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Research article

Physical and chemical soil alterations from wildfires in forests of *San Miguel del Carrizal*, State of *Sinaloa*

Alteraciones físicas y químicas del suelo por incendios forestales en Bosques de San Miguel del Carrizal, Sinaloa

Erik Orlando Luna Robles[1], Ixchel Abby Ortiz Sánchez[2], José Guadalupe Colín[1], Silvia Janeth Bejar Pulido[1]*

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[1]Tecnológico Nacional de México, Instituto Tecnológico de El Salto. México.

[2]Tecnológico Nacional de México, Instituto Tecnológico del Valle del Guadiana. México.

*Autor para correspondencia; correo-e: siljan2411@gmail.com
*Corresponding author; e-mail: siljan2411@gmail.com

Abstract

Forest fires are becoming increasingly frequent; they alter the physical and chemical properties of the soil, affecting its productivity and health. Therefore, this study evaluated and compared these properties in soils affected and unaffected by wildfires in *El Carrizal*, *Sinaloa*. Two areas were considered: one that had been burned and one control area (unburned). In each area, composite soil samples were collected to determine physical properties (bulk density and hydrophobicity) and chemical properties (pH, electrical conductivity, organic matter, carbon, and carbon pool) at two depths: 0-15 and 15-30 cm. The results indicated that the surface layer of the burned area showed more significant changes in the soil's physical and chemical properties; in addition, water repellency was classified as strong and slight for the second depth, whereas in the control area, it was nonexistent. In particular, soil bulk density and porosity decreased and increased, respectively, in the burned area compared to the control area. The pH and electrical conductivity increased, an effect attributed to the presence of fire residues. The soil organic carbon pool was higher in the burned area, consistent with numerous studies indicating that this variable increases significantly after three months. Changes in soil properties varied widely, with increases observed in some cases and decreases in others.

Keywords: dynamics, fire, hydrophobicity, carbon pool, waste, health.

Resumen

Los incendios forestales son cada vez más frecuentes, alteran las propiedades físicas y químicas del suelo, afectando su productividad y salud. Por ello, en este estudio se evaluaron y compararon dichas propiedades en suelos afectados y no afectados por incendios forestales en El Carrizal, Sinaloa. Se consideraron dos áreas, una incendiada y otra testigo (sin incendio); en cada una se recolectaron muestras compuestas de suelo, para determinar las propiedades físicas (densidad aparente e hidrofobicidad) y químicas (pH, conductividad eléctrica, materia orgánica, carbono y el reservorio de carbono), a dos profundidades: 0-15 y 15-30 cm. Los resultados indicaron que la parte superficial del área incendiada presentó cambios más significativos sobre las propiedades físicas y químicas del suelo; además de una repelencia al agua catalogada como fuerte y ligera para la segunda profundidad; mientras que en el área testigo fue nula. En particular la densidad aparente y porosidad del suelo disminuyeron e incrementaron, respectivamente en la zona incendiada, en comparación con la testigo. El pH y conductividad eléctrica aumentaron, lo que se atribuyó a la presencia de residuos derivados del incendio. El reservorio de carbono orgánico del suelo fue superior en el área de incendio coincidiendo con múltiples estudios que señalan que después de tres meses esta variable se incrementa significativamente. Las modificaciones sobre las propiedades del suelo fueron muy contrastantes, observándose en algunos casos aumentos y en otras disminuciones.

Palabras clave: dinámica, fuego, hidrofobicidad, reservorio de carbono, residuos, salud.

Introduction

Forests provide a wide range of ecosystem services that are essential to life in general; these services depend on soil, water and biodiversity, so an imbalance in any one of these elements has an immediate impact on the functionality and harmony of the ecosystem, of which humans are a part (Luna-Robles et al., 2022).

Forests cover a total area of more than four million hectares, which is equivalent to one-third of the Earth's land surface; this gives an idea of the importance of these ecosystems (Organización de las Naciones Unidas para la Alimentación y la Agricultura [ONUAA], 2020).

In Mexico, forests cover 70.6 % of the country’s territory (138.7 million hectares) (Secretaría de Medio Ambiente y Recursos Naturales [Semarnat], 2020); 48.1 % of this area consists of temperate forests and rainforests (66.7 million hectares). In this regard, forest soils play a vital role through the ecosystem services they provide, such as regulating the water cycle, as they act as regulators, purifiers and providers of water resources (Rodríguez-Reta et al., 2024); play a key role in mitigating climate change, because they have the ability to store 3 to 4.5 times more carbon than the biosphere (Luna-Robles et al., 2024a).

Forest fires have a significant impact on the soil, particularly on its physical and chemical properties; they alter *pH*, increase electrical conductivity, and raise bulk density; porosity is significantly reduced by the presence of residues (ash and charred remains), which also make the soil hydrophobic, thereby reducing its infiltration capacity and increasing the risk of erosion. They also cause changes in the concentrations and pools of soil organic carbon (*SOC*) (Alfaro-Leranoz et al., 2024; Gonzáles et al., 2024; Luna-Robles et al., 2024b).

In Mexico, the frequency of wildfires and the area affected have increased significantly over the past five years as a result of anthropogenic factors, as well as changes in drought and precipitation patterns (Luna-Robles et al., 2024b). In this regard, the National Forest Commission (Comisión Nacional Forestal [Conafor], 2026) recorded a total of 6 996 fires in 2025, affecting an area of 1 208 376 ha. The state of *Sinaloa* ranked fourth among the states with the largest affected areas (106 815 ha), trailing only *Chihuahua* (215 462 ha), *Guerrero* (108 974 ha), and *Durango* (107 472 ha). It should be noted that most of the possible causes were classified as intentional.

Therefore, the objective of this study was to evaluate the physical and chemical properties of soils affected by wildfires in *El Carrizal*, located in the state of *Sinaloa*. The selection of this area is important because it represents a forested area susceptible to disturbances that can alter soil quality and ecosystem dynamics, which are a fundamental component of the provision of ecosystem services in Southern *Sinaloa*.

Materials and Methods

Study area

The study area is located in the forests of *San Miguel del Carrizal ejido*, in the *Concordia* municipality of *Sinaloa*, situated in the *Sierra Madre Occidental*, at an average altitude of 1 990 m, between 23°35’21” N and 105°49’11” W (Figure 1). The vegetation is dominated by *Pinus herrerae* Martínez and *Pinus douglasiana* Martínez (González-Elizondo et al., 2012). The area's topography consists of a plateau and gently sloping hills; the climate is warm subhumid/dry with high evaporation, and rainfall is concentrated in the summer, with an average of 600-790 mm per year (García, 2004). The predominant soil type is Leptosol, a shallow, stony soil with low moisture retention found in mountainous areas and rugged terrain (Instituto Nacional de Estadística, Geografía e Informática [INEGI], 2017).

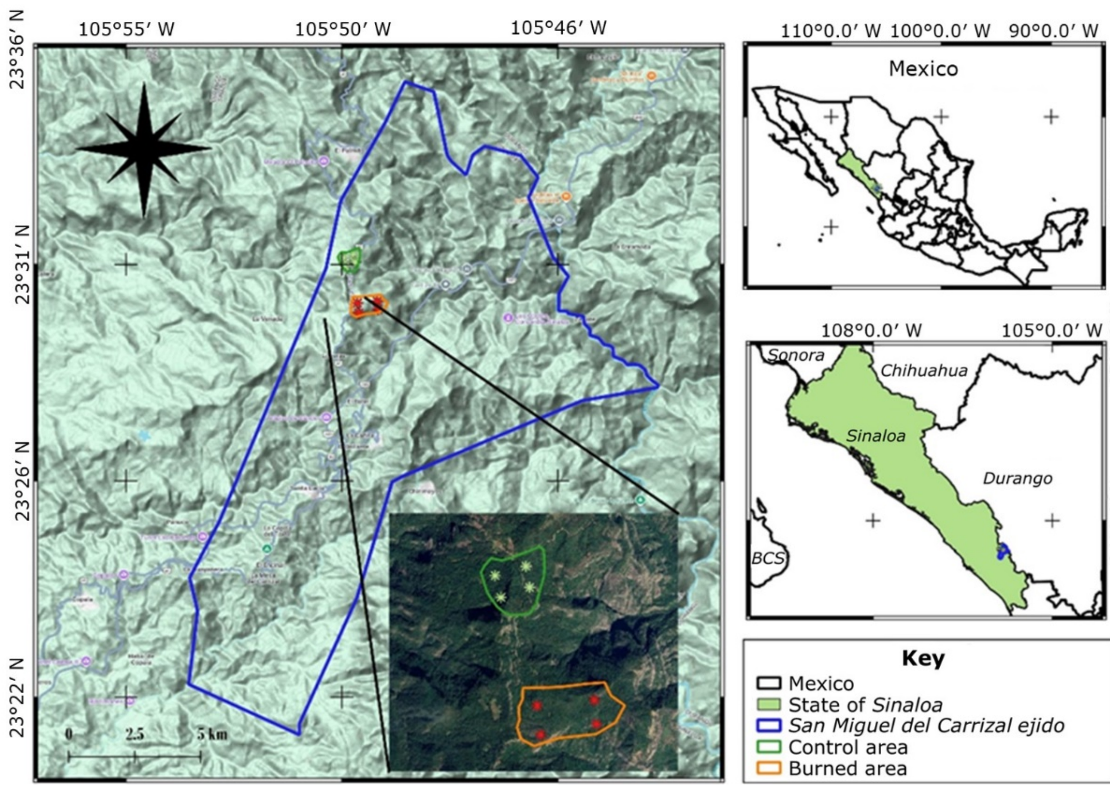


Figure 1. Location of the study area: *San Miguel del Carrizal ejido*, *Concordia* municipality, *Sinaloa*, Mexico.

Experiment design

The assessment was conducted in two forest areas, one of which was affected by a wildfire that lasted 13 days between May and June 2025, over 91 ha. This fire was classified as of high severity because the fire caused high mortality in the tree stand (>60 % affection), with a significant impact on the soil and remaining vegetation (Lydersen et al., 2016). Specifically, much of the plant material was consumed, causing slight erosion and a loss of organic matter (Clemente-Quezada et al., 2025). Due to the topography of the site, the fire spread through the tree canopies, significantly damaging all components of the ecosystem (stems, canopies and ground cover).

This area was compared with an adjacent area that was not burned (control), which covered 57 ha, where the thickness of the leaf litter and humus layers was measured at 20 and 8 cm, respectively; it is note worthy that the burned area did not have these layers.

Sampling and soil analysis

Sampling was conducted using random blocks three months after the wildfire occurred (Muñoz-Rojas et al., 2016); the changes in the physical and chemical properties of the soil were considered to typically persist for up to six months after the fire (Agbeshie et al., 2022), since a gradual recovery tends to occur after revegetation and rainfall; however, the soil structure may take longer to stabilize (Vega-Martínez et al., 2023). Based on this, on-site and off-site measurements were made in each area, taking into account the nature of the variable being evaluated; these measurements are described below.

To collect soil samples, four 100×100 m plots were established in each of the evaluated areas with low or no slope. Eight composite samples weighing 1 kg each (a mixture of four individual subsamples) were collected at two depths (four from 0-15 cm and four from 15-30 cm), for a total of 16 samples, which were dried at room temperature and passed through a 2-mm sieve. They were then transferred to the soil laboratory at the *Instituto Tecnológico del Valle del Guadiana* (*Guadiana* Valley Institute of Technology) for analysis.

Chemical variables of the soil

Table 1 shows the chemical properties evaluated, the method used to determine them, and the units of measurement used.

Table 1. Methods for assessing soil chemical properties.

Variable	Determination method	Unit
pH	AS-23 of the norm NOM-021-RECNAT-2000 (Semarnat, 2002)	Scale: 0 a 14
EC	Rapid determination in a 1:5 soil-water suspension. AS-18 of the norm NOM-021-RECNAT-2000 (Semarnat, 2002)	μS cm^{-1}
SOM	Walkley and Black modified. AS-07 of the norm NOM-021-RECNAT-2000 (Semarnat, 2002)	%
C	Correction factor 0.58 (Nelson & Sommers, 1982)	%

EC = Electrical conductivity; *SOM* = Soil organic matter; *C* = Organic carbon content of the soil sample.

The soil organic carbon reservoir was determined using the equation proposed by Cantú-Silva and Bejar-Pulido (2024), which is expressed as follows:

$$SOC = BD \times C\% \times DR \quad (1)$$

Where:

SOC = Soil organic carbon expressed in Mg ha^{-1}

BD = Bulk density of the soil expressed in g cm^{-3}

C% = Organic carbon content of the soil sample, expressed as a percentage

DR = Depth range analyzed, expressed in cm

Physical variables

Bulk density and total porosity of the soil. Soil samples for bulk density were dried in a forced-air oven (model DNE910 Yamato Scientific America Inc.®) 24 to 48 hours at 105 °C. The samples were weighed using a precision analytical scale (model CP2202S Sartorius®, Germany); once the weight of the samples was determined, the bulk density was estimated using Equation 2 (Yáñez-Díaz et al., 2019):

$$BD = \frac{W}{CV} \quad (2)$$

Where:

BD = Bulk density (g cm^{-3})

W = Dry weight of the sample with the cylinder (g)

CV = Cylinder volume (cm^3)

The total soil porosity was estimated based on the calculated values of bulk density, assuming an average particle density of 2.65 g cm^{-3} (Yáñez-Díaz et al., 2019); the equation is shown below:

$$P = \left[1 - \left(\frac{BD}{PD}\right)\right] \times 100 \quad (3)$$

Where:

P = Porosity expressed as a percentage

BD = Bulk density of the soil in g cm^{-3}

PD = Particle density of 2.65 g cm^{-3}

Hydrophobicity. The Water Drop Penetration Time Method (WDPT) (Veneris & Farid, 2024) was used; this involves applying water droplets to a flat surface of the soil and quantifying the penetration time. To this end, 0.50×0.50 m plots were established in each area. These were carefully cleared to expose the bare mineral soil. Next, 20 drops of distilled water were placed randomly on the soil surface, and the penetration times were recorded. The procedure was repeated at a depth of 2 cm, given that the hydrophobic response tends to decrease significantly over the next few centimeters (Dekker & Jungerius, 1990; García-Ledezma et al., 2025).

The average time records by area and depth were used to classify the level of repellency based on the assessment shown in Table 2.

Table 2. Water repellency rating.

Degree of persistence	Rating range in seconds	Level of water repellency
0	<5	Null
1	5-60	Light
2	60-600	Strong
3	600-3 600	Severe
4	>3 600	Extremely severe

Source: Dekker and Jungerius (1990).

Statistical analyses

All variables (*SOM*, *C*, *pH*, *EC*, *BD*, *P*, and *SOC*) were tested for normality (Shapiro-Wilk) and homogeneity of variances (Levene), and the necessary transformations were performed (arctangent [$tang^{-1}(x)$] and exponential arc [e^x] in *BD* and *P*, respectively), with the exception of hydrophobicity. Subsequently, a two-factor analysis of variance was performed to assess the significant variance in soil response to fire by area and depth. The analyses were conducted with a 95 % confidence level. To assess hydrophobicity, a Mann-Whitney *U* test was performed for each factor (area and depth). All analyses were performed using the SPSS statistical software package, version 22.0 (International Business Machines [IBM], 2025).

Results

Table 3 presents the tests for normality and homogeneity of variances for each variable, confirming that the assumptions are met.

Table 3. Tests of normality (Shapiro-Wilk) and homogeneity of variances (Levene) for the physical and chemical soil variables.

Variable	**Shapiro-Wilk**		**Levene**	
	W	**Sig.**	***F***	**Sig.**
SOM (%)	0.838	0.058	4.533	0.064
C (%)	0.838	0.058	4.532	0.064
pH	0.891	0.059	3.905	0.057
EC (μS cm^{-1})	0.752	0.071	1.037	0.411
BD (g cm^{-3})	0.905	0.096	0.964	0.441
P (%)	0.898	0.075	0.935	0.454
SOC (Mg ha^{-1})	0.885	0.056	0.778	0.528
Hydrophobicity (S^{-1})	0.614	0.001	387.339	0.001

SOM = Soil organic matter; *C* = Carbon content; *EC* = Electrical conductivity; *BD* = Bulk density; *P* = Porosity; *SOC*= Soil organic carbon. *W* = Test statistic; *F* = *F* value; Sig. = Significance.

According to the results of the analysis of variance, all variables showed significant differences between areas and depth ($p<0.05$), with the exception of *pH*, while the interaction of the two factors was significant only for *pH*, *EC*, and carbon reservoir ($p<0.05$) (Table 4).

Table 4. Two-way analysis of variance for soil physical and chemical variables.

Factor	Variable	*SS*	*df*	*MSE*	*F*	Sig.
Surface area	*SOM* (%)	11.54	1	11.54	11.73	0.005
	C (%)	3.88	1	3.88	11.73	0.005
	pH	1.46	1	1.46	25.51	0.000
	EC (μS cm^{-1})	720 376.56	1	720 376.56	3 278.47	0.000
	BD (g cm^{-3})	0.21	1	0.21	15.85	0.002
	P (%)	1.40	1	1.40	16.29	0.002
	SOC (Mg ha^{-1})	8 427.16	1	8 427.16	38.72	0.000
Depth	*SOM* (%)	23.11	1	23.11	23.48	0.000
	C (%)	7.78	1	7.78	23.53	0.000
	pH	0.01	1	0.01	0.09	0.767
	EC (μS cm^{-1})	10 353.06	1	10 353.06	47.12	0.000
	BD (g cm^{-3})	0.19	1	0.19	14.23	0.003
	P (%)	1.25	1	1.25	14.58	0.002
	SOC (Mg ha^{-1})	10 626.24	1	10 626.24	48.83	0.000

SOM = Soil organic matter; *C* = Carbon content; *EC* = Electrical conductivity; *BD* = Bulk density; *P* = Porosity; *SOC*= Soil organic carbon. *SS* = Sum of squares; *df* = Degrees of freedom; *MSE* = Mean squared error; *F* = *F* value; Sig. = Significance.

SOM (%) and *C* (%)

According to Figure 2, the *SOM* (%) and *C* (%) contents were higher in the surface layer in both areas evaluated; however, the highest *SOM* (15.94±1.84 %) and *C* (9.25±1.07 %) contents were recorded at a depth of 0-15 cm in the burned area. On the other hand, the *SOM* in the control area averaged 12.6 %, and *C* (%) averaged 7.3.

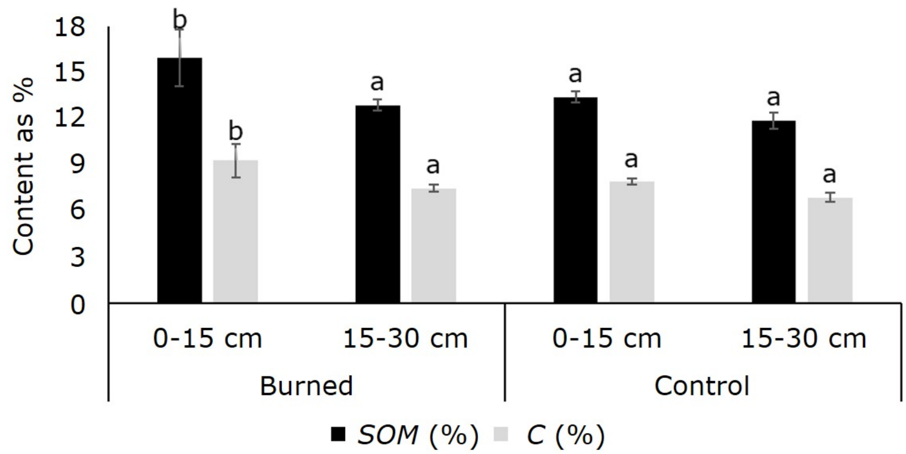


Figure 2. *SOM* and *C* content (%) in the evaluated areas.

pH and electrical conductivity (*EC*)

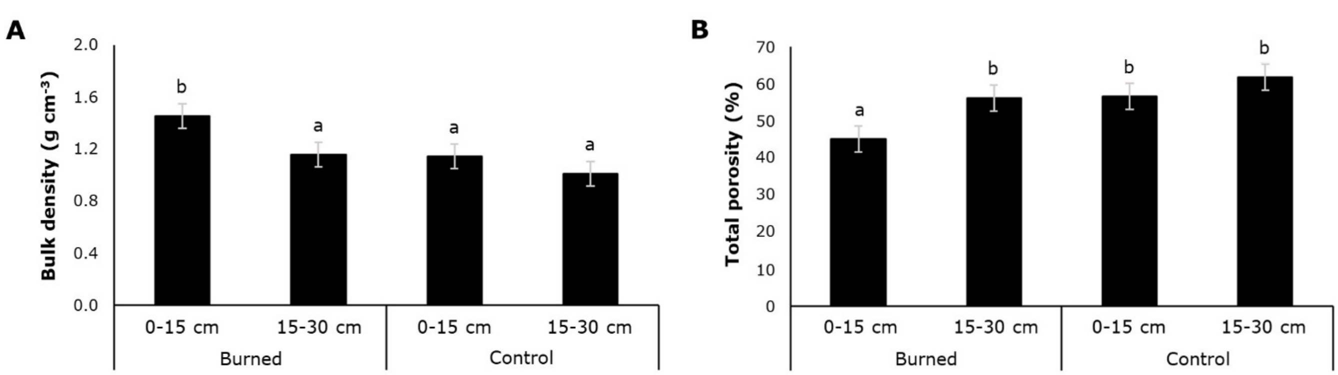
Table 5 presents the descriptive statistics for *pH* and *EC*. The burned area had the highest *pH* values at both depths, whereas the *pH* in the control area was 6.92 and 7.15 at the first and second depths, respectively. In both cases, the standard deviations were low, indicating little variation in the data. As for the *EC*, the burned area showed more noticeable changes compared to the control sample; at both depths, the standard deviations ranged between 8.27 and 23.38 (μS cm^{-1}).

Table 5. Descriptive statistics, mean values±standard deviation of *pH* and *EC* for the evaluated areas.

Areas	Depth	*pH*	*EC* (µS cm^{-1})
Burned	0-15 cm	7.79±0.34a	656.50±10.63d
	15-30 cm	7.48±0.33a	626.50±8.27c
Control	0-15 cm	6.92±0.17a	253.00±23.38b
	15-30 cm	7.15±0.05a	181.25±12.28a

Bulk density and total porosity of the soil

Figure 3 shows the values for *BD* and *P* in the soil. Specifically, the burned area had a *BD* value of 1.45 g cm^{-3} from 0 to 15 cm, while the *BD* value recorded for the control area was less than 20 % of that of the burned area. At a depth of 15-30 cm, the *BD* decreased significantly in both areas ($p<0.05$) (burned: 1.16 g cm^{-3} and control: 1.02 g cm^{-3}). On the other hand, the average *P* value for the topsoil layer of the burned area was 45 %, and 56 % in the control plot. To 15-30 cm, the average *P* was 56 % for the burned area and 61 % for the control area.



A = Bulk density; B = Total porosity.

Figure 3. Average values for bulk density and total porosity by depth for each evaluated area.

Hydrophobicity

The results of the water penetration test for the two areas and for both depths are shown in Table 6. According to the Mann-Whitney *U* test, there were significant differences between areas (W=36, p=0.001). Significant differences were observed in depth measurements for the burned area (W=10, p=0.029); this was not the case for the control area (W=13, p=0.200). Based on the assessment proposed by Dekker and Jungerius (1990), the surface layer of the burned area showed the most evident and significant damage compared to the layer below it and the control area. At a depth of 2 cm in the burned area, the degree of persistence was classified as mild; whereas at both depths in the control area, it was 0, which means they lack hydrophobicity.

Table 6. Classification of hydrophobicity by area and depth.

Areas	Depth	Penetration in s^{-1}	*DWR*	Level
Burned	1 cm	68.97	2	Strong
	2 cm	6.02	1	Light
	Average	36.86	1	Light
Control	1 cm	2.42	0	Null
	2 cm	1.89	0	Null
	Average	2.05	0	Null

s^{-1} = Time for water to penetrate the soil; *DWR* = Degree of water repellency persistence.

SOC reservoir (Mg ha^{-1})

The soil organic carbon reservoir at 0-15 cm deep in the burned area increased by 67 % compared to the control; at the next depth, the organic carbon stock decreased, and the values were statistically similar in both evaluated areas (Table 7). When considering the two depth ranges of the profile (0 to 30 cm), the *SOC* pool was as follows in descending order: burned (331.3 Mg ha^{-1})>control (239.5 Mg ha^{-1}).

Table 7. *SOC* reservoir by depth for each evaluated area.

Areas	Depth	*SOC* (Mg ha^{-1})
Burned	0-15 cm	201.66±20.44b
	15-30 cm	129.63±14.69a
Control	0-15 cm	135.27±12.53a
	15-30 cm	104.22±8.93a

Discussion

The results show that the physical and chemical properties of a Leptosol change in the short term following a wildfire. This is consistent with Mongil-Manso et al. (2024), who define these variables as sensitive and responsive to the presence of fires, leading to soil degradation.

For *SOM* and *C*, it was observed that fire significantly increased organic matter and carbon, consistently with the findings of González-Pérez et al. (2004) and Luna-Robles et al. (2024b), who attribute this trend to fire intensity (high) and soil group. However, the variability of these properties suggests changes in the chemical stability of the organic fraction (Pellegrini et al., 2022). According to Minervini et al. (2018), fire accelerates the breakdown and destruction of organic matter, directly affecting the soil's organic carbon content. Likewise, the increase (26.5 % *SOM*, 26.7 % *C*) compared to the area not affected by fire could also be attributed to the transport of particles by rain (García-Ledezma et al., 2025); therefore, the results appear to be influenced by the timing of the sampling, which was conducted at the beginning of the rainy season.

pH* and *EC

García-Ledezma et al. (2025) and Sousa-Lima et al. (2025) point out that fires have a direct impact on *pH* and *EC* levels. These tend to increase compared to areas not affected by fire. This may be due to the removal of organic acids from the soil and the accumulation of ash rich in calcium, magnesium, and potassium (Pellegrini et al., 2022; Santana et al., 2018). Furthermore, Bielińska et al. (2008) note that pyrolyzed organic matter influences *pH* dynamics. The change in *pH* following a fire also depends on the nature of the soil (texture, mineralogy, and previous organic matter content) (Bárcenas-Moreno et al., 2022). According to the norm NOM-021-RECNAT-2000 (Semarnat, 2002), the *pH* of the burned area was moderately alkaline at both depths. In contrast, the control area had a neutral *pH*.

As for the *EC*, there was a significant increase in the area affected by fire. However, salinity levels were found to be negligible (Semarnat, 2002). This allows plants to take up nutrients without osmotic stress or toxicity.

BD and porosity

The physical properties of soil—such as bulk density, porosity, and hydrophobicity—are generally considered to be the most sensitive and to be immediately affected by wildfires. The first few centimeters have the greatest impact, and some effects—such as hydrophobicity—can even have long-term consequences with negative effects on the ecosystem (Luna-Robles et al., 2025).

In the first 15 cm of the burned area, bulk density increased by 20 %, pore space decreased, and water repellency also increased. This can be attributed to the fire burning the vegetation and organic matter in the soil, which left ashes and charred particles that filled the soil's macro- and micropores (Roshan & Biswas, 2023).

The results from the control area show low bulk density, high porosity, and no hydrophobicity, consistently with the findings of Or et al. (2021), who note that the absence of physical disturbances promotes the development of soil structure. This stability is observed at both depths analyzed, demonstrating the system's intrinsic resilience under conditions free of thermal stress. In a similar way, Rodríguez-Reta et al. (2024) note that the vegetation cover and biomass promote soil structure and mineralization.

Hydrophobicity

The surface layer of the burned area exhibited very strong water repellency (60 to 600 seconds), which may be due to the fact that, in this zone, the accumulation and redistribution of hydrophobic compounds resulting from the fire (terpenes, lipids, waxes, fatty acids, etc.) is higher than in other parts of the soil profile (Jiménez-Morillo et al., 2022).

SOC

The significant increase in *SOC* following the fire suggests profound changes in biogeochemical cycles. Cheng et al. (2023) note that fires can increase soil carbon stocks by incorporating charred biomass and pyrogenic carbon, which is resistant to degradation (Hudiburg et al., 2023). However, Pellegrini et al. (2022) note that fire intensity and frequency are key factors, since severe fires deplete nitrogen and limit the future input of organic matter.

The variability in the results is consistent with Ribeiro-de Faria et al. (2026), as factors such as humidity and vegetation type determine whether carbon is gained through ash or lost through combustion. Thus, the increase in *SOC* suggests that the soil acts as a resilient sink, provided conditions allow the remaining organic matter to stabilize.

Conclusions

Three months after the forest fire, the Leptosol exhibits significant changes in its physical and chemical properties, which are quite contrasting, with both increases and decreases.

The results show that fires can affect the ecosystem’s hydrological processes, as they increase bulk density, reduce porosity, and create hydrophobic conditions, which in turn reduce water infiltration into the soil.

Likewise, the significant increase in *pH* and electrical conductivity (*EC*) can be attributed to the accumulation, in the top few centimeters of the soil, of ashes resulting from the combustion or incineration of organic matter.

Overall, the results show that the evaluated Leptosol has a high carbon sequestration capacity, highlighting its importance in mitigating climate change, as carbon is stabilized in organic matter and soil aggregates, helping it remain in the soil and preventing its release into the atmosphere as CO_2.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contributions by author

Erik Orlando Luna Robles: experiment design and management, fieldwork, and drafting of the manuscript; Ixchel Abby Ortiz Sánchez: revision of the manuscript and fieldwork; José Guadalupe Colin: fieldwork and editing of the manuscript; Silvia Janeth Bejar Pulido: fieldwork, revision and editing of the manuscript.

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