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Compaction Characteristics under Modified Proctor and Agriculture Engineering Tests Influenced by Organic Matter Application Level

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ABSTRACT

Soil compaction is a major challenge in modern agriculture, reducing soil quality, restricting crop growth, and decreasing the efficiency of agricultural machinery. Factors such as soil texture, organic matter, and soil moisture during machine trafficking are key contributors to compaction and must be effectively managed to sustain soil health. This study investigates the potential of organic matter (OM), specifically cow manure, to mitigate soil compaction in sandy clay loam soils. The research examines three moisture levels (9.40%, 13.59%, and 16.99%) and four compaction energy levels (2475, 7425, 12375, and 56000 ft–lb/ft^3), with OM applied at a 5% concentration at three depths (0 cm, 4 cm, and 8 cm). Two compaction methods, the Modified Proctor Test and the Agricultural Engineering Test, were employed. Results show that increased compaction energy directly correlates with higher soil bulk density, with rises of 27.95% and 33.08% at the highest energy levels. Moisture content significantly influenced bulk density, with increases of 6.84% and 11.99% observed in the Agricultural Engineering and Modified Proctor Tests, respectively. Surface–applied OM resulted in the lowest bulk density across both methods. These findings highlight the effectiveness of organic matter in alleviating soil compaction and improving soil structure. Optimizing OM application and managing soil moisture are practical strategies for enhancing agricultural productivity and promoting sustainable soil management.

Keywords: Soil compaction, agricultural loading, organic carbon content, moisture content

INTRODUCTION

Mechanization has profoundly altered soil properties, particularly its structure, compaction, aeration, and nutrient dynamics. Soil compaction, in particular, leads to increased bulk density and strength while reducing porosity and hydraulic properties. Soil compaction reduced seed emergence and crop yields, as shown by several key studies (Radford *et al.*, 2001; Shaheb *et al.*, 2021).

Intensive machinery use during land preparation has led to widespread soil compaction. For example, conventional land preparation in Australia often involves 8–10 tillage operations, with some regions requiring up to 18. Similarly, in Thailand, an average of 13 tillage operations is needed (Grange *et al.*, 2005). The heavy equipment and frequent machinery passes significantly contribute to soil compaction worldwide (Horn *et al.*, 2019; Keller *et al.*, 2019; Shaheb, 2020), limiting growth and yield potential, which challenges the sustainability of crop production. Research by Ramadhan (2014) and Abbaspour–Gilandeh and Sedghi (2015) shows that soil compaction hinders plant growth by limiting root access to essential air, nutrients, and water. Bengough and Mullins (2006) demonstrated that root growth is significantly inhibited when cone penetration resistance exceeds 2 MPa. Additionally, Taylor and Gardner (1963) showed that compaction levels above 3 MPa restrict root penetration in cotton plants, leading to reduced growth and yield.

Studies by Arshad *et al.* (1996) and Ekwue and Stone (1995) indicate that optimal bulk densities for plant growth exist, with organic matter playing a critical role in reducing soil compaction. Ekwue and Stone's research demonstrated that organic matter decreases soil strength and bulk density, with the effects influenced by moisture content and the type of organic material applied. Furthermore, Usaborisut and Ampanmanee (2015) emphasized the role of organic matter in mitigating soil compaction, especially under heavy machinery use. Their findings revealed that organic matter enhances soil structure, improves resilience against mechanical loads, and promotes soil aggregation and pore formation. This results in better porosity, reduced bulk density, and improved water movement, root penetration, and gas exchange within the soil. Organic matter also serves as a water reservoir, gradually releasing moisture to plant roots over time (Green *et al.*, 2021; Gupta *et al.*, 2019).

The aim of the study was to reduce the adverse effects of soil compaction on agriculture and enhance crop growth, considering factors such as organic matter application, energy input, and soil moisture content. Specifically, the study investigated how organic matter influences soil compaction and identified optimal application methods to improve agricultural outcomes.

MATERIALS AND METHODS

The sandy clay loam soil used in this study was collected from a sugarcane field in Nakhon Pathom Province, central Thailand. Standard laboratory procedures were followed to analyze the soil properties. Particle size analysis was performed using the hydrometer method (ASTM D422–63**,** 2007). The consistency limits, which indicate the moisture levels at which the soil transitions between different states, were determined using ASTM D4318–84 (2000). The organic matter (OM) content of the soil was measured according to ASTM D2974–14 (2014). The soil was sun–dried and sieved to a particle size of 2.00 mm or smaller. To prepare the mixtures, the required percentage of OM was added to the soil and thoroughly mixed by hand.

The three target moisture content levels were chosen to reflect soil conditions commonly encountered in agricultural practices. These ranged from the moisture content at which the highest bulk density is obtained to the plastic limit, which represents the recommended moisture content for tillage. The three levels included a moisture content of 9.40% (the critical value for achieving the highest bulk density using the Modified Proctor method), 13.59% (equivalent to 0.8 times the plastic limit, as described by Mosaddeghi *et al*. (2000) and 16.99% (corresponding to the plastic limit of the soil). To achieve the desired moisture contents, the amount of water to be added was calculated using the following equation 1.

$$\Delta w = \frac{S}{(1+W_i)x\left(W_f - W_i\right)} \qquad (1)$$

where
Δw = amount of required water to be added to the mixture, g
S = weight of soil–organic matter mixture, g
W_f = final desired moisture content, g
W_i = initial moisture content of the mixture, g
Bulk density and soil moisture content were determined by oven–drying the soil samples at 105°C for 24 hours.

The effect of organic matter placement on soil compaction was studied by incorporating OM at three depths: 0 cm, 4 cm, and 8 cm. These depths correspond to practical field depths of 0 cm, 15 cm, and 30 cm, respectively. Each treatment consisted of a 5 cm thick soil–organic matter mixture, with either no added OM (0.46% existing OM) or 5% OM by dry weight. To evaluate soil behavior after compaction, a standard mold (**Figure 1a**) was used. The mold was divided into four sections with heights of 2 cm, 2.50 cm, 5 cm, and 2.15 cm, as shown in **Figure 1b**.

(a) (b)

Figure 1. (a) The mold, base plate, collar, and hammer used in the Modified Proctor Test, and (b) the modified mold consisting of four sections: 2 cm, 2.50 cm, 5 cm, and 2.15 cm, along with two sets of hammers.

Two compaction methods were evaluated. The first method was the Modified Proctor Test (ASTM D1557–12, 2021), commonly used in civil engineering, which involved compacting the soil in five layers. The second method was a single–layer compaction test, referred to as the Agricultural Engineering Test, which was designed to simulate the effects of agricultural machinery traffic on the soil surface. The compaction energies applied were 2475, 7425, 12375, and 56000 ft–lb/ft^3. The first three energy levels were based on typical compaction caused by agricultural machinery (Ekwue and Stone, 1995; Ohu *et al.,* 1994; Ohu *et al.,* 1985). The final energy level, 56000 ft–lb/ft^3, is the value recommended in the Modified Proctor Test method. The first three energy levels were achieved using a 1.5262 kg hammer dropped from a height of 50 cm, while the final energy level was achieved using a 3.9242 kg hammer dropped from a height of 44 cm. The number of blows for each case was calculated using equation 2. The Agricultural Engineering Test was performed using a single layer of soil, while the Modified Proctor Test involved five layers of soil (**Figure 2**).

$$N_b = \frac{E \ x \ V_s}{W \ x \ h \ x \ N_l} \qquad (2)$$

where
N_b = Number of blow per layer
E = The compaction energy, ft–lb/ft^3
V_s = Volume of soil, ft^3
W = Weight of hammer, lb.
h = Height of drop, in
N_l = Number of layer

Figure 2. The compaction test conducted at energy levels of 2475, 7425, 12375, and 56000 ft–lb/ft^3

The experiment was designed as a Randomized Complete Block Design (RCBD) with two replications. The factors studied included the presence or absence of added organic matter, the placement depth of 5% organic matter (0 cm, 4 cm, and 8 cm), compaction energy levels (2475, 7425, 12375, and 56000 ft–lb/ft³), and the two compaction methods (the Modified Proctor Test and the Agricultural Engineering Test).

RESULTS AND DISCUSSION

Soil characteristics

Particle size analysis classified the test soil as sandy clay loam, consisting of 52.05% sand, 27.58% silt, and 20.37% clay. The soil's plastic and liquid limits were determined to be 16.99% and 17.27%, respectively, with an initial organic matter (OM) content of 0.46%. Cow manure, serving as the OM source, contained 56.36% organic matter. Baseline measurements for soil moisture content and bulk density were 1.98% and 1.44 g/cm³, respectively. These initial soil characteristics provided a foundation for evaluating the effects of OM on soil compaction and moisture relationships.

Moisture content and bulk density relationship

The Modified Proctor method revealed a relationship between moisture content and maximum bulk density. For soil without OM, the average highest bulk density (1.960 g/cm³) was observed at a moisture content of 9.40% (db). Adding 5% OM increased the moisture content at maximum bulk density to 11.00% while reducing the bulk density to 1.887 g/cm³. This demonstrates that OM enhances soil structure by reducing susceptibility to compaction. Similar observations by Shahgholi and Jnatkhah (2018) indicated shifts in critical moisture content due to organic amendments, supported by findings from Shirani *et al.* (2010) and Mosaddeghi *et al.* (2000), who noted OM broadens the moisture range suitable for agricultural activities.

The increased moisture content required for maximum bulk density highlights OM's role in altering soil physical properties. By forming absorbed water films on soil particles, OM increases water–holding capacity, which delays soil deformation (Ohu *et al.*, 1994). Additionally, OM raised the plastic and liquid limits, enhancing the soil's plasticity and cohesion through OM–water interactions. Studies by Zhang (1994) and Baver (1930) corroborated these findings, emphasizing that OM characteristics significantly influence soil behavior.

Impact of compaction energy

Higher compaction energy levels produced increased bulk densities, as shown in both the Modified Proctor and Agricultural Engineering Tests (**Figure 3**). The Modified Proctor Test yielded consistently higher bulk densities due to its layered compaction mechanism compared to the single–layer compaction of the Agricultural Engineering Test. For instance, at the highest energy level (56,000 lb–ft/ft³), bulk densities reached 2.07 g/cm³ and 1.95 g/cm³ for the Modified Proctor and Agricultural Engineering Tests, respectively. These results underscore the importance of compaction methodology in evaluating soil properties.

Consistent with Ohu *et al.* (1994), higher compaction levels consistently resulted in increased bulk density. Factors such as soil texture and moisture conditions influenced compaction potential, with sandy clay loam demonstrating lower susceptibility to compaction than finer–textured soils. Other factors, including machinery traffic, moisture content, and tire configuration, further affected compaction. Studies by Shaheb *et al.* (2021) and Pulido–Moncada *et al.* (2019) emphasized that lower tire inflation pressure reduces compaction, highlighting the importance of optimizing machinery configurations.

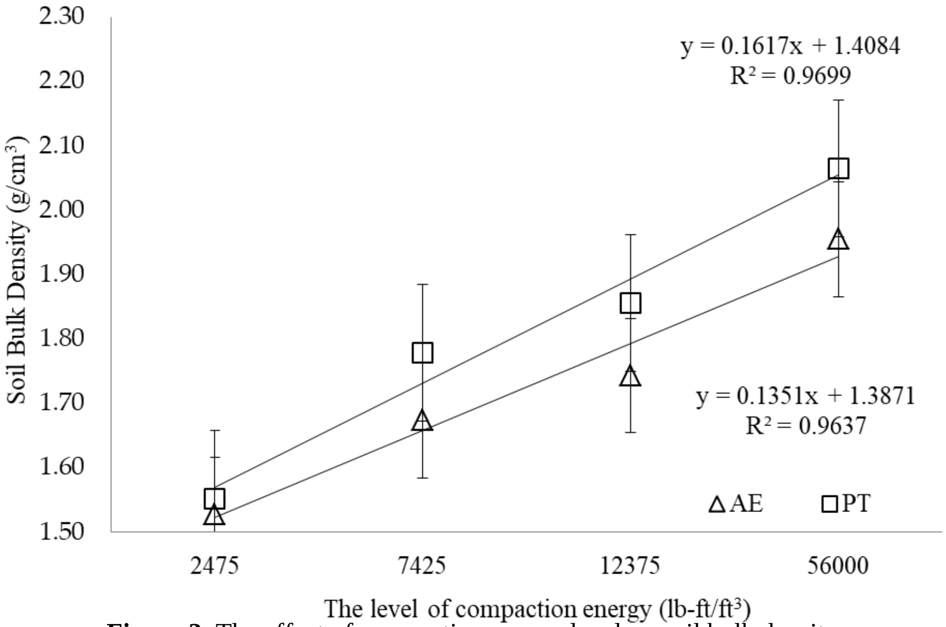

Figure 3. The effect of compaction energy level on soil bulk density

Organic matter placement

The addition of OM consistently reduced bulk density compared to controls, with reductions varying by placement depth (**Figure 4**). Surface placement (0 cm) resulted in the lowest bulk densities (1.80 g/cm³ and 1.67 g/cm³ for the Modified Proctor and Agricultural Engineering Tests, respectively), demonstrating its effectiveness in mitigating compaction. Deeper placements (4 cm and 8 cm) also reduced bulk density but were less effective than surface placement. The Agricultural Engineering Test indicated a greater reduction in dry density with surface–level OM placement (**Figure 5**), particularly under conditions simulating machinery traffic, due to the direct interaction with applied forces. This is supported by Agili et al. (2011), who noted that OM acts as a cushioning layer, absorbing and redistributing external loads, thereby reducing compaction effects.

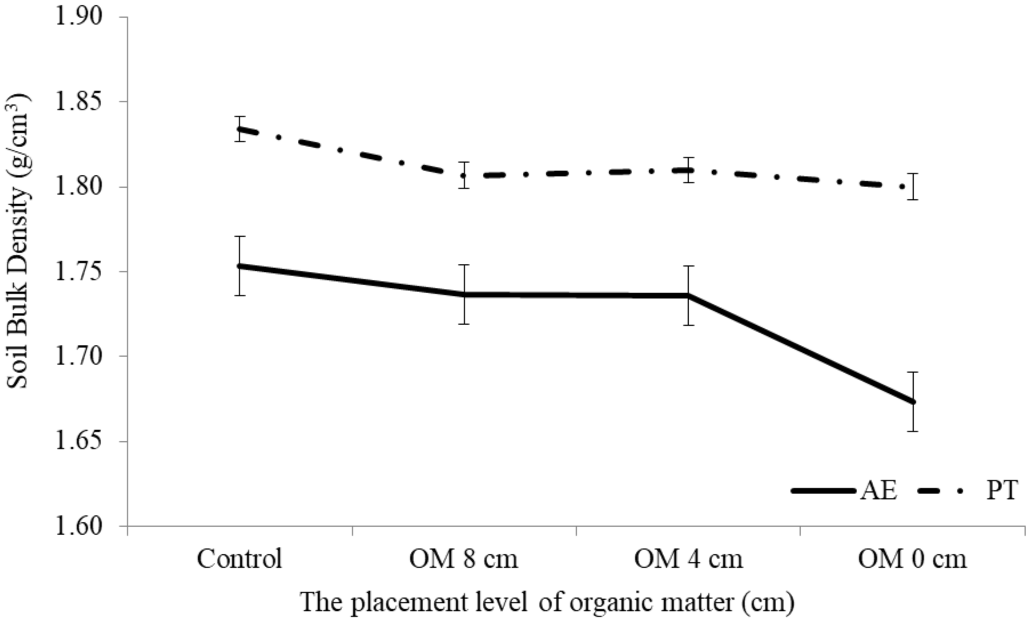

Figure 4. The effect of the placing level of adding organic matter on soil bulk density

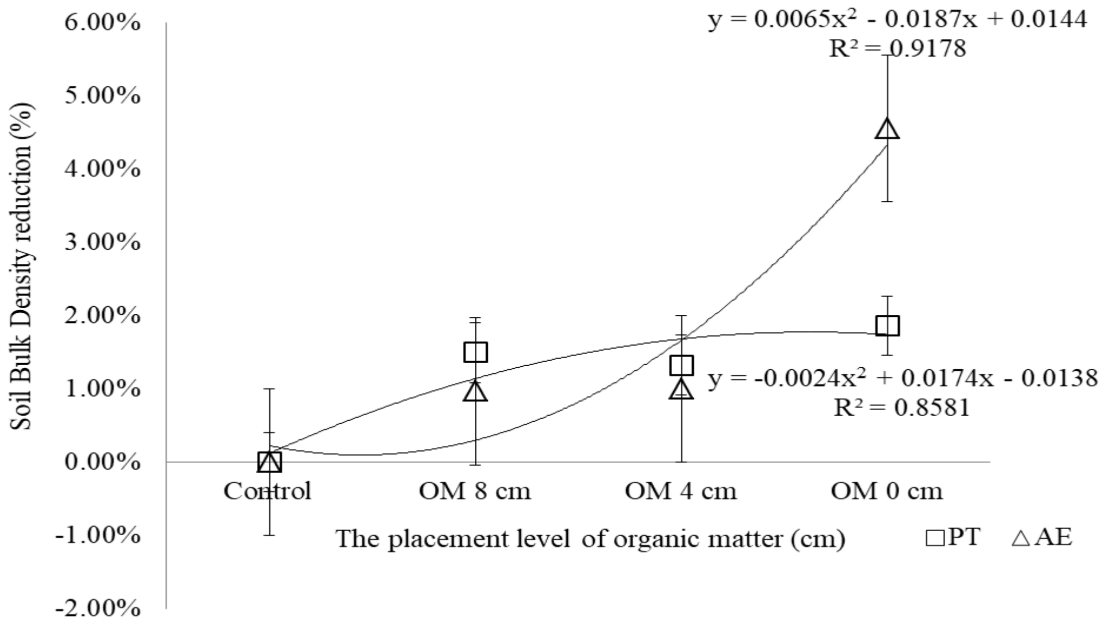

Figure 5. Relationship between the OM placing position and percentage reduction in soil bulk density

Moisture content effects

Bulk density increased with higher soil moisture levels, peaking at 1.89 g/cm³ and 1.78 g/cm³ under the Modified Proctor and Agricultural Engineering Tests, respectively, at a moisture content of 16.99% (**Figure 6**). The lowest bulk densities were recorded at 9.40% moisture content. These trends highlight the critical role of moisture content in soil compaction, with compaction effects exacerbated near or above the soil's plastic limit. Traffic under such conditions can cause significant structural damage (Soane and van Owerkerk, 1994).

Strategies to minimize compaction include restricting field operations to moisture levels below 0.9 times the plastic limit (Allmaras *et al.,* 1967). Although high soil moisture increases compaction risk, compaction under dry conditions has occasionally been associated with yield improvements (Chamen *et al.,* 2015). These contrasting outcomes underscore the importance of careful moisture management to balance risks and benefits.

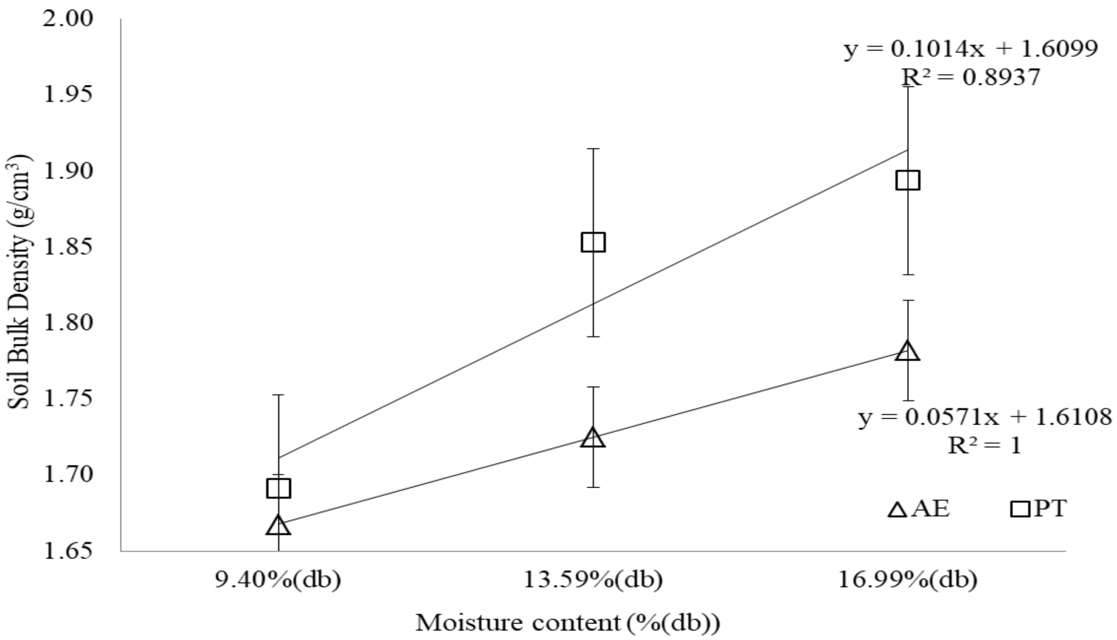

Figure 6. The effect of the level of moisture content on soil bulk density

Interaction of Factors

The interaction between compaction energy, OM placement, and moisture content significantly influenced bulk density. Surface–level OM placement (0 cm) consistently reduced bulk density across all compaction energy levels in the Agricultural Engineering Test. Similar trends were observed in the Modified Proctor Test, although differences between placement depths were less pronounced (**Table 1**), likely due to the layered compaction process in the Modified Proctor Test.

Moisture content and compaction energy had a notable influence on bulk density, with higher values of both factors resulting in increased bulk density. A marked reduction in bulk density was observed at a moisture content of 9.40%, even under identical compaction energy levels (**Table 2**). These findings align with Mosaddeghi *et al*. (2000), who reported that bulk density is significantly influenced by moisture content, OM levels, and compaction passes. Ohu et al. (2001) similarly demonstrated that OM addition mitigates soil compaction, contingent upon soil moisture conditions during compaction. OM placement at 0 cm consistently yielded lower bulk densities compared to deeper placements and controls (**Table 3).** Soane (1990) suggested that OM addition reduces soil stress while increasing moisture content, thereby affecting compactibility. OM incorporation altered soil properties such as Atterberg limits, maximum dry density, and optimal water content, improving water retention and reducing compaction susceptibility. Surface–level OM placement is particularly effective under simulated machinery traffic due to its direct interaction with applied forces.

Table 1. Soil bulk density (g/cm³) under different organic matter application levels and compaction energy levels

The placement level of organic matter	Agriculture Engineering Test					Modified Proctor Test				
	Compaction energies (ft–lb/ft³)					Compaction energies (ft–lb/ft³)				
	2475	7425	12375	56000	Mean	2475	7425	12375	56000	Mean
Control (No OM)	1.5413Aa	1.7196Bb	1.7708Bb	1.9821Bc	1.7534B	1.5833Aa	1.8175Ab	1.8567Ab	2.0788Ac	1.8341B
8 cm	1.5483Aa	1.6787Bb	1.7613Bc	1.9575ABd	1.7365B	1.5475Aa	1.7558Ab	1.8546Ac	2.0687Ad	1.8067AB
4 cm	1.5358Aa	1.6808Bb	1.7675Bc	1.9596ABd	1.7359B	1.5446Aa	1.7796Ab	1.8608Ac	2.0542Ad	1.8098AB
0 cm	1.4858Aa	1.6146Ab	1.6742Ab	1.9200Ac	1.6736A	1.5317Aa	1.7604Ab	1.8488Ac	2.0592Ad	1.8000A
Mean	1.5278a	1.6734b	1.7434c	1.9548d		1.5518a	1.7783b	1.8552c	2.0652d	
Mean	1.7249a					1.8126b				

Remark: Base on Multiple Range Test (DMRT) at a 95% significance level
1. Figures in the same column with the same uppercase letter are not significantly different.
2. Figures in the same row and block with the same lowercase letter are not significantly different.

Table 2. Soil bulk density (g/cm³) under different moisture contents and compaction energy levels

Moisture level	Agriculture Engineering Test					Modified Proctor Test				
	Compaction energies (ft–lb/ft³)					Compaction energies (ft–lb/ft³)				
	2475	7425	12375	56000	Mean	2475	7425	12375	56000	Mean
9.40%(db)	1.4972Aa	1.6003Ab	1.6653Ac	1.9081Ad	1.6677A	1.4544Aa	1.6197Ab	1.6784Ac	2.0119Ad	1.6911A
13.59%(db)	1.4931Aa	1.6888Bb	1.7513Bc	1.9672Bd	1.7251B	1.5494Ba	1.8041Bb	1.9078Bc	2.1506Bd	1.8530B
16.99%(db)	1.5931Ba	1.7313Bb	1.8137Cc	1.9891Bd	1.7818C	1.6516Ca	1.9113Cb	1.9794Cc	2.0339Ac	1.8938C
Mean	1.5278a	1.6734b	1.7434c	1.9548d		1.5518a	1.7783b	1.8552c	2.0652d	
Mean	1.7249a					1.8126b				

Remark: Base on Multiple Range Test (DMRT) at a 95% significance level
1. Figures in the same column with the same uppercase letter are not significantly different.
2. Figures in the same row and block with the same lowercase letter are not significantly different.

Table 3. Soil bulk density (g/cm³) under different moisture contents and organic matter application levels

Moisture level	Agriculture Engineering Test					Modified Proctor Test				
	Organic matter level (cm)					Organic matter level (cm)				
	Control (No OM)	8 cm	4 cm	0 cm	Mean	Control (No OM)	8 cm	4 cm	0 cm	Mean
9.40%(db)	1.6903Ab	1.6800Ab	1.6800Ab	1.6206Aa	1.6677A	1.6934Aa	1.6766Aa	1.6956Aa	1.6988Aa	1.6911A
13.59%(db)	1.7522ABb	1.7262Bab	1.7438Bb	1.6781ABa	1.7251B	1.8841Bb	1.8412Bab	1.8534Bab	1.8331Ba	1.8530B
16.99%(db)	1.8178Bb	1.8031Cb	1.7841Bb	1.7222Ba	1.7818C	1.9247Ba	1.9022Ca	1.8803Ba	1.8681Ba	1.8938C
Mean	1.7534b	1.7365b	1.7359b	1.6736a		1.8341b	1.8067ab	1.8098ab	1.8000a	
Mean	1.7249a					1.8126b				

Remark: Base on Multiple Range Test (DMRT) at a 95% significance level
1. Figures in the same column with the same uppercase letter are not significantly different.
2. Figures in the same row and block with the same lowercase letter are not significantly different.

CONCLUSION

This study underscores the critical role of organic matter (OM) placement, compaction energy, and moisture content in managing soil bulk density. Higher compaction energy consistently increased bulk density, highlighting the importance of optimizing machinery configurations and minimizing excessive compaction to protect soil structure. Moisture content significantly influenced bulk density, with the highest values occurring near the soil's plastic limit (16.99%db). To reduce compaction risks, field activities should be conducted when soil moisture levels are below the plastic limit. Surface–level OM placement (0 cm) proved the most effective in lowering bulk density, acting as a cushioning layer that redistributed mechanical forces from machinery traffic. These findings support the use of OM amendments and surface applications as practical strategies to enhance soil structure and reduce susceptibility to compaction. Future research should focus on field testing OM placement under varying soil textures and moisture conditions to develop sustainable soil management practices specific to different agricultural environments.

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