carried out in the municipalities of San Pedro Pochutla, Candelaria Loxicha and Pluma Hidalgo. The three municipalities are characterized by having a warm subhumid climate, with summer rains (800 to 3,500 mm) and a temperature range between 18° and 28°C. A description of four soil profiles was carried out, each of them in a coffee plantation on the coffee farms; 1) ``*La Galera*``; 2) ``*El Pacífico*``; 3) ``*La Concordia*``; y 4) ``*Cerro Espino*``. Figure 1 shows the geographical location of the sampling sites and Table 1 shows their general characteristics.

Soil samples were taken from each horizon identified in the described profiles and the samples were subjected to the determination of their physical and chemical properties in accordance with NOM-021-RECNAT-2000 (SEMARNAT, 2002).

Soil analyses were carried out based on the methodology established by Van Reeuwijk, (2002) considering the following physical properties: bulk density (g.cm^{-3}); Wet color and granulometric analysis. The chemical properties corresponded to pH; Organic Carbon (%); Organic Matter (%); Nitrogen (%); Calcium Carbonates (%); Phosphorus (Mg Kg^{-1}); Sodium ($Cmol_{(+)}$ Kg^{-1}); Potassium ($Cmol_{(+)}$ Kg^{-1}); Calcium ($Cmol_{(+)}$ Kg^{-1}) and Magnesium ($Cmol_{(+)}$ Kg^{-1}).

RESULTS AND DISCUSSION

The results of the laboratory analyses of the soils at the sampling sites are shown in Tables 2, 3, 4 and 5. Firstly, it can be seen that the values of the bulk density are high. (> de 1.45 g cm^{-3}) starting from the subsurface horizon, accordingly with medium to coarse textures and low contents of Organic Matter. The pH values correspond to the strongly acidic category in the La Galera and Pacific and to moderately acidic in La Concordia and Cerro Espino. Due to these values, the presence of aluminum ions could occur, particularly affecting the availability of Phosphorus. Additionally, the decomposition of Organic Matter is slower under these conditions.

An outstanding characteristic of the studied horizons is that in general the surface horizon has high values of Organic Carbon, Organic Matter, total Nitrogen, Phosphorus and Potassium. On the contrary, the contents of the aforementioned elements decrease drastically in the subsurface horizons, representing considerable deficiencies for plant nutrition. Even in all profiles there were horizons in which the presence of Phosphorus was not detected.

When soil samples are taken in the surface stratum, generally from 0 to 30 cm, an inaccurate impression is obtained that the nutrients are present in adequate quantities for the crop (Rosas et al., 2008; Correa-Pérez, et al., 2014) because the subsurface horizons are not explored as occurs when soil samples are taken from horizons identified in soil profiles.

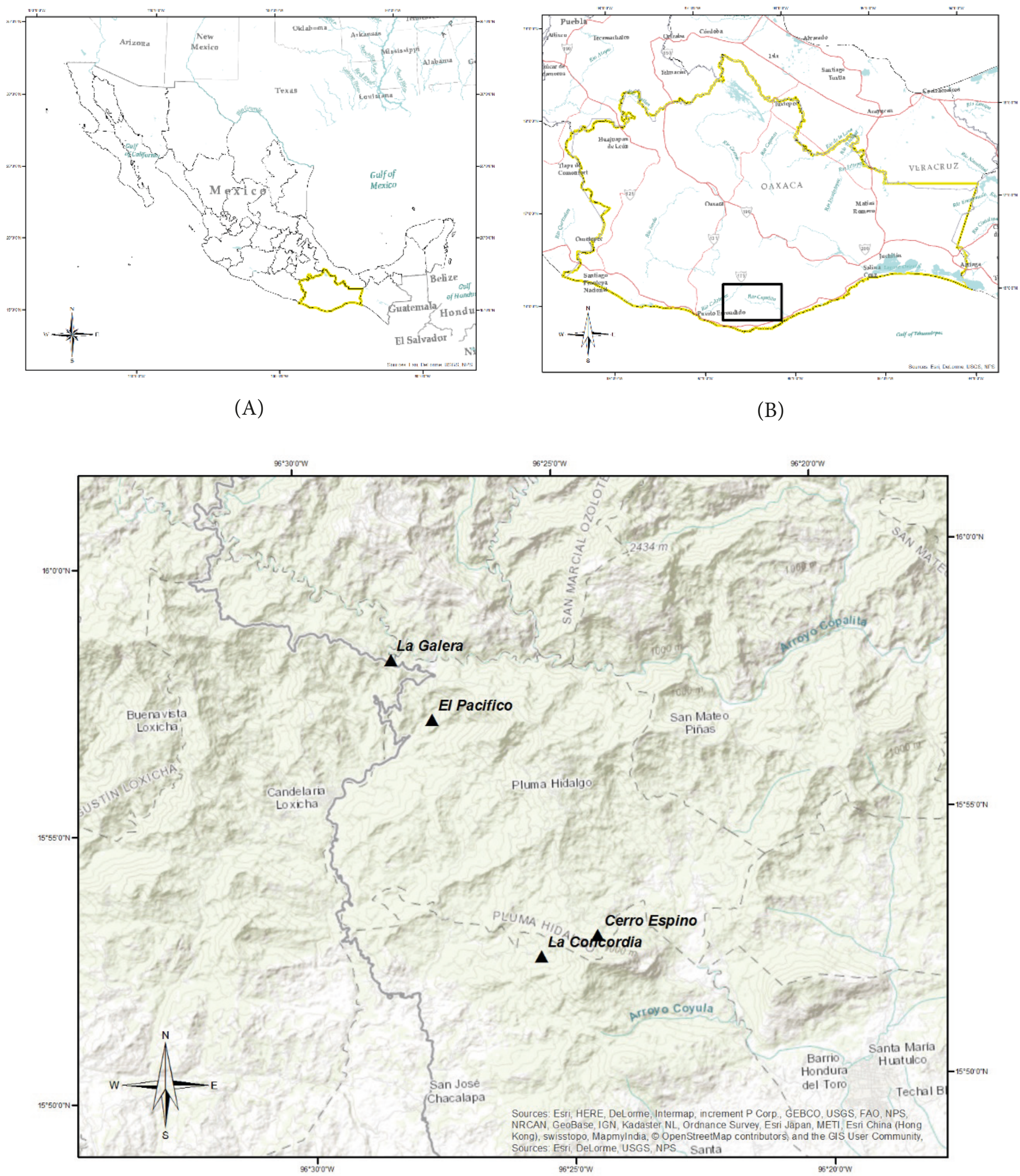

Figure 1: Location of the study area in Mexico (A), state of Oaxaca (B) and sampling sites (C)

Estate	Place	City	Altitude (msnm)	Longitude	Latitude
La Concordia	*San Rafael Toltepec*	*San Pedro Pochutla*	720	-96.42532	15.87406
La Galera	*Santiago la Galera*	*Candelaria Loxicha*	1160	-96.47032	15.96810
El Pacífico	*Candelaria Loxicha*	*Candelaria Loxicha*	718	-96.45771	15.94906
Cerro Espino	*Pluma Hidalgo*	*Pluma Hidalgo*	724	-96.40700	15.88007

Table 1: General characteristics of the sites under study

Depth (cm)	Da	Wet Color	Texture Class	pH	CO	MO	N	$CaCO_3$	P_2O_5	Na	K	Ca	Mg
0 – 25	1.35	7.5YR 3/2	``*Loam*``	4.8	3.14	5.40	0.18	0.52	1.18	0.33	0.60	1.59	1.33
25 – 55	1.53	5YR 4/6	``*Loamy sand*``	4.7	0.52	0.90	0.04	1.04	1.62	0.44	0.39	0.77	0.14
55 – 83	1.75	5YR 5/6	``*Loamy sand*``	4.7	0.37	0.64	0.01	1.04	0.00	0.18	0.25	0.59	0.12
83 – 95	1.67	5YR 5/6	``*Loamy sand*``	4.6	0.22	0.39	0.00	1.10	0.66	0.24	0.25	1.14	0.55
95 – 115	1.35	7.5YR 4/6	``*Loamy sand*``	4.2	0.30	0.51	0.01	0.98	0.88	0.26	0.26	1.28	0.12

Table 2: Physical and chemical properties of soil in the ``Finca La Galera``.

Da= Bulk density ($g.cm^3$); pH= Hydrogen Potential; CO=Organic Carbon (%); MO=Organic Matter (%); N=Nitrogen (%); $CaCO_3$=Calcium Carbonates (%); P_2O_5=Phosphorus (Mg Kg^{-1}); Na=Sodium ($Cmol_{(+)}$ Kg^{-1}); K=Potassium ($Cmol_{(+)}$ Kg^{-1}); Ca=Calcium ($Cmol_{(+)}$ Kg^{-1}); Mg=Magnesium ($Cmol_{(+)}$ Kg^{-1});

Depth (cm)	Da	Wet Color	Texture Class	pH	CO	MO	N	$CaCO_3$	P_2O_5	Na	K	Ca	Mg
0-24	1.45	7.5YR 4/2	``*Loam*``	4.3	2.54	4.38	0.18	1.22	0.74	0.26	0.51	8.38	2.90
24-40	1.46	7.5YR 5/6	``*Loam*``	4.7	0.30	0.51	0.01	0.46	0.00	0.18	0.39	2.26	2.59
40-55	1.87	5YR 4/6	`` Loamy sand ``	4.8	0.30	0.51	0.01	0.35	0.30	0.16	0.26	1.88	2.19
55-78	1.92	7.5YR 4/6	`` Loamy sand ``	4.8	0.30	0.51	0.01	0.52	0.00	0.18	0.23	1.63	2.53
78-110	1.77	10YR 5/6	`` Loamy sand ``	4.8	0.70	0.13	0.01	0.35	0.00	0.18	0.20	1.47	2.78

Table 3: Physical and chemical properties of the soil at ``*Finca El Pacífico*``.

Da= Bulk density ($g.cm^3$); pH= Hydrogen Potential; CO=Organic Carbon (%); MO=Organic Matter (%); N=Nitrogen (%); $CaCO_3$=Calcium Carbonates (%); P_2O_5=Phosphorus (Mg Kg^{-1}); Na=Sodium ($Cmol_{(+)}$ Kg^{-1}); K=Potassium ($Cmol_{(+)}$ Kg^{-1}); Ca=Calcium ($Cmol_{(+)}$ Kg^{-1}); Mg=Magnesium ($Cmol_{(+)}$ Kg^{-1});

Depth (cm)	Da	Wet Color	Texture Class	pH	CO	MO	N	$CaCO_3$	P_2O_5	Na	K	Ca	Mg
0-5	1.37	5YR 3/2	``Loam``	5.3	2.39	4.12	0.17	0.23	1.48	0.31	0.50	9.48	2.34
5-26	1.45	5YR 4/2	`` Loam ``	5.3	2.31	3.99	0.13	0.75	0.00	0.39	0.23	7.32	1.88
26-50	1.52	7.5YR 4/2	`` Loam ``	5.4	1.64	2.83	0.08	1.16	0.00	0.26	0.15	6.03	1.34

Table 4: Physical and chemical properties of soil in the ``*Finca La Concordia*``.

Da= Bulk density ($g.cm^3$); pH= Hydrogen Potential; CO=Organic Carbon (%); MO=Organic Matter (%); N=Nitrogen (%); $CaCO_3$=Calcium Carbonates (%); P_2O_5=Phosphorus (Mg Kg^{-1}); Na=Sodium ($Cmol_{(+)}$ Kg^{-1}); K=Potassium ($Cmol_{(+)}$ Kg^{-1}); Ca=Calcium ($Cmol_{(+)}$ Kg^{-1}); Mg=Magnesium ($Cmol_{(+)}$ Kg^{-1});

Depth (cm)	Da	Wet Color	Texture Class	pH	CO	MO	N	$CaCO_3$	P_2O_5	Na	K	Ca	Mg
0-18	1.37	5YR 3/2	`` Loam ``	6.5	3.38	6.69	0.23	0.79	0.00	0.31	0.46	14.23	1.88
18-30	1.45	5YR 4/2	`` Loam ``	6.6	2.69	4.63	0.22	1.04	0.00	0.22	0.29	0.91	0.89
30-45	1.52	7.5YR 4/2	`` Loam ``	6.2	1.42	2.45	0.17	1.04	0.37	0.22	0.26	4.21	0.66

Table 5: Physical and chemical properties of the soil at the Cerro Espino

Da= Bulk density ($g.cm^3$); pH= Potential Hydrogen; CO=Organic Carbon (%); MO=Organic Matter (%); N=Nitrogen (%); $CaCO_3$= Calcium Carbonates (%); P_2O_5= Phosphorus (Mg Kg^{-1}); Na=Sodium ($Cmol_{(+)}$ Kg^{-1}); K=Potassium ($Cmol_{(+)}$ Kg^{-1}); Ca=Calcium ($Cmol_{(+)}$ Kg^{-1}); Mg=Magnesium ($Cmol_{(+)}$ Kg^{-1});

Profile	Depth (cm)	Da ($t\ m^{-3}$)	Total N (%)	Soil volume (m3 ha^{-1}) 1/	Soil weight (t ha^{-1}) 2/	Total N (t) 3/	Inorganic N (t). 4/
La Galera	0 a 25	1.35	0.18	2500	3375	6.075	0.3038
El Pacifico	0 a 24	1.45	0.18	2400	3480	6.264	0.3132
Concordia	0 a 5	1.37	0.17	500	685	1.165	0.0582
Concordia	5 a 26	1.45	0.13	2100	3045	3.959	0.1979
Cerro Espino	0 a 18	1.37	0.23	1800	2466	5.672	0.2836
Cerro Espino	18 a 30	1.45	0.22	1200	1740	3.828	0.1914
Cerro Espino	30 a 45	1.52	0.17	1500	2280	3.876	0.1938

Table 6: Estimation of inorganic nitrogen content in the surface layers of soil profiles.

1/. 10,000 (m2)*Depth (m); 2/ Soil volume (m3)*Da (t m-3); 3/ Soil weight (t) * Total N; 4/ Total N * 0.05

The topographic conditions in the study area correspond to soil slopes with values greater than 50% and even 100% slope values are common. Under these conditions, only a small proportion of rainwater penetrates the soil profile and most of it is lost through surface runoff. This causes the movement of nutrients to hardly go beyond twenty cm of the surface horizon.

Estimating the amount of inorganic nitrogen from the total nitrogen content in the surface horizons of the profiles, contents of 303.8 kg ha-1; 313.2 kg ha-1; 256.2 kg ha-1 and 668.8 kg ha-1 can be observed in the profiles of La Galera, El Pacifico, La Concordia and Cerro Espino respectively (Table 6).

Although the surface layer of the soil has adequate nutrient contents, these are not enough to supply the needs of coffee plants to produce adequate yields. According to Partelli et al (2020), approximately 37.5% of the root system of Coffee arabica reaches up to 20 cm next to the trunk of the plant and decreases in depth to five cm at 50 cm distance from the plant. This is the proportion of roots that would be taking advantage of the inorganic nitrogen available in the surface layer (between 0 and 25 cm deep). Another important fraction would be part of the 28.4% that is found at a depth of 10 to 20 cm at a distance of 25 to 75 cm from the trunk of the plant.

The rest of the root system is found at depths exceeding 60 cm at 35 and 30 cm from the trunk of the plant and would not be taking advantage of the total inorganic nitrogen available in the surface horizon.

Based on the estimates of the inorganic nitrogen content in the surface horizons of the profiles, a first very useful recommendation for producers is that, when planting coffee trees, they must make sure to place the surface layer of soil at the bottom of the plantation hole, since it contains the largest amount of nutrients.

Considering that the amount of inorganic nitrogen present in the surface horizons of the soil is not fully utilized by the plant, a good nutrition plan is required. that combines synthetic fertilizers (in plantations not certified as organic) with organic fertilizers, providing additional amounts of nitrogen, phosphorus and potassium.

CONCLUSIONS

The predominant soils are medium to coarse textures with high bulk density values that reduce the amount of water storage in the soil and present some resistance to penetration by plant roots.

Although the surface layer of the soil has adequate nutrient contents, these are not enough to supply the needs of the coffee plants to produce adequate yields.

When planting coffee trees, make sure to place the surface layer of soil at the bottom of the plantation hole, since it contains the greatest amount of nutrients.

When sampling soil to determine the conditions of nutrient availability, it is important to do so taking into account the vertical distribution of the soil layers to have a reliable estimate.

A good nutrition plan is required that combines synthetic fertilizers (in plantations not certified as organic) with organic fertilizers, providing additional amounts of nitrogen, phosphorus and potassium.

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