Exploring Innovative Proctor Apparatus for Comprehensive Assessment of Soil Compaction: Implications for Surface and Sub-surface Integrity

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Abstract

Soil compaction is a significant issue affecting agricultural productivity and soil health. This research paper delves into the development and application of an innovative Proctor apparatus, which represents a novel method for assessing both surface and sub-surface soil compaction. The study focuses on six different soil types: Clay, Clay loam, Silt, Silt loam, Silty clay, and Silty clay loam. Traditional methods for measuring soil compaction often focus on soil compatibility at surface conditions, limiting the comprehensive understanding of soil integrity. The soil samples were collected, prepared, and subjected to compaction using varying compaction efforts and moisture contents. The relationship between moisture content and dry density, known as the Proctor curve, was analyzed for each soil type. The results demonstrated that the maximum dry density (MDD) increased with increasing compaction effort, indicating denser packing of soil particles. The slope of the Proctor curve provided insights into the compaction characteristics of the soil, with steeper slopes indicating higher susceptibility to compaction. The research highlights the importance of understanding soil compaction and offers valuable information for optimizing agricultural machinery and practices to mitigate and sustain soil productivity. A comprehensive understanding of soil compatibility and compaction patterns was obtained by considering multiple depths and moisture contents. The improved Proctor apparatus proved to be an effective tool in assessing soil compaction, providing valuable insights for sustainable agricultural practices and soil management. This study contributes to the existing knowledge by expanding the understanding of soil degradation processes and the role of compaction, particularly in subsoil regions.

Keywords: soil compaction, subsoil, proctor test, sand, maximum dry density, critical water content.

1 Introduction

Throughout human history, soil has played a pivotal role in civilization and will remain vital in the future. Agriculture, of which soil is a founding member, owes its success to the soil. However, soil degradation, which results from natural and artificial phenomena, has risen. Intensive agriculture, which utilizes fertilizers, pesticides, and mechanized techniques, significantly contributes to artificial soil degradation, although it has increased production and productivity(Poesen (1981)). Although productivity has increased, there has been a significant decrease in the soil's ability to support biological activity. Soil compaction is a physical form of soil degradation that alters soil structure and impacts productivity (Mueller et al. (2013)). The extensive use of heavy machinery in modern farming practices is primarily responsible for soil compaction. Tractors have become increasingly heavy over the past seven decades, weighing around twenty tons from their three-ton weight (DeJong-Hughes et al. (2001)).

Soil compaction refers to the reorganization of soil grains that reduces void space, causing an increase in bulk density (Taylor (1971)). This process is accompanied by soil air displacement, soil structure alterations, and macroscopic increases in soil strength (Brunori et al. (1989)). Soil productivity is directly influenced by the structural arrangement of soil, which impacts crop aeration, water infiltration, water-holding capacity, and root penetration resistance (Al-Durrah and Bradford (1981)).

Soil physical, chemical, and biological processes are impacted by soil compaction, depending on the degree of compaction (DeJong-Hughes et al. (2001)). Soil compaction affects the top layer of soil (topsoil) and occurs at a certain depth (subsoil). Although soil compaction is a complex phenomenon, categorizing it into surface and subsurface compaction provides a clear understanding. While there are no established standards for distinguishing between surface and subsurface compaction, it is generally accepted that compaction occurs in the top 0-15 cm layer of soil and is considered surface compaction. In contrast, compaction below this layer is classified as subsurface compaction. Subsoil compaction is a significant problem because it is costly and difficult to remedy (Ren et al. (2015)). When subsoil compaction was carried out at a depth of 15 cm to a bulk density of 1.93 g/cc, a 38 % reduction in grain yield of wheat crops was reported (Patel et al. (2020)). The quantification of soil compaction is crucial to comprehend better and determine appropriate interventions for mitigating or controlling soil compaction. The Proctor test, developed by R.R. Proctor in the 1930s, offers a widely accepted procedure for studying the compatibility of disturbed soils across a range of soil water contents under a standardized dynamic load (Hillel (1980)). In contrast, civil engineers use the Proctor test to determine a soil sample's maximum dry density and optimal moisture content (Connelly et al. (2008)).

The Proctor test is a well-established method for measuring soil compaction, but it has limitations, particularly in its ability to evaluate soil at subsoil depths (Nazir and Sharma (2020)). This information can optimize agricultural machinery and practices to reduce soil compaction and sustain soil productivity (Kowalska (2016), Ahmadi and Ghaur (2015)). Previous studies aimed to correlate soil compactibility as determined by the Proctor test with easily accessible soil parameters (AragoÂna et al. (2000), Nhantumbo et al. (2006), Sulewska and Tymosiak (2018)). However, these studies only considered soil compatibility at different moisture levels and not the compaction behavior at subsoil regions. This research seeks to enhance the Proctor apparatus's ability to determine soil compatibility in surface and subsurface regions.

2 Material and methods

2.1 Sampling and preparation

The first step involves collecting and preparing a soil sample for a Proctor test. A location free from any debris, vegetation, or other objects is chosen to avoid sample contamination. To ensure better collection, soil samples are taken from various locations around AEC & RI. A soil sampler, including a shovel or an auger, is employed for collecting the soil sample. The soil sample is then sieved to eliminate extraneous material, such as rocks, roots, or other debris. The gathered soil sample is then dried in an oven at temperatures ranging from 105 °C to 110 °C until completely dry.

Soil samples were categorized into three groups based on their texture: sand, silt, and clay. The soil sample was then passed through a sieve shaker and test sieves to segregate the soil into different-sized fractions. The gravity separation method was also used to extract very fine clay fractions. The soil texture classification is based on the United States Department of Agriculture's (USDA) soil classification, and the test sieve sizes used for this purpose are tabulated (Table: 1).

Table 1: BSS test sieve size used for the textural classification of soil samples

Sl.No	Soil type	Particle sizes	Test sieve No. based on BSS
1.	Sand	>0.1 mm	60
2.	Silt	0.002 - 0.05	200
3.	Clay	<0.002	400

Table 2: Percentage of sand, silt, and clay used to prepare soil sample group

Sl.N	Soil type	Sample 1 (S_1)			Sample 2 (S_2)			Sample 3 (S_3)		
		sand (%)	silt (%)	clay (%)	sand (%)	silt (%)	clay (%)	sand (%)	silt (%)	clay (%)
1.	Sand	90	0	10	90	10	0	100	0	0
2.	Loamy sand	80	10	10	75	15	10	70	15	15
3.	Sandy loam	60	20	20	55	30	15	65	10	25
4.	Sandy clay loam	60	10	30	50	10	40	65	15	20
5.	Sandy clay	60	0	40	50	5	45	50	0	50
6.	Loam	35	25	30	25	30	35	30	30	40

2.2 Test sample preparation

To create the test sample, the soil is first sieved to obtain a fraction of the desired texture. Then sand, silt, and clay are mixed in the appropriate proportion according to the soil textural triangle. This process is carried out for six different types of soils, resulting in three sample groups for each type. (Table: 2).

2.3 Development of improved proctor test apparatus

The Proctor test determines the moisture content at which a soil sample will reach maximum density and the energy needed for compaction. There are two types of Proctor tests: the standard and the modified. The modified Proctor test differs from the standard test regarding compaction effort and range of moisture contents used. The modified compaction test involves a higher compaction effort level and a broader range of moisture contents, providing a more comprehensive understanding of the soil's overall compatibility and the energy required for compaction. Both tests determine the energy required for soil compaction and its overall compatibility.

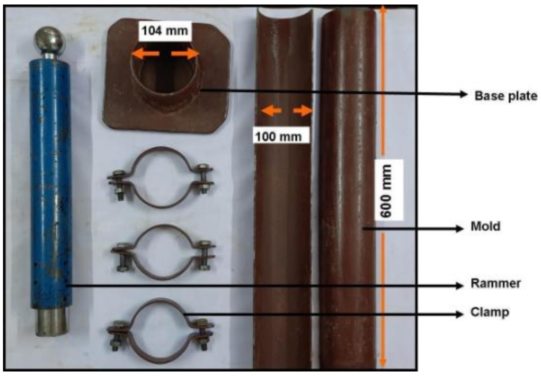


Figure 1: Improved proctor apparatus

To determine compaction at different regions (depth) of the soil layer improved proctor test apparatus was developed (Fig : 1). The improved proctor test apparatus contains a base plate, split mould, clamps, and rammer.

The apparatus consists of (i) a cylindrical metal mold of internal diameter 102 mm and an effective height of 600 mm, with a volume of 4.7 liters; (ii) a detachable base plate; and (iii) a 50 mm diameter rammer of weight 2.5 kg and a height of fall of 300 mm, moving in a metallic outer sleeve. (iv) detachable clamp.

The cylindrical mold used in this setup, similar to a standard Proctor test, is detachable and can be split into two halves. This feature enables the observation of compaction levels at different depths. Clamps are used to securely hold the split mould together during ramming. The ramming device applies reciprocating stress to the soil within the mould. Three rammers were fabricated with different masses, specifically 2.5, 3.5, and 4.5 kg. The base plate is 5 mm thick and welded with a hollow cylinder that is 104 mm in diameter to hold the cylindrical mould.

2.4 Design of experiment

The study was carried out on six distinct soil types: Clay, Clay loam, Silt, Silt loam, Silty clay, and Silty clay loam. To minimize experiment errors, three samples were collected for each soil type. Compaction was measured at three distinct depths and five different loading cycles, with pressure applied to assess compaction at various layers. The compaction at different depths was measured at different moisture contents, ranging from near saturation to low levels. Each experiment was repeated three times.

2.5 Laboratory test using improved proctor test apparatus

Approximately 3 kg of air-dried and pulverized soil is passed through a 4.75 mm sieve. The soil is then mixed with a reasonable amount of water to achieve a moisture content of around 4 % for coarse-grained soils and 10 % for fine-grained soils. The moist soil is covered with a wet cloth and allowed to rest for 15 to 30 minutes. Next, the detachable mold is fixed using a detachable clamp and cleaned and dried. The weight of the empty mold, along with the base plate but without the collar, is recorded, and the mold is attached to the base plate.

The soil is filled manually into the mould in three layers. The height of each layer is 20 cm for layer 3, 20 cm for layer 2, and 15 cm for layer 1. A 0.08 mm thick paper with a 10 cm diameter is placed after filling each layer to mark the boundary between the layers. Figure 2 illustrates the different layers of soil filling, identified by the paper inside the Proctor apparatus. After filling, the soil is compacted by applying the required blows of the rammer. The rammer is pulled in the sleeve to the maximum height and allowed to fall freely to compact the soil. The position of the rammer is changed each time to distribute the compactive energy evenly to the soil.

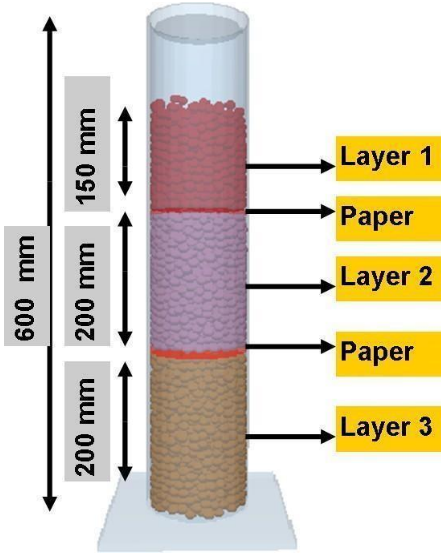


Figure 2: Soil Filling inside mould

The number of blows of the rammer was varied from 5 to 25 to observe the behavior of soil compaction at different pressures. The mechanical reduction of the volume of air spaces in the soil leads to an increase in soil density, referred to as soil compaction. Various methods for measuring soil compaction, such as penetration resistance, soil structure, water infiltration rate, plant growth, and bulk density, are expressed in g/cm^3 and directly measure soil compaction.

Bulk density measurement involves detaching the mold from the base plate and unscrewing the clamps to open the mold. The height and mass of each soil layer are then measured using a ruler and a weighing machine, respectively. An image in Fig: 3 depicts a soil sample of sand after being rammed at a 22% moisture content (dry basis) and subjected to a load of 10 cycles. The different layers of soil separated by paper (indicated by a red line) are visually observed, and the height of each layer is measured using a ruler. Once the layer heights are determined, each layer is isolated and weighed separately to determine the soil mass.

The bulk unit weighty γ (or bulk unit density) of the soil is obtained by dividing the weight of the soil W_s by the volume of the soil V.

$$Bulk\ density\ \gamma\ (g/cm^3) = \frac{mass\ of\ soil\ W_s\ ,g}{Volume\ of\ mold\ V,Cm^3} = \frac{W_s}{\pi r^2 h} \qquad (1)$$

W = mass of soil in the respective soil layer, g ; r = radius of mold, cm

h = height of soil in the respective soil layer, cm; Since π = 3.14 and r = 5 cm

$$Bulk\ density\ \gamma\ (g/cm^3)\ =\ \frac{W_s}{15.7\ h} \qquad (2)$$

A representative sample of the compacted soil is taken from the mould and its water content w% is determined using a moisture meter. The dry density γ_d (or dry unit weight) of the soil is obtained as

$$\gamma_d\ =\ \frac{\gamma}{1+\frac{w}{100}} \qquad (3)$$

The soil is broken by hand and remixed with increased water to raise its water content by 2 to 4%. After maturing, the soil is compacted as previously described, and the corresponding dry density (γd) and water content (W%) are determined. The test is repeated with at least six different water contents. The weight of the compacted soil indicates whether the number of readings is adequate since it first increases with an increase in water content up to a specific value and then decreases. The test must be conducted to establish this peak. The 'compaction curve,' the water content vs. dry density curve, is plotted. The graph determines the optimum water content and the corresponding maximum dry density (or dry unit weight). This test was adopted based on a standard test by the AASHO (American Association of State Highway Officials), also known as AASHO Test.

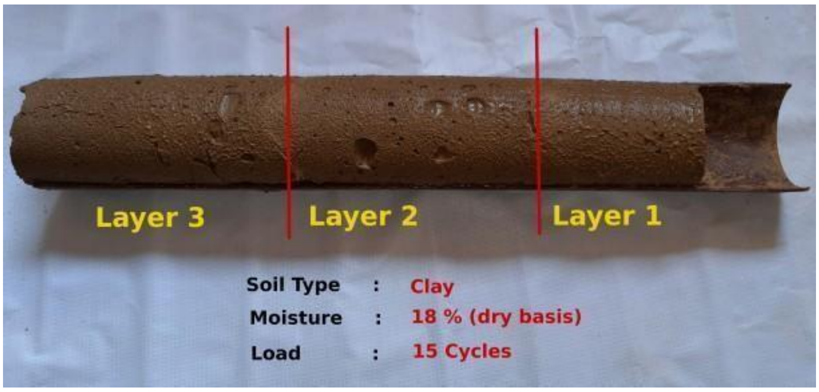


Figure 3: Soil sample of Clay after being subjected to ramming

2.5 Calculating the Force and Pressure Exerted on Soil

The objective of the experiment is to examine how the impact force from a rammer affects a soil sample. The force calculation is determined using Newton's second law of motion, which is expressed as:

$$F = m \, X \, a \tag{4}$$

F = force, N ; m = mass of an object, Kg ; a = acceleration m/s^2

Hence,

$$\text{Force of rammer } (F_r) = \text{mass of rammer X acceleration}$$

Pressure applied by the 50.8 mm diameter rammer of circular cross-section is given by

$$Pressure\ of\ Rammer\ (P_r)\ =\ \frac{Force\ (F),\ N}{Unit\ area\ (A),\ m^2} \qquad (5)$$

$$Cross\ -\ area\ of\ rammer\ (A)\ =\ \frac{\pi}{4}d^2\ =\ 0.785\ *\ (0.0508)^2 \qquad (6)$$

$$A = 0.785 * 0.00258 = 0.0020253\ m^2$$

The time taken for the rammer to drop from a height of 30 cm is less than 1 second, hence neglecting the time the force for Different rammer is computed.

For Rammer 1 of mass 2.5 Kg

$$F_{r1}\ =\ 2.5\ KgX\ 9.81\ m/s^2\ =\ 24.525\ N$$

$$P_{r1}\ =\frac{24.525}{0.0020253}\ = 11945.932\ N/cm^2\ =\ 11.9\ KN/m^2$$

For Rammer 2 of mass 3.5 Kg

$$F_{r2}\ =\ 3.5\ KgX\ 9.81\ m/s^2\ =\ 34.335\ N$$

$$P_{r1}\ =\frac{34.335}{0.0020253}\ =\ 16953.043\ N/cm^2\ =\ 16.95\ KN/m^2$$

For Rammer 3 of mass 4.5 Kg

$$F_{r3}\ =\ 4.5\ KgX\ 9.81\ m/s^2\ =\ 44.145\ N$$

$$P_{r3}\ =\ \frac{44.145}{0.0020253}\ =\ 21796.77085\ N/cm^2\ =\ 21.796\ KN/m^2$$

The principle of superposition of forces are employed to convert the cyclic force applied by the rammer at different times to a single unit of force. This is necessary since the rammer is dropped from the same height but at different times during the experiment.

The principle of superposition of forces states that the total force acting on a particle is equal to the algebraic sum of the individual forces acting on that particle. It means that if several forces act on a particle simultaneously, adding all the individual forces together can calculate the resultant force.

If five forces F_1, F_2, F_3, F_4, and F_5 act on a body, the net force is given by.

$$Fnet = F1 + F2 + F3 + F4 + F5 \qquad (7)$$

Therefore, if a rammer of the same mass dropped five times (5 force) from the same direction and height, the net force the rammer applies is the vector sum of the individual forces.

$$F5cycle = \sum_{i=1}^{i=5} Fr1_i = Fr1_1 + Fr1_2 + Fr1_3 + Fr1_4 + Fr1_5$$

$$F_{5cycle} = 24.525 + 24.525 + 24.525 + 24.525 + 24.525 = 122.625 \text{ N}$$

Sl.No	Rammer 1 (2.5 Kg)	Rammer 2 (3.5 Kg)	Rammer 3 (4.5 Kg)
1.	$F_{5cycle} = \sum F_{r1} = 122.625\,N$	$F_{5cycle} = \sum F_{r2} = 171.675\,N$	$F_{5cycle} = \sum F_{r3} = 220.725\,N$
2.	$F_{10cycle} = \sum F_{r1} = 245.250\,N$	$F_{10cycle} = \sum F_{r2} = 343.350\,N$	$F_{10cycle} = \sum F_{r3} = 441.450\,N$
3.	$F_{15cycle} = \sum F_{r1} = 367.875\,N$	$F_{15cycle} = \sum F_{r2} = 515.025\,N$	$F_{15cycle} = \sum F_{r3} = 662.175\,N$
4.	$F_{20cycle} = \sum F_{r1} = 490.500\,N$	$F_{20cycle} = \sum F_{r2} = 686.700\,N$	$F_{20cycle} = \sum F_{r3} = 882.900\,N$
5.	$F_{25cycle} = \sum F_{r1} = 613.125\,N$	$F_{25cycle} = \sum F_{r2} = 858.375\,N$	$F_{25cycle} = \sum F_{r3} = 1103.625\,N$

3 Result and discussion

Fig: 5, 6, 7, 8, 9, 10 is the graphical representation that illustrates the relationship between the moisture content and dry density of soil during compaction. It is also known as the Proctor curve or compaction curve. The Proctor curve is derived from the results of Proctor compaction tests, which are widely conducted to evaluate the compaction characteristics of soils (Wagner et al. (1994), Arago na et al. (2000), Connelly et al. (2008)).

The curve typically exhibits a distinctive shape, starting with low dry density at low moisture content, gradually increasing to a peak value, and then decreasing as the moisture content further increases. The peak of the curve represents the maximum dry density (MDD) that can be achieved for a particular soil. The moisture corresponds to maximum dry density is the soil's critical moisture content (CMC). After the CWC point, the dry density decreases with the increased moisture content.

Within each plot, it was observed that the maximum dry density (MDD) also increased as the compaction effort increased. This can be attributed to reduced air voids between soil particles, leading to denser packing and an overall increase in soil density. The slope of the curve representing this relationship provides valuable insights into the compaction characteristics of the soil (Baldwin and Butler (1985), Reddy and Jagadish (1993)).

A steeper slope indicates that the soil is more susceptible to compaction, as it experiences a significant increase in density with relatively small increments in compaction effort (Paxton et al. (2002), Horpibulsuk et al. (2008), Gurtug et al. (2018)). This suggests that the soil particles readily rearrange and compact under applied forces, resulting in higher densities. Soils with steep slopes are considered easily compactable.

Conversely, a shallower slope implies that the soil is more resistant to compaction, as it requires larger increments in compaction effort to achieve notable increases in density. This indicates that the soil particles are more stable and less prone to rearrangement under applied forces. Soils with shallow slopes exhibit a higher level of resistance to compaction (Ray and Chapman (1954), Yaldo (1999), Gurtug et al. (2018)).

Upon examining the data, we have discovered, The soil types, from the highest to the lowest maximum dry density, are silt loam, clay loam, silty clay loam, silty clay, silt, and clay. Silt loam, being a soil type with a relatively higher proportion of silt particles, exhibits the highest maximum dry density among the given samples (Gupta et al. (1989),Richard et al. (2001),Horpibulsuk et al. (2008)). Silt particles have a moderate size range and possess good compaction characteristics. They can pack relatively closely together, resulting in higher dry density values (Russo et al. (2007)). clay loam comes next with a slightly lower maximum dry density. Clay loam contains a greater proportion of clay particles compared to silt loam. Clay particles are smaller and have a greater tendency to agglomerate, leading to reduced compaction efficiency and lower maximum dry density (Lambe (1958), Bulmer and Simpson (2005), Kodikara et al. (2018)).

The following soil types, silty clay loam, silty clay, silt, and clay, all exhibit further decreases in maximum dry density. Silty clay loam contains a higher proportion of clay, while silty clay has even more clay content. These soils tend to have a higher proportion of fine particles, such as clay and silt, with limited compaction potential. Consequently, their maximum dry densities are lower than silt loam and clay loam.

Finally, silt and clay exhibit the lowest maximum dry densities. Silt particles are even finer than clay particles and offer less resistance to compaction, resulting in lower maximum dry densities. Clay, with its small particle size and strong, cohesive properties, poses significant challenges to achieving high compaction densities and therefore has the lowest maximum dry density among the tested soil types (Hansbo (1957), Young and Gilmore (1976), Yang et al. (2008)).

Soil compaction is influenced by various factors, including soil type, compaction effort, and the presence of contaminants or additives Greacen and Sands (1980), Batey (2009), Shah et al. (2017).

Soil compaction can also be exacerbated by low organic matter, animal trampling, engine vibrations, and tillage at high moisture contents Shah et al. (2017). The presence of contaminants such as petroleum hydrocarbons can affect the maximum dry density and Atterberg limits of soil Pandey et al. (2021). Compaction effort can affect the optimum moisture content and maximum dry density of soil. Higher compaction effort results in lower optimum moisture content and higher maximum dry density Kozlowski (1999), Pentoś et al. (2021).

Soil compaction has negative effects on plant growth and yield, particularly in heavily used recreation areas, construction sites, urban areas, timber harvesting sites, fruit orchards, agroforestry systems, and tree nurseries (Taylor (1971), Pentoś et al. (2021)). Soil compaction can also affect the soil microbial community, favoring organisms capable of tolerating anoxic conditions Schnurr-Pütz et al. (2006).

The critical moisture content is the moisture content at which soil is more vulnerable and attains maximum compaction (Proctor (1933), Modi (2010)). The difference in critical moisture content for the different soil types *viz.*, clay, clay loam, silt, silt loam, silty clay, and silty clay loam can be attributed to their physical properties and composition variations.

Table 3: Critical Moisture Content (CMC) in the percentage of the dry basis for Different soil at Different compaction effort

Soil Type	**Rammer 1 (2.5kg)**	**Rammer 2 (3.5kg)**	**Rammer 3 (4.5kg)**
Silt	15 %	13 %	12 %
Silty clay	20 %	15 %	13 %
Silty clay loam	18 %	16 %	13 %
Silty loam	16 %	16 %	14 %
Clay	23 %	21 %	19 %
Clay loam	18 %	16 %	15 %

Table 4: Maximum Dry Density (MDD) in g/cc for Different soil at Different compaction effort

Soil Type	Rammer 1 (2.5kg)			Rammer 2 (3.5kg)			Rammer 3 (4.5kg)		
	Top	Middle	Bottom	Top	Middle	Bottom	Top	Middle	Bottom
Silt	1.691	1.595	1.500	1.778	1.670	1.522	1.894	1.791	1.542
Silty clay	1.780	1.642	1.526	1.900	1.780	1.567	2.113	1.912	1.612
Silty clay loam	1.881	1.772	1.547	2.114	1.890	1.569	2.239	2.119	1.592
Silty loam	1.956	1.827	1.560	2.211	1.944	1.588	2.413	2.195	1.609
Clay	1.654	1.517	1.490	1.822	1.715	1.501	1.941	1.860	1.529
Clay loam	1.924	1.806	1.511	2.149	1.942	1.540	2.316	2.119	1.576

Soil texture refers to the relative proportions of sand, silt, and clay particles in soil. Clay soils with a higher proportion of fine particles tend to have higher critical moisture content (Millán-Romero and Millan-Paramo (2020)). Clay particles have a greater surface area and stronger cohesive forces, requiring more water for compaction (Mante et al. (2022)). On the other hand, sandy soils, which have a higher proportion of coarse particles, generally have lower optimum moisture content (Towner (1973), Nhantumbo et al. (2006)).

Table 3 shows the relation between compaction effort and CWC. As the compaction effort increases, the CWC decreases. As the compaction effort increases, the soil particles become more closely packed together, and the air voids between the soil particles are reduced ((Tinjum et al., 1997), Oluyemi-Ayibiowu (2019)). This reduction in air voids means that less water is required to achieve the same level of compaction, decreasing the CWC (Fondjo et al. (2021), Nwaiwu et al. (2021)). The same effect is observed in all six types of soil.

The densification of the soil particles under compaction increases the interparticle contact forces, reducing the ability of water to lubricate and facilitate the movement of soil particles (Olinic and Olinic (2014),Millán-Romero and Millan-Paramo (2020)). Hence, as the compaction effort increases, the soil particles become more tightly packed, and the water required to achieve maximum dry density decreases (Kirkegaard et al. (1993)). Soils with higher CWC are generally considered less susceptible to compaction, while soils with lower CWC are more susceptible to compaction (Chung and Chu (2022)).

The result indicates (Tables: 3 and 4) that increasing the compactive effort decreases the CWC and also increases MDD. Higher compactive effort and lower moisture content lead to greater particle rearrangement and interlocking, resulting in a denser soil structure (Bhat et al. (2015), Chung and Chu (2022)). However, the effect of compaction on MDD is not always straightforward, and there may be cases where increasing the compactive effort or decreasing the moisture content does not increase MDD (Hassan et al. (2017)). For example, if the soil particles are already densely packed, further compaction may not significantly increase density. Similarly, if the soil is too dry, it may become too stiff and resist further compaction, resulting in a lower MDD (Ren et al. (2015)).

The compaction effort exerted during soil compaction significantly determines the soil's maximum dry density (MDD) (Ekwue and Seepersad (2015)). The experimental investigation involved varying the compaction effort while measuring the corresponding MDD for a specific soil type (Yang et al. (2008)). The compaction efforts were controlled by altering factors such as the number of compaction passes, compactor weight, or energy input. The results demonstrated a clear relationship between the compaction effort and MDD (Azmi et al. (2017),Alharthi and Hanna (2019)).

As the compaction effort increased, the MDD also increased. This trend can be attributed to the increased energy input and compaction forces applied to the soil(Alibrahim and Uygar (2021)). With higher compaction efforts, the soil particles experience greater compaction and rearrangement, resulting in higher densities. This phenomenon is consistent with the principles of soil mechanics and compaction theory (Birle et al. (2008)). Additionally, the rate at which the MDD increased with increasing compaction effort varied depending on the soil type (Spagnoli and Shimobe (2020)).

For cohesive soils, such as clays, the increase in MDD was relatively steep initially, but it gradually approached a plateau. This behavior is due to the higher water content and plasticity of cohesive soils, which allows for greater compaction and rearrangement of particles (Hafez et al. (2010)). However, there is a limit to the achievable density due to the cohesive nature of these soils.

On the other hand, granular soils, such as sands, exhibited a more gradual increase in MDD with increasing compaction effort (Weidinger and Ge (2009)). Granular soils have lower plasticity and are less prone to rearrangement, resulting in a slower density increase rate than cohesive soils (Mirzaii and Yasrobi (2012)). However, these soils have higher inherent density due to their grain characteristics, which leads to higher MDD values overall.

Several theories explain the compaction process and its relationship to specific conditions and soil types. Proctor’s Capillarity theory emphasizes the role of water in compaction, with water expulsion causing soil particles to come closer together. The lubrication theory analyzes fluid behavior in narrow gaps and thin films (Proctor (1933)). Lambe’s physicochemical theory considers the interaction between soil particles and the water film, influencing cohesive soil properties (Lambe (1959)). The elastic compaction theory applies to low to moderate stress levels, where soil particles behave like elastic spheres. This theory suggests that compaction occurs primarily through particle rearrangement without significant particle crushing or fracture (Teeuw (1971),Li et al. (2019)). On the other hand, the plastic theory expands upon the elastic theory by considering soil behavior beyond the elastic range (Michrafy et al. (2002),Frenning (2007)). Thixotropy theory recognizes the time-dependent nature of soil compaction. Some soils exhibit thixotropic behavior, transitioning from a solid-like state to a fluid-like state when subjected to external forces such as compaction machinery(Nalezny and Li (1967),Rahman et al. (2014)). When the forces are removed, the soil particles regain their solid state, resulting in compaction.

The electrostatic theory of compaction focuses on the influence of electrostatic forces between soil particles. This theory is particularly significant in fine-grained soils where clay particles carry electrical charges. These charges can promote particle rearrangement and compaction when external forces are applied (Horn et al. (1963)Osipov (2015)). The contact theory emphasizes the direct contact between soil particles during compaction. As external forces are applied, the increased contact points between particles lead to rearrangement and compaction (Olson (1963), Kim and Chun (2016)). Based on this theory, interparticle friction and interlocking mechanisms are crucial for compaction.

The swelling and shrinkage theory comes into play for soils that undergo significant volume changes due to moisture content fluctuations, such as expansive clays (Day (1994), Mishra et al. (2008), Kodikara et al. (2018)). The compaction process in these soils involves reducing void spaces through particle rearrangement and water expulsion.

Lambe's physicochemical theory becomes particularly relevant in cohesive soils, emphasizing the influence of pore water chemistry and electrochemical forces on the soil's mechanical behavior (Suedkamp (1971)). This theory focuses on the interaction between soil particles and the water film surrounding them, taking into account electrochemical forces and attractive forces between particles (Lambe (1958), Warkentin et al. (1958)). Clay loam soil, which combines clay and loam properties, can also be analyzed using Lambe's theory, as it considers the particle-water interaction, which is important regardless of the soil's textural composition (Kurucuk et al. (2008)).

Silt soil, characterized by fine particles with low cohesion, aligns well with the elastic compaction theory (Bodman et al. (1965)). This theory examines the temporary deformation of particles under external forces, which is a key mechanism in the compaction behavior of silt soils where particle rearrangement plays a significant role (Garcia-Bengochea et al. (1979), Ma et al. (2016)). Similarly, with its intermediate characteristics between silty and loamy soils, silt loam soil can be effectively studied using the elastic theory as it also focuses on particle deformation and rearrangement during compaction (Garcia-Bengochea et al. (1979), Wiermann et al. (2000), Berney et al. (2003)).

Silts clay soil, a combination of clay and silt, benefits from the application of both Lambe's physicochemical theory and Proctor's Capillarity theory (Winterkorn (1958), de Magistris et al. (1998)). Lambe's theory provides insights into the interaction between soil particles and the water film, considering electrochemical and attractive forces (Lambe (1960)). Meanwhile, Proctor's theory highlights the role of water in compaction, where the expulsion of water brings the particles closer together (Proctor (1933)). Silty clay loam soil, with its composition of clay, silt, and loam properties, similarly requires the combined application of Lambe's physicochemical theory and Proctor's Capillarity theory for a comprehensive understanding of its compaction behavior.

Optimal compaction effort promotes healthy plant growth and maximizes crop yield. Excessive compaction can lead to increased soil bulk density, reduced soil porosity, and decreased water infiltration rates (Gupta and Allmaras (1987)). These factors can impede root penetration, limit nutrient availability, and hinder the exchange of gases necessary for plant respiration (Allmaras et al. (1988)). Consequently, crops grown in compacted soils may experience stunted growth, reduced productivity, and increased vulnerability to environmental stresses (Taylor (1971), Raper and Mac Kirby (2006)).

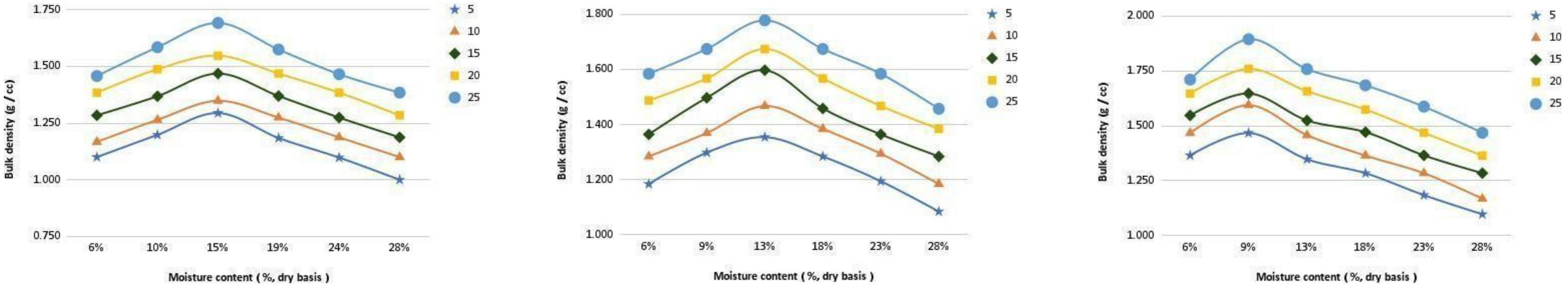
Farmers and agricultural professionals can make informed decisions regarding soil management and cultivation practices by understanding the relationship between compaction effort and maximum dry density. They can optimize compaction efforts during field preparation, taking into account factors such as soil type, crop requirements, and prevailing weather conditions (Godlewska et al. (2020), Badalíková (2010)).

One of the primary reasons for measuring compaction in the sub-surface region is to evaluate the soil's physical properties and its ability to support plant growth for a long time. Farmers can design appropriate drainage systems, irrigation practices, and soil amendments by quantifying compaction levels to improve water infiltration and retention. This enables efficient water use, prevents waterlogging or drought stress, and ultimately enhances crop yield and quality (Janssen and van der Weert (1977)).

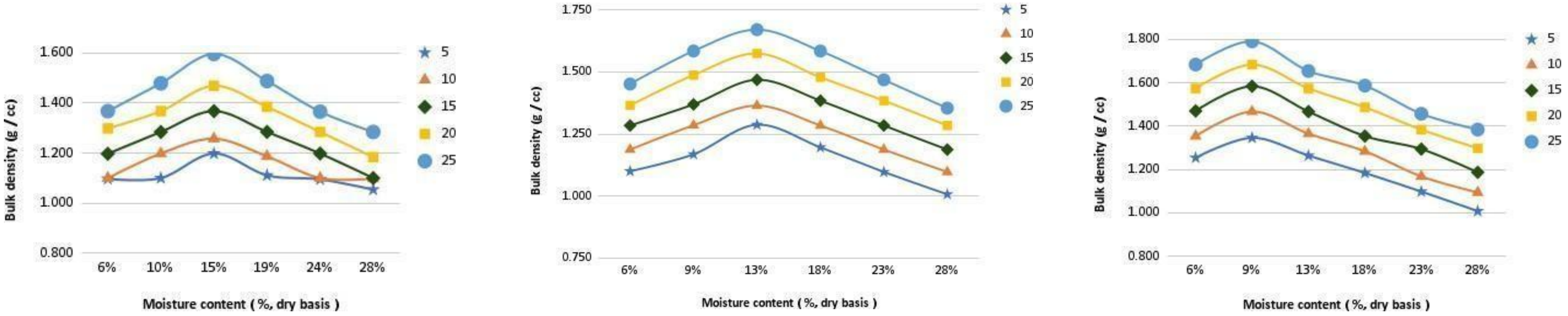
Compacted soils are more challenging to till and cultivate, resulting in increased fuel consumption, machinery wear and tear, and reduced overall efficiency (McGarry (2003)). Farmers can adjust their tillage practices, implement controlled traffic systems, or adopt precision agriculture technologies to minimize compaction and optimize machinery operations by understanding the compaction levels(Lipiec and Stępniewski (1995)). The soil is more vulnerable to being compacted at CMC than at different moisture. Hence selecting the correct moisture content is important for the ease of tillage operations and for reducing soil degradation.

Rammer 1 (2.5 Kg) **Rammer 2 (2.5 Kg)** **Rammer 3 (3.5 Kg)**

Top Layer



Middle Layer



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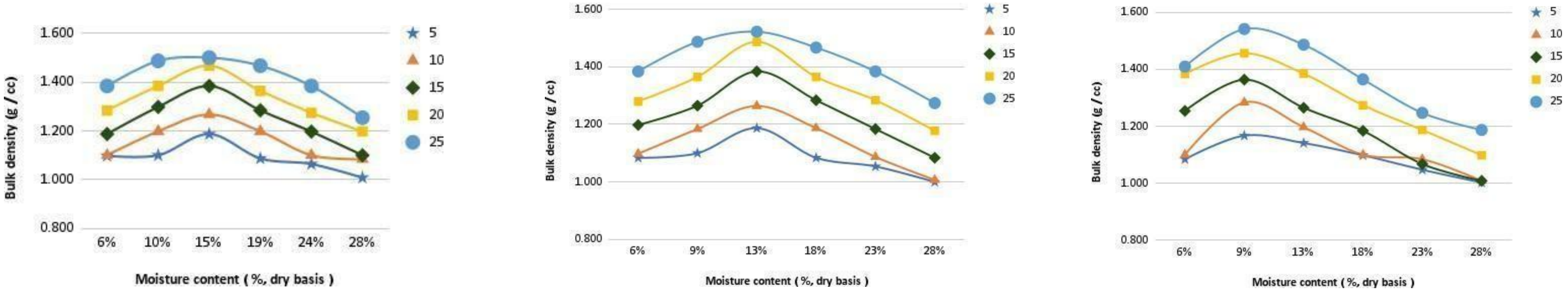


Table 5: Silt soil moisture dry density (compaction) curve

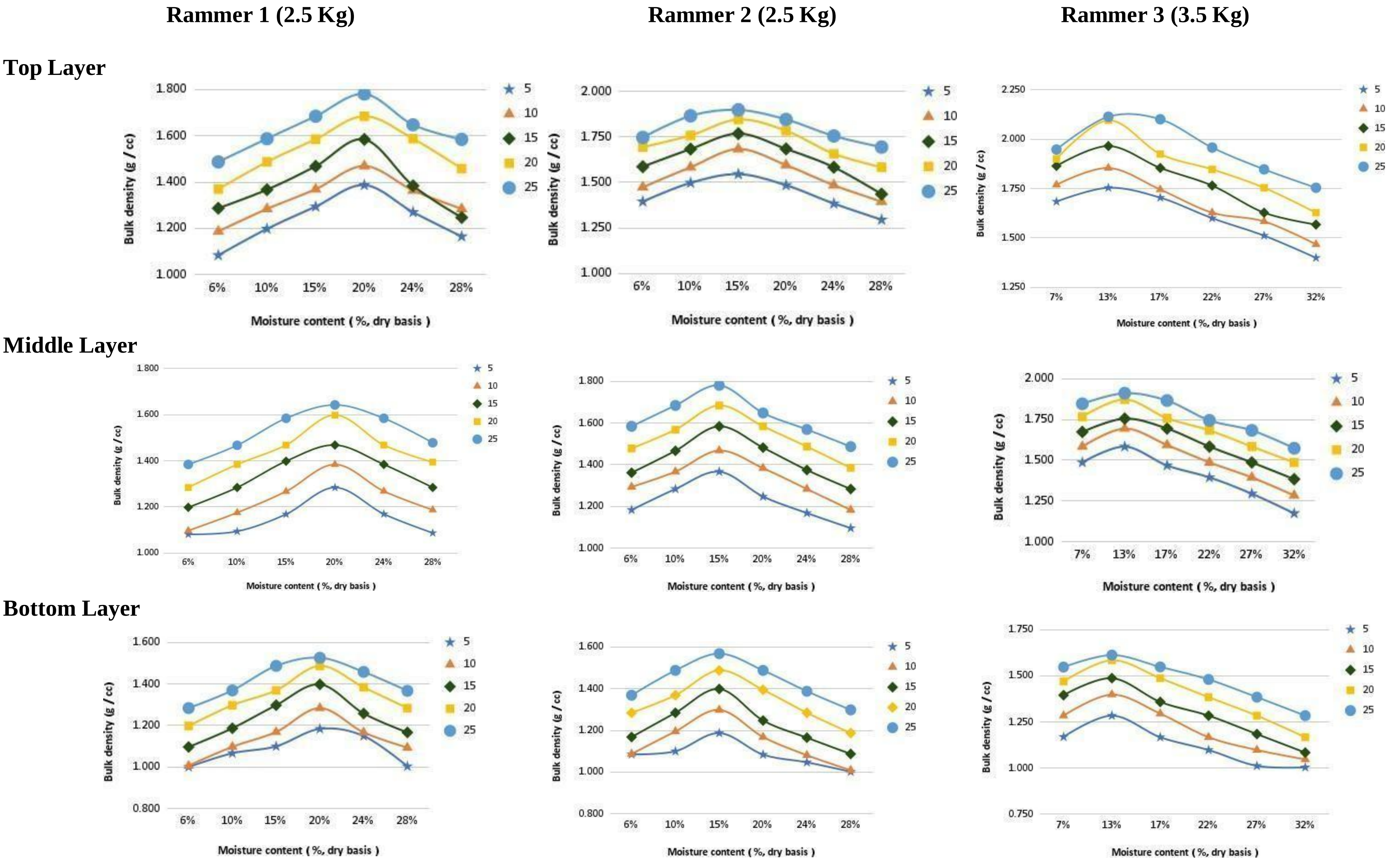
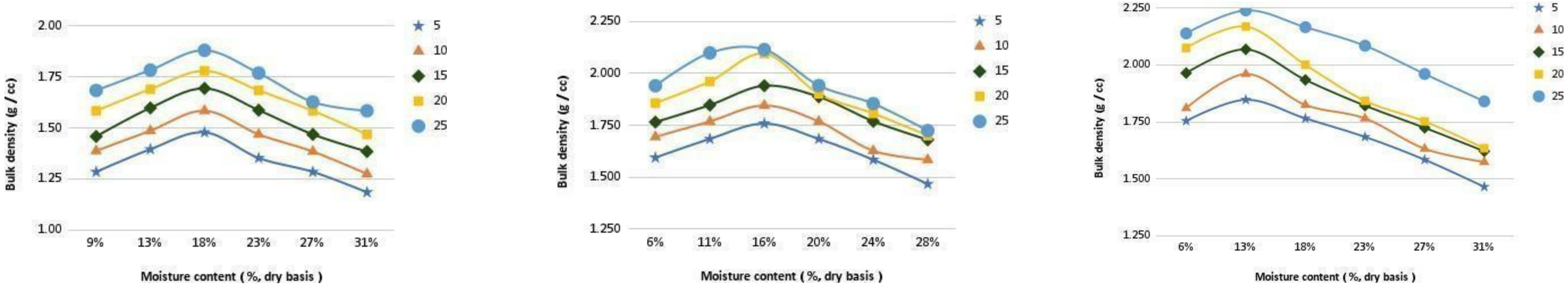


Table 6: Silty clay soil moisture dry density (compaction) curve

Rammer 1 (2.5 Kg) **Rammer 2 (2.5 Kg)** **Rammer 3 (3.5 Kg)**

Top Layer



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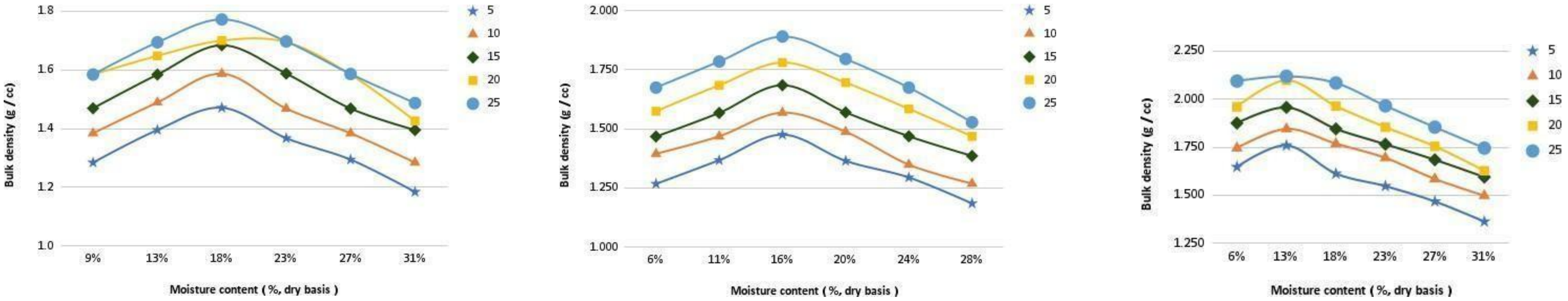


Bottom Layer

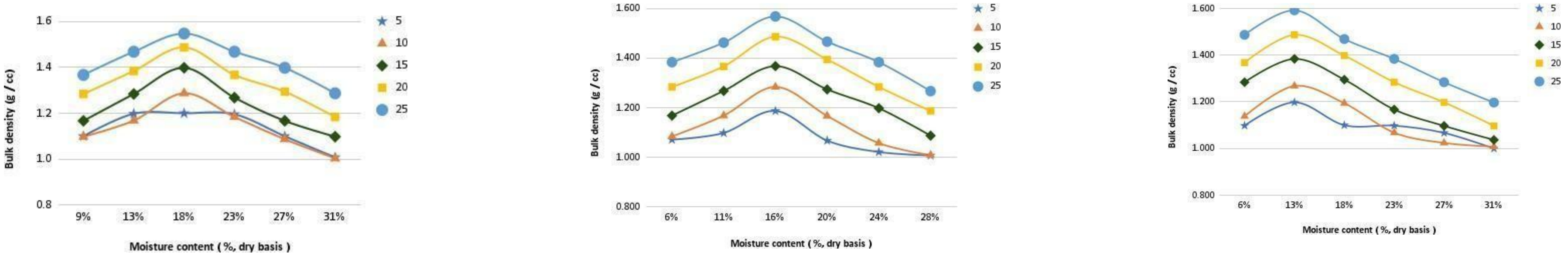


Table 7: Silty clay loam moisture dry density (compaction) curve

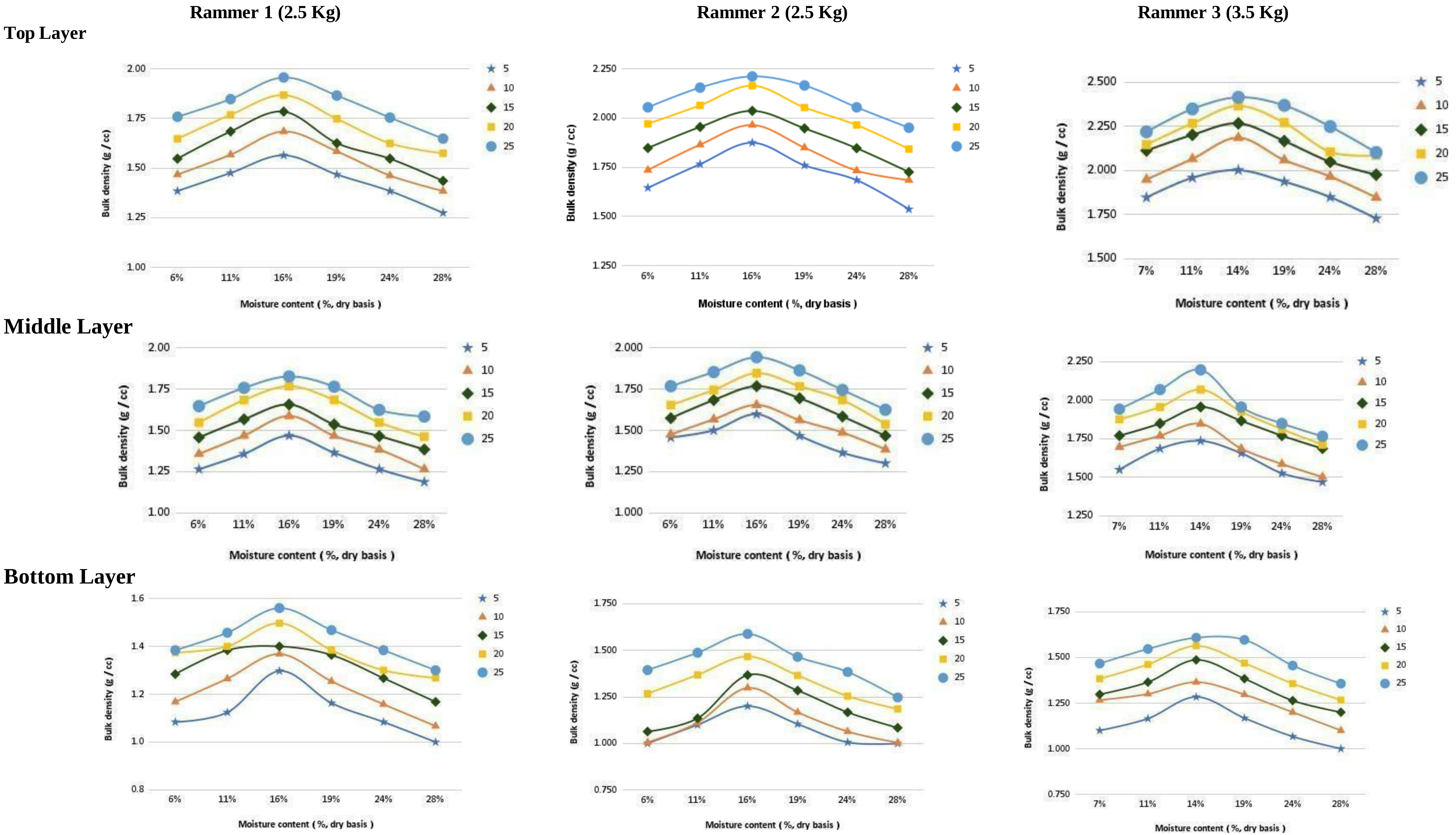
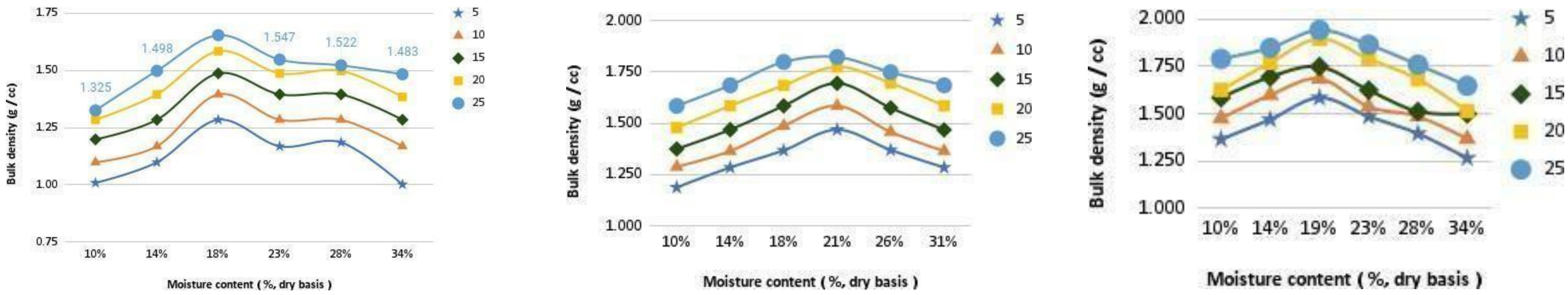


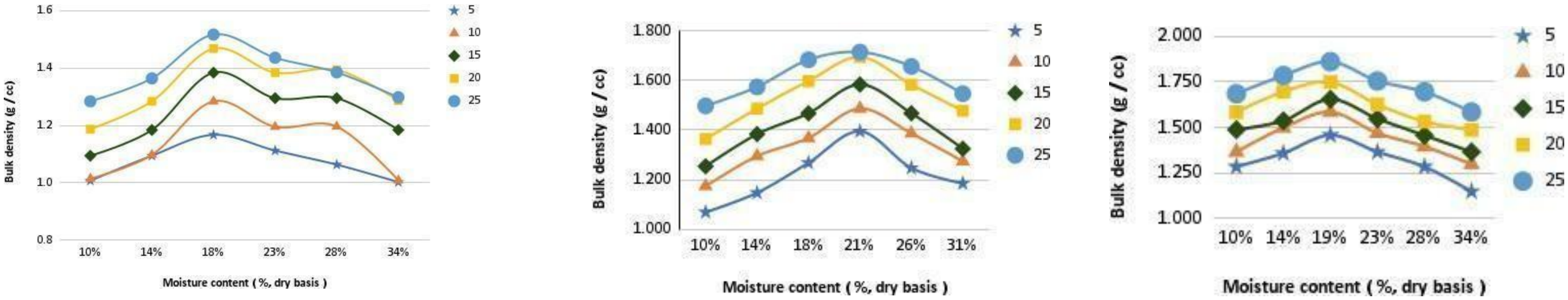
Table 8: Silty loam soil moisture dry density (compaction) curve

Rammer 1 (2.5 Kg) **Rammer 2 (2.5 Kg)** **Rammer 3 (3.5 Kg)**

Top Layer



Middle Layer



Bottom Layer

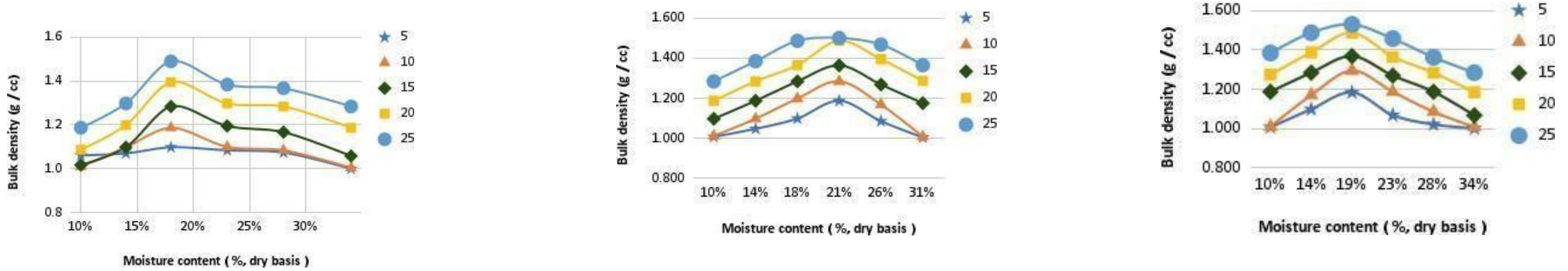
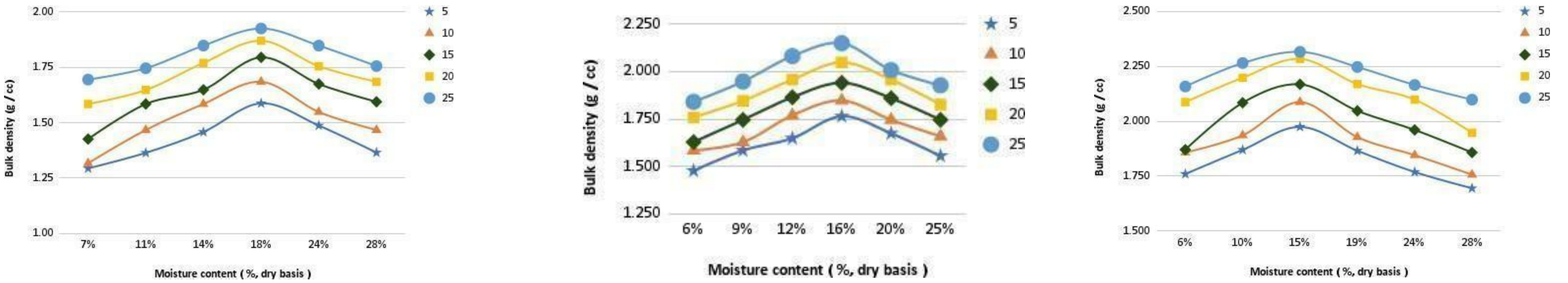


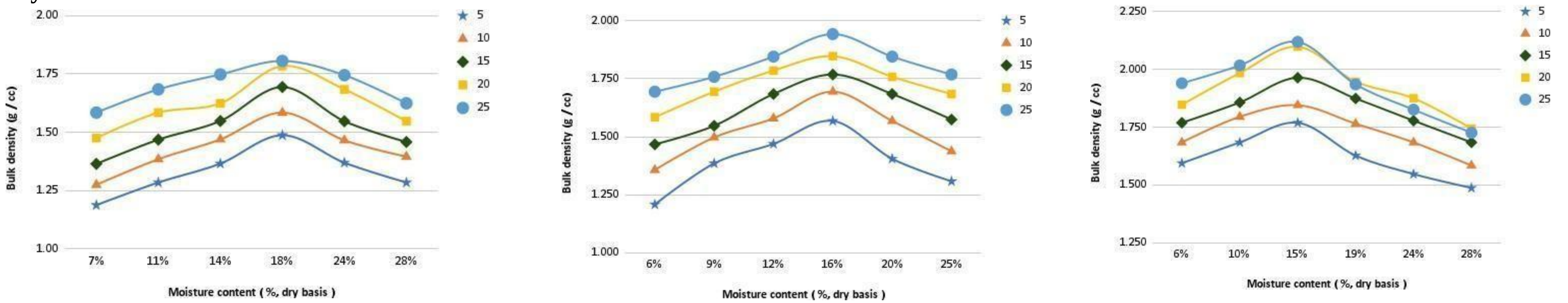
Table 9: Clay soil moisture dry density (compaction) curve

Rammer 1 (2.5 Kg) **Rammer 2 (2.5 Kg)** **Rammer 3 (3.5 Kg)**

Top Layer



Middle Layer



Bottom Layer

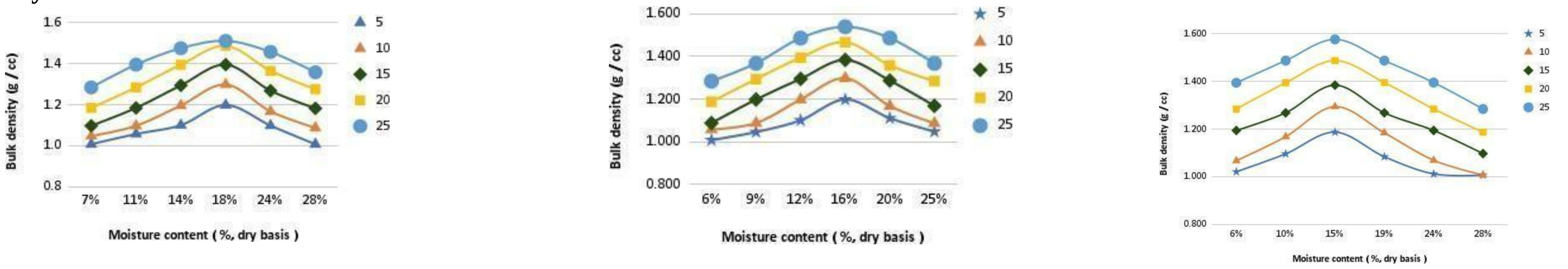


Table 10: Clay loamy soil moisture dry density (compaction) curve

4 Conclusion

This study has emphasized the significance of soil compaction in agriculture and highlighted the need to consider both surface and subsurface regions for a comprehensive understanding of soil compatibility. The findings contribute to the knowledge base of soil degradation processes and provide valuable insights for sustainable agricultural practices and management. This research demonstrated that intensive agriculture, characterized by the increased use of heavy machinery, leads to soil compaction. The compaction behavior varied across different soil types, with clay and silty clay soils exhibiting higher compaction levels than silt and loam soils. By examining compaction at multiple depths and moisture contents, this study uncovered the complex relationship between soil compaction and its impact on the soil's physical, chemical, and biological processes.

The improved Proctor apparatus in this research proved to be a reliable tool for assessing soil compaction in surface and subsoil regions. Its ability to determine compatibility across different soil water contents under standardized dynamic loads provided valuable data for understanding compaction behavior. This information can be used to develop targeted strategies for soil management, including appropriate tillage practices, crop rotation, and the use of cover crops to mitigate soil compaction and improve soil health. The findings of this study have practical implications for agriculture. Farmers and land managers can utilize this knowledge to make informed decisions regarding field operations and soil conservation practices. Implementing precision agriculture techniques, such as variable-rate application of inputs, can help minimize compaction by reducing unnecessary traffic and optimizing soil conditions. Conservation practices, such as contour plowing, strip-till, or no-till farming, can also preserve soil structure and minimize compaction risks. Future research should explore additional soil parameters and their relationship with compaction behavior to advance our understanding of soil compaction and its implications for agriculture. Additionally, long-term studies monitoring the effects of different soil management practices on soil compaction and crop productivity would provide valuable insights for sustainable farming systems.

5 Conflicts of Interest

I declare that we have no conflicts of interest related to the research presented in this paper. This includes any financial, personal, or professional relationships that could be perceived as influencing the objectivity, interpretation, or presentation of the research findings. There are no financial relationships or affiliations with any organizations or entities that could bias the research or its outcomes. Additionally, there are no patent applications, patents, or any other financial or non-financial competing interests related to the research described in this paper.

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