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Effect of the application of organic materials on the physical properties of an Inceptisol

Efecto de la aplicación de materiales orgánicos sobre las propiedades físicas de un Inceptisol

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ABSTRACT

Agricultural production from soils is vital for ensuring people's nutrition. However, improper use has led to soil degradation, reducing its productive capacity. he addition of organic matter improves the physical properties of soil. This study aimed to evaluate how incorporating organic materials affects certain soil physical properties on the 'La María' farm. A completely randomized design was used with five treatments: applying raw rice husk, toasted rice husk, chicken manure, liquid organic fertilizer, and a control. No significant differences were observed in soil penetration resistance (PR), a property linked to soil compaction and root growth potential, with values ranging from 500 to 1250 kPa at depths of 2.5 to 17.5 cm. PR also showed temporal variation depending on rainfall. Organic material additions reduced the bulk density compared to the control, from 1.63 to to 1.45 g/cm^3; however, this effect is temporary, and materials should be reapplied about every six months. All tested organic materials promoted soil particle aggregation, increasing it from 3.28 to 5.23 mm. Higher application rates of these materials are recommended to achieve a greater impact on the soil's physical properties.

Keywords: bulk density; gravimetric water content; mean weighted diameter; soil penetration resistance; soil structure; volumetric water content.

RESUMEN

La producción agrícola de los suelos es fundamental para asegurar la alimentación de la población; no obstante, el uso inadecuado ha generado la degradación del suelo disminuyendo el potencial productivo. La aplicación de materia orgánica tiene un efecto positivo sobre las propiedades físicas del suelo; por lo tanto, el objetivo del presente estudio fue evaluar el efecto de la incorporación de materiales orgánicos sobre algunas propiedades físicas del suelo de la granja 'La María'. Se realizó un diseño completamente aleatorizado con cinco tratamientos, que consistieron en la aplicación de cascarilla de arroz cruda, tostada, gallinaza, un compost orgánico líquido y un testigo. La aplicación de los tratamientos no generó diferencias significativas en la resistencia a la penetración (RP); aún así, esta tiene una relación directa con la profundidad del suelo y varió de 500 a 1250 kPa, desde los 2,5 a los 17,5 cm, respectivamente. Así mismo, la RP mostró una variación temporal dependiente de la precipitación. Los materiales orgánicos aplicados lograron disminuir la densidad aparente de 1,63 a 1,45 g $cm^{-3;}$ no obstante, el efecto es relativamente corto en el tiempo por lo que el uso de cualquiera de estos materiales se debe aplicar semestralmente. La aplicación de cualquiera de los materiales orgánicos evaluados ayudó a promover la agregación de las partículas del suelo, ya que esta se incrementó desde los 3,28 mm a los 5,23 mm. Se recomienda evaluar dosis más elevadas de los materiales orgánicos aplicados para lograr afectar en mayor medida las propiedades físicas del suelo.

Palabras clave: densidad aparente; diámetro ponderado medio; estructura del suelo; humedad gravimétrica; humedad volumétrica; resistencia a la penetración del suelo.

INTRODUCTION

Soil is a critical, non-renewable natural resource that underpins global agriculture by providing essential support and nutrients for plant growth (Silver *et al*., 2021). Beyond its role in sustaining plants, soil acts as a vital reservoir for water, making it available for plant uptake and supporting diverse soil microbial communities. Additionally, soil plays a significant role in regulating atmospheric composition by acting as both a source and sink for greenhouse gases, thereby contributing to global climate balance (Oertel *et al*., 2016).

Currently, soil degradation is one of the most critical challenges confronting agriculture (Bhattacharyya *et al*., 2015). It leads to a decline in soil productivity and disrupts vital ecosystem functions, including water regulation, biogeochemical cycling, and carbon dioxide retention, ultimately contributing to broader environmental imbalances (Burbano-Orjuela, 2016).

In Colombia, agricultural land accounts for 1.8% (2,074,098 ha) of the national territory, with 93% of this area exhibiting some degree of erosion (Instituto de Estudios Ambientales y Meteorología [IDEAM], 2017). The predominant cause of soil degradation in the country is inappropriate land use, where land is utilized for activities unsuited to its inherent potential, such as converting agriculturally viable land to livestock grazing (Burbano-Orjuela, 2016). Soil degradation is primarily an anthropogenically induced process, leading to a diminished current and future productive capacity. This is further accelerated by practices such as overgrazing, unsustainable agricultural methods, and industrial activities (Maximillian *et al*., 2019). Specifically, overgrazing exacerbates soil compaction and impedes infiltration processes, consequently reducing water movement through the soil profile. This, in turn, restricts plant growth and promotes erosion (Centeri, 2022). Another significant degradation process observed is the loss of soil organic matter (OM). A decline in OM negatively impacts biological activity and compromises soil aggregate formation (Mitchell *et al*., 2022), both crucial for maintaining healthy soil structure and function.

Soil organic matter (SOM) is a complex, heterogeneous mixture comprising plant and animal residues at various stages of decomposition. It plays a pivotal role in soil fertility, carbon cycling, and the sequestration or transformation of numerous soil pollutants (Tiwari *et al*., 2023). The application of organic matter has been fundamental to agricultural practices since their inception due to its profound positive influence on soil physical properties. Specifically, SOM contributes to improved structural stability, reduced penetration resistance, enhanced water retention, and the formation of stable soil aggregates (Gurmu, 2019).

Furthermore, SOM positively impacts key soil quality indicators such as bulk density, total porosity, penetration resistance, and aggregate stability (Borges *et al.*, 2016). The incorporation of composted organic materials, in particular, has been shown to increase both nutrient availability within the soil and overall microbial activity (Li *et al.*, 2024).

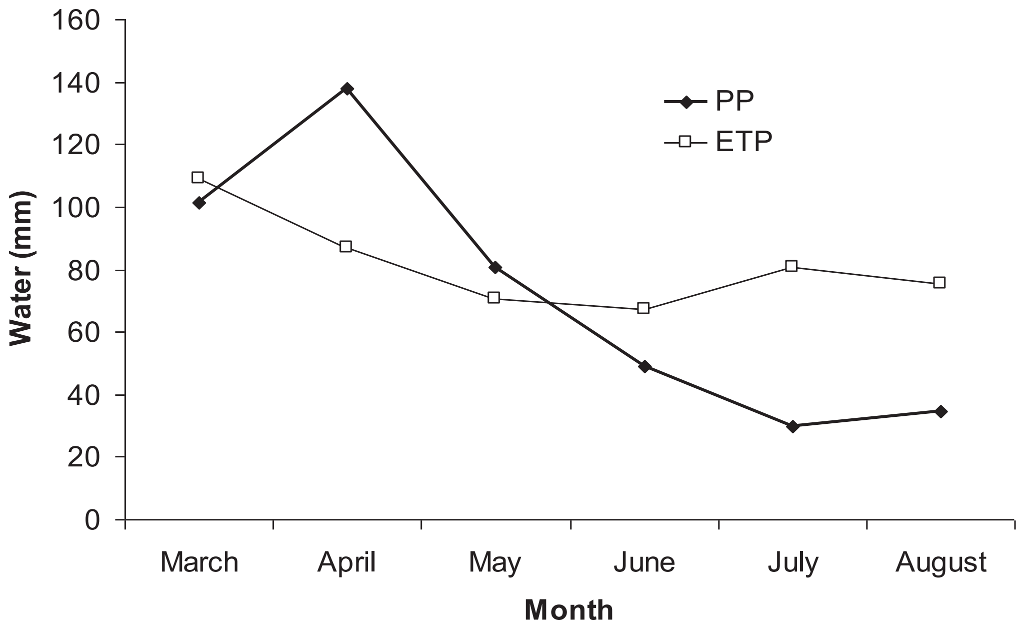
The incorporation of organic matter is crucial for soil remediation and health, primarily due to its capacity to enhance fertility and mitigate compaction. This study specifically evaluated the effects of various organic amendments on the physical properties of a compacted Inceptisol. The research was conducted on the 'La María' farm, located at the Universidad Pedagógica y Tecnológica de Colombia. The overarching objective was to assess the potential of these amendments to improve soil conditions, thereby supporting sustainable crop production in the region. It was hypothesized that the integration of diverse organic materials would positively influence key soil physical parameters, including bulk density, water retention, structural stability, and penetration resistance.

MATERIAL AND METHODS

Location

The field trial was conducted at the 'La María' farm, part of the Pedagogical and Technological University of Colombia (UPTC) in Boyacá, Colombia. This site is geographically located at 5°33'06" N latitude and 73°21'30" W longitude, at an altitude of 2,692 m. The area is characterized by an average temperature of 12.9 °C and an annual precipitation of 645 mm, exhibiting a bimodal rainfall distribution (IDEAM, 2017). All subsequent soil analyses were performed at the soil laboratory associated with the Faculty of Agricultural Sciences at UPTC. Precipitation and evaporation data pertinent to the study area were obtained from the UPTC weather station (Figure 1A).

A



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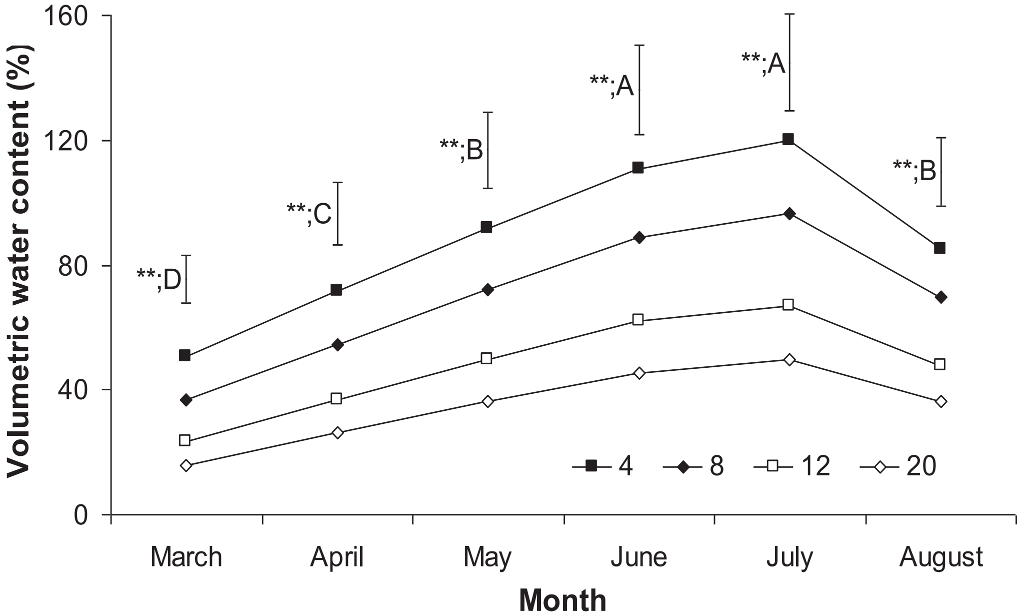


** indicate significant differences between treatments for the same time according to the ANOVA (α<0.01) before the comma, and different letters indicate significant differences between the measurements over time according to the Tukey test groupings (p ≤0.05) after the comma. Vertical bars indicate the standard error (n=20).

Figure 1. *A: Precipitation (PP) and potential evapotranspiration (ETP) for the March-August 2019 season. Source: UPTC Weather Station; B: Volumetric water content (qv) at 4, 8, 12, and 20 cm depth during the March-August 2019 season.*

Materials

The organic materials evaluated included raw rice husk (RRH; Bioespacio, Colombia, reference 15020-15021; Table 1), roasted rice husk (RoRH; Bioespacio, Colombia, reference 15030-15041), processed to an 80% roasting level (Table 2), composted chicken manure(ABIMGRA, 2020) (CM; Abimgra Ltda., Colombia) applied at a rate of 10 t ha^{-1} (Table 3), and Abonex® liquid organic fertilizer (LOF), a product derived from vermicomposting leachate (Table 4), applied at a dose of 0.42 L m^{-2} at 5%. These specific materials were selected based on their local availability and cost-effectiveness.

The experimental soil, classified as an Inceptisol, is located on a relatively flat terrain with minimal topographic variation. Soil textural analysis revealed a clayey texture, comprising 50.88% clay, 29.12% sand, and 20% silt. Key chemical and physical properties included a pH of 5.57, an electrical conductivity of 0.10 dS m^{-1}, organic matter content of 1.29% and a bulk density of 1.57 g cm^{-3}. This Inceptisol has been under continuous agricultural use for over 40 years and has been intermittently subjected to cattle grazing.

Table 1. *Physical and chemical properties of raw rice husk (RRH)*

Parameter	Unit	RRH
Thickness	mm	0-4
Length	mm	2-7
Color	---	blonde yellow
Density	g cm^{-3}	0.1
Porosity	%	64.75
Water retention	%	25.85
pH	---	6.8
Composition		
Niacin	mg kg^{-1}	1.6-4.2
Calcium	mg kg^{-1}	60-130
Iron	mg kg^{-1}	3.9-9.5
Zinc	mg kg^{-1}	0.9-4.0
Phosphate	mg kg^{-1}	0.03-0.07
Potassium	%	2.0-6.3

Table 2. *Physical and chemical properties of raw rice husk (RoRH)*

Parameter	Unit	RoRH
Water retention	%	10-13
Ash percentage	%	20
Density	g cm^{-3}	0.67-0.74
Electric conductivity	dS m^{-1}	0.0359
pH	---	6.0
Silica	%	96.51
Potassium oxide	%	1.1
Sodium oxide	%	0.78
Calcium oxide	%	0.25
Magnesium oxide	%	0.23
Sulfates	%	1.13

Table 3. *Physical and chemical properties of composted chicken manure (CM)*

Parameter	Unit	CM
Ash percentage	%	54.5
Volatilization	%	32.9
Organic carbon	%	10.9
Cation exchange capacity	meq 100 g^{-1}	23.7
pH	---	6.98
Electric conductivity	dS/m	38.9
Moisture retention	%	62.9
Density	g cm^{-3}	0.77
Nitrogen (N)	%	1.10
Phosphorus (P_2O_5)	%	2.30

Parameter	Unit	CM
Potassium (K_2O)	%	1.80
Calcium (CaO)	%	21.4
Magnesium (MgO)	%	0.73
Sulfur (S)	%	2.08
Silicon (SiO_2)	%	15.5

Table 4. *Chemical and biological characteristics of Abonex® liquid organic fertilizer obtained from vermicomposting leachate (LOF) at 10% concentration.*

Parameter	Unit	LOF
Nitrogen (N)	mg. L^{-1}	20-32.2
Phosphorus (P_2O_5)	mg. L^{-1}	14-40.3
Potassium (K_2O)	mg. L^{-1}	20-35.2
Calcium (CaO)	mg. L^{-1}	1.2
Magnesium (MgO)	mg. L^{-1}	3.2
Sodium	mg. L^{-1}	1.2
Sulfur	mg. L^{-1}	29
Iron	mg. L^{-1}	2
pH	---	5.24
bacteria	LogCFU ml^{-1}	6.1
Actinomycetes	LogCFU ml^{-1}	4.1
Fungus	LogCFU ml^{-1}	2
Yeasts	LogCFU ml^{-1}	2.5
Lactobacilli	LogCFU ml^{-1}	3.8

CFU: colony forming units
Note. Adapted from Zamora *et al.* (2017) and Abonex (2018).

Experimental design

The experiment was conducted using a completely randomized design, comprising five treatments: raw rice husk (RRH), roasted rice husk (RoRH), composted chicken manure (CM), liquid organic fertilizer (LOF), and a control. Each treatment was replicated three times, resulting in a total of 15 experimental units (EUs). Each EU consisted of a 16 m² plot, with a 2 m buffer zone separating it from adjacent experimental units. The total study area, which exhibited homogeneous soil properties, spanned 640 m².

Soil preparation involved a single harrowing pass over the study area. Subsequently, the experimental units (EUs) were measured and demarcated. Organic matter for the RRH, RoRH, and CM treatments was then broadcast, while the LOF treatment was applied via foliar spraying with a backpack sprayer. Material incorporation was achieved through two additional harrowing passes: one in a south-north direction and the second in an east-west direction.

Response variables

Measurements of the different variables were conducted monthly from March to August 2019, commencing with the incorporation of the treatments. For penetration resistance and volumetric humidity, four measurements were taken per experimental unit (EU) due to their in-field assessment. Conversely, apparent density, mean weight diameter, and gravimetric humidity were measured only once per EU, as these parameters required laboratory analysis.

Soil penetration resistance (PR) was measured using a Fieldscout SC 900 digital conical penetrometer (Spectrum Technologies, Inc., Aurora, IL). Data were recorded every 2.5 cm to a depth of 20 cm and expressed in kPa. Volumetric water content (θv), expressed as a percentage, was determined with a TDR 100 (Spectrum Technologies, Inc., Aurora, IL) at depths of 4, 8, 12, and 20 cm. Undisturbed soil samples were collected with an AMS 77455 soil core sampler (AMS, Inc., Harrison St., ID). Bulk density (r*b*) and gravimetric water content (θg) were subsequently calculated using Equations (1) and (2), respectively, based on mass-volume relationships obtained from the known-volume cylinder methodology.

$$\rho_b = \frac{M_{dry}}{V_T} \qquad (1)$$

$$\theta_g = \frac{M_{wet} - M_{dry}}{M_{dry}} \qquad (2)$$

Where: VT: total volume of the sample (cm3); *Mwet*: mass of wet soil (g); and *Mdry*: mass of dry soil (g), at 105°C for 24 hours.

Soil structure was quantified using the mean weight diameter (MWD). For this analysis, a 120 g soil sample was placed in a granular composition test set 8.05 (Royal Eijkelkamp B.V., Netherlands), which has a measurement range of 0.063 µm to 8 mm and a 200 mm diameter. Each sample was shaken for 10 minutes at a constant speed. The soil mass retained on each sieve was then determined using an Acculab VIC 612 electronic balance with 0.01g precision (Sartorius Spain, Madrid). Finally, MWD was calculated using Equation (3).

$$MWD = \sum_{i=1}^{n} \bar{x}_i \times \frac{W_i}{100} \qquad (3)$$

Xi: average diameter of the fraction; Wi: percentage of the total weight retained on each sieve.

Data analysis

A Shapiro-Wilk normality test was performed to verify the assumptions for the Analysis of Variance (ANOVA). Subsequently, ANOVA was conducted to establish statistical differences between treatments and measurements over time. Finally, treatments were classified using a Tukey mean comparison test ($p \leq 0.05$). All statistical analyses were performed using SAS® v. 9.2 (SAS Institute Inc., Cary, NC).

RESULTS

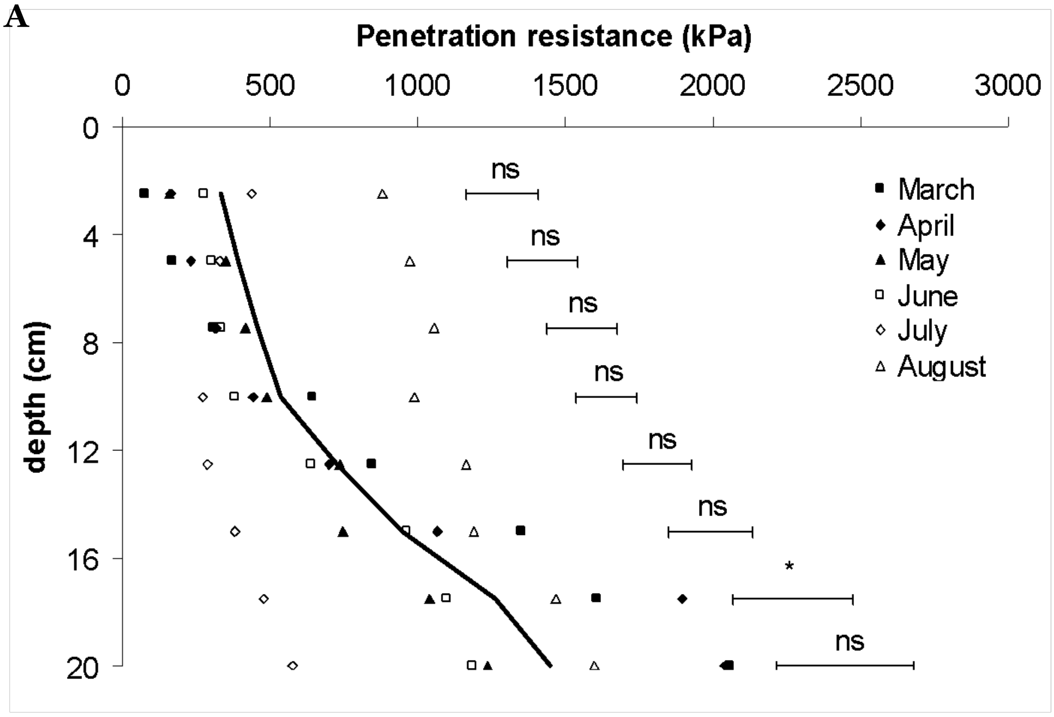
Volumetric water content (θv)

Volumetric water content (θv) showed no significant statistical differences among the evaluated treatments. However, it consistently increased from March to July and then decreased in August across all treatments and depths. Average θv values for all assessed treatments and sampled months ranged from 50.53% to 119.79% at 4 cm, 36.58% to 96.28% at 8 cm, 23.46% to 66.73% at 12 cm, and 15.71% to 49.79% at 20 cm (Figure 1B). Precipitation and evapotranspiration appeared to be key factors influencing soil moisture content.

Soil Penetration Resistance (PR)

Penetration resistance (PR) consistently increased with soil depth across all months and treatments. Values generally ranged from approximately 577 to 2055 kPa from the surface to a 20 cm depth. However, PR did not exhibit significant statistical differences ($p < 0.05$) among treatments for most depths and months evaluated (Figure 2A). Significant differences were only observed at a 17.5 cm depth in March, where CM and RRH applications recorded PR values of 1278.67 and 1411.58 kPa, respectively. In April, PR was higher in the superficial soil layer (2.5 cm) for treatments incorporating RRH, RoRH, and LOF compared to the CM application and the control.

A



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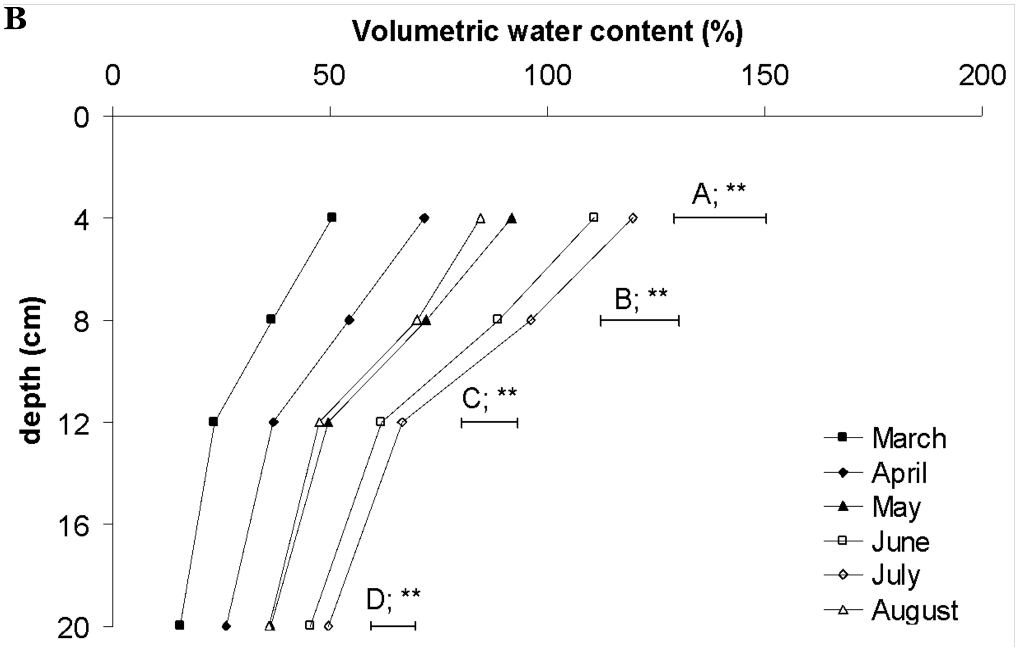

ns: not significant; * and ** indicate significant differences between the months of measurement according to the ANOVA test ($p< 0.05$ and $p< 0.01$, respectively). Different letters indicate significant differences between the measurement depths according to the Tukey test groupings ($p<0.05$). Horizontal bars indicate the standard error (n=24).

Figure 2. *Average of A: resistance to penetration; B: volumetric water content for different applications of organic matter in March, April, May, June, July, and August of 2019.*

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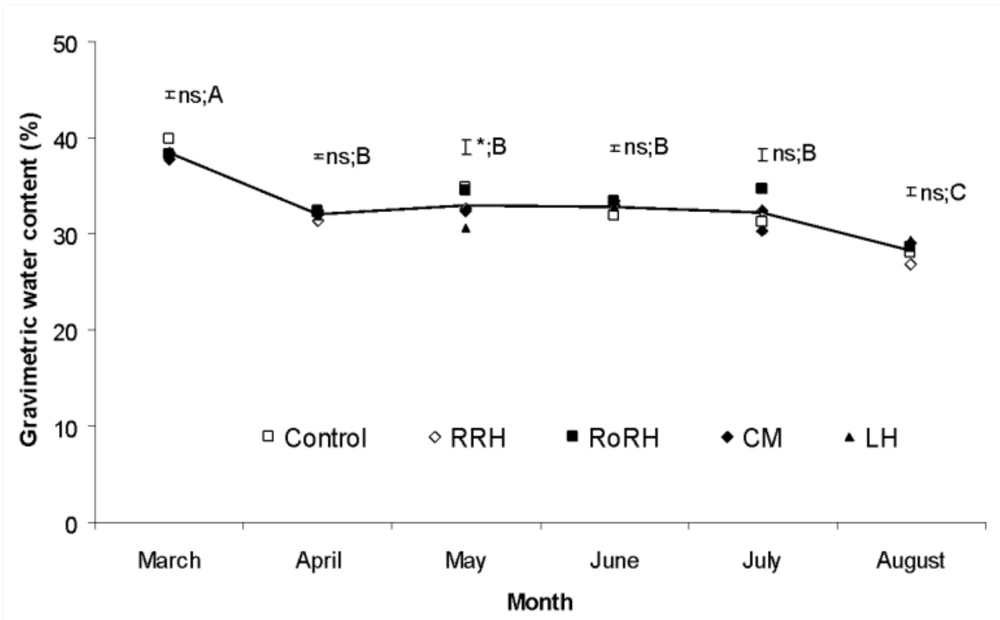

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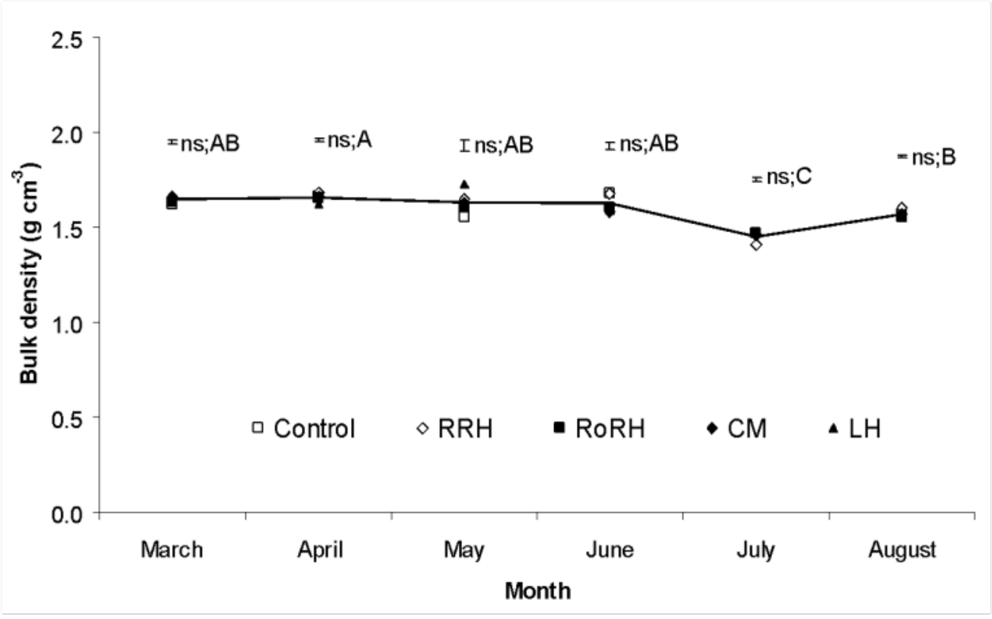

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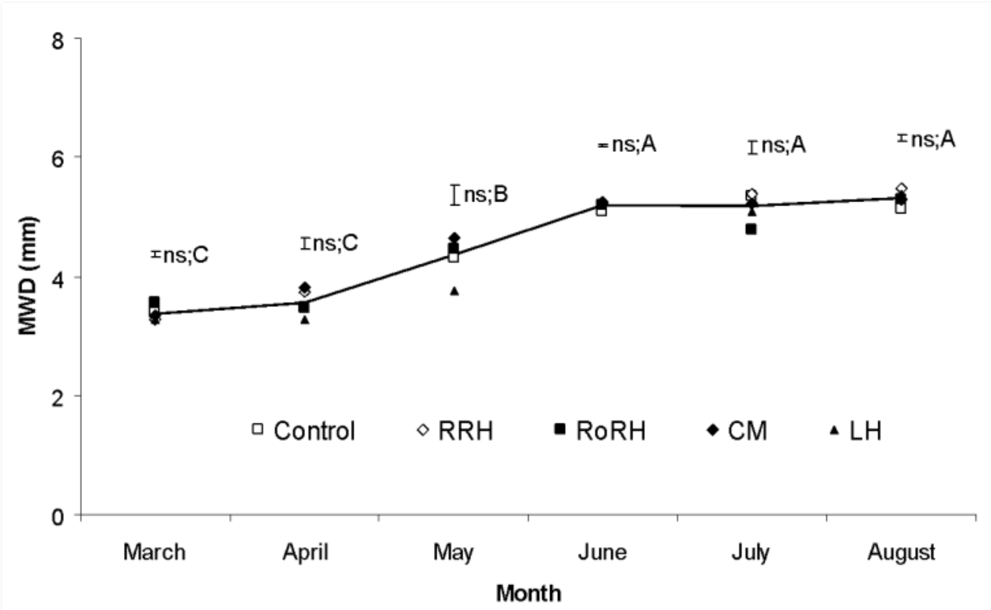

ns: no significant; * indicates significant differences between treatments for the same time according to the ANOVA (α<0.05) before the comma, and different letters indicate significant differences between the measurements over time according to the Tukey test groupings (p<0.05) after the comma. Vertical bars indicate the standard error (n=20).

Figure 3. *A: Gravimetric water content; B: bulk density; C: mean weighted diameter (MWD) for different applications of organic matter in March, April, May, June, July, and August of 2019.*

Bulk density (ρb)

Bulk density (ρb) showed no significant statistical differences (p < 0.05) among treatments throughout the evaluation period. However, the highest ρb values were observed with the addition of RRH and LOF, both reaching 1.61 g cm^{-3}. ANOVA for ρb did reveal significant statistical differences (p < 0.05) between months, with average values of 1.66, 1.45, and 1.57 g cm^{-3} recorded in April, June, and August, respectively (Figure 3b).

Soil aggregate stability (SAS)

No significant differences were observed among treatments in any of the evaluated months. However, when analyzing measurements over time, a significant change in soil structure was evident. It transitioned from a moderate structure in March and April (3.28 mm) to a stable structure in May (4.36 mm), becoming very stable in June, July, and August (5.23, 5.16, and 5.31 mm, respectively) (Figure 3c).

DISCUSSION

This effect was most noticeable in June and July, even though the highest rainfall occurred earlier, in March and April (Figure 1A). This suggests a delayed impact, as June marks the fourth month after the organic materials' incorporation. Therefore, the effect of these earlier rains on moisture content within the first 20 cm of the soil appeared to be delayed by approximately two months. The results indicate that as the mineralization of RRH, RoRH, CM, and LOF progressed, the increased contribution of organic substances favored long-term moisture retention. This was likely due to improved aggregate stability and a decreased infiltration rate, which also helped maintain nutrient availability on particle surfaces (Gabriel *et al.*, 2021).

Volumetric water content (θv) decreased with increasing soil depth, and highly significant differences were observed for each depth across the evaluated months (Figure 2B). After the incorporation of organic matter (OM) into the soil, its mineralization and humification were enhanced by precipitation. This likely accelerated the decomposition rate, leading to increased respiration, higher values of microbial biomass carbon, and greater biological activity of the soil's OM (Ullah *et al.*, 2023). These processes may have contributed to increased soil moisture retention from March through July, a phenomenon potentially associated with the low land slope and the clayey particle size distribution in these areas (Zucco *et al.*, 2014). Conversely, the increase in humidity as a function of depth showed an inverse relationship, consistent with findings by Montoya *et al.* (2018) in corn-cultivated soils.

Penetration Resistance (PR) variation was more strongly influenced by rainfall and soil moisture than by treatment effects, with higher PR values observed during drier months. This relationship is further supported by the finding that prior-month rainfall moistens the soil, leading to lower PR at the time of sampling (Souza *et al.*, 2021). Although organic matter (OM) can influence compaction, the low dose applied (10 t ha^{-1}) likely limited its impact. This limited impact could also be attributed to lower soil moisture resulting from reduced rainfall in that month (50 mm), which aligns with Souza *et al.* (2021), who reported higher PR in dry soils with low rainfall compared to moist soils.

Penetration Resistance (PR) serves as a crucial indicator of compaction in agricultural soils (Fernandes *et al.*, 2020). Values exceeding 1.6 MPa suggest some degree of soil compaction (Gabriel *et al.*, 2021), which can negatively affect root growth (Wahlström *et al.*, 2021). The PR values observed in the soil profile align with those reported by Pinto-Acero *et al.* (2016) and Pinzón-Gómez *et al.* (2016). These studies similarly indicate that this behavior is independent of the tillage type, vegetation cover, moisture content, and bulk density (Moraes *et al.*, 2024).

Higher soil moisture content correlates with lower compaction values (Liu *et al.*, 2023), making organic matter (OM) addition crucial for maintaining moisture retention (Gabriel *et al.*, 2021). Thus, applying Abimgra and/or RoRH likely helps quickly reduce soil penetration resistance (PR) due to their superior moisture retention capacity (Quintero *et al.*, 2012). Conversely, the incorporation of RRH, with its high silicon content, exhibited low degradability and wettability (Bracho *et al.*, 2009). The lack of statistical differences with the applied organic materials suggests that the 10 t ha^{-1} dose may have been too low to significantly impact PR. Supporting this, Velázquez-Duarte *et al.* (2016) found that OM doses of 60 t ha^{-1} are necessary to achieve improved crop yields and a greater effect on soil physical properties.

The decrease in gravimetric water content (θg) primarily coincided with precipitation patterns. This behavior may also be linked to the soil's clay texture and porosity (Rabbi *et al.*, 2024). Additionally, to a lesser extent, it could be attributed to an increase in the soil's specific surface area (Padmavathiamma *et al.*, 2008), which promotes water loss through the formation of organic-mineral complexes by fulvic and humic acids (Zamora *et al.*, 2017). While these complexes improve soil structure and facilitate water infiltration, they also increase the cationic exchange capacity, which can prevent water adsorption (Miranda *et al.*, 2021). Similar results were observed with vermicompost application (Cruz-Crespo *et al.*, 2019). The vermicomposting process, involving the interaction of worms and microorganisms, enhances substrate fragmentation and conditioning, increases surface area, and thereby boosts microbiological activity (Tiwari *et al.*, 2023).

Conversely, gravimetric water content (θg) exhibited significant statistical differences between months, with treatment averages ranging from 38.02% in March to 28.31% in August. This suggests that the incorporation of organic matter (OM) and rainfall likely enhanced microbial activity, thereby favoring processes such as adsorption and increasing the soil's specific surface area (Tiwari *et al.*, 2023). However, the lowest θg content occurred in August, which coincides with the highest rates of mineralization and humification of the applied materials. This could indicate that the effect of OM application on moisture retention may have diminished by then due to advanced decomposition (Miranda *et al.*, 2021). In this context, Kranz *et al.* (2020) reported that the effect of compost incorporation can persist for three to 15 months post-application.

Similarly, the non-significant changes in bulk density (ρb) align with other studies reporting that substantial reductions in ρb require much higher organic matter (OM) application rates or longer durations. For instance, Olivares-Campos *et al.* (2012) and Zanor *et al.* (2018) found no significant changes with the addition of 4 t ha^{-1} of vermicompost. This outcome likely occurs because the soil-amendment interaction time was insufficient to induce rapid changes in this soil property; depending on conditions, alterations in soil physical properties can sometimes take several years (Roper *et al.*, 2021). These results also reflect the physical properties of RRH (Table 1), such as its high porosity (91%) and low bulk density (0.14 g cm^{-3}), which influence the soil only slightly, rather than significantly (Bracho *et al.*, 2009; Quintero *et al.*, 2012). Ultimately, this is likely because the OM dose applied was insufficient to generate significant changes (Velázquez-Duarte *et al.*, 2016). In this regard, Kranz *et al.* (2020) reported that an application of 540 t ha^{-1} -a quantity 53 times higher than that used in the present study- resulted in a 19% to 21% reduction in bulk density.

The absence of significant differences in soil aggregate stability aligns with findings by Menon *et al.* (2020), who emphasized the inherent physical stability of soil aggregates as fundamental to maintaining soil quality. In this study, the lack of soil disturbance during the evaluation period likely allowed microbial activity to thrive and effectively decompose the applied organic matter (OM). This suggests the subsequent production of humic substances, which contribute to the formation of both mineral aggregates (through clay particle binding) and organic-mineral aggregates (involving clay particles and organic colloids) (Miranda *et al.*, 2021). These observations underscore the critical role of OM application in maintaining soil structure and promoting soil particle aggregation (Tiwari *et al.*, 2023).

Although the study area has been subject to mechanization for approximately 20 years, this agricultural practice has been shown to decrease aggregate size and increase bulk density (Li *et al.*, 2022). For the soil studied, the Mean Weight Diameter (MWD) averaged 4.35 mm. This relatively low value suggests that the soil structure requires improvement, especially when compared to findings by Ciric *et al.* (2012), who reported MWD values of approximately 7.58 mm for cultivated soils and 5.61 mm for forest areas. This low MWD is likely attributable to the combined effects of prolonged mechanization and recent grazing activities in these soils. Despite consistent additions of green manures and crop residues, these management practices have contributed to the observed reduction in soil aggregate size.

CONCLUSIONS

While penetration resistance did not show statistically significant differences, the results indicate that bulk density and soil structure responded positively to organic material application, especially after three to four months. The most notable improvements were observed in MWD, which increased steadily from March to August, indicating enhanced soil aggregation and structural stability over time. Bulk density exhibited a temporary reduction, particularly in June, signifying improved porosity and moisture retention. Although rainfall was the short-term moisture retention, making it a secondary driver of seasonal trends in gravimetric and volumetric water content. These findings collectively suggest that the effects of organic amendments are more pronounced in the medium term, and their influence could be further enhanced by increasing the application rates. Therefore, optimizing application rates is recommended to maximize the benefits for soil physical properties.

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CONFLICT OF INTEREST

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

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