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Impacts of soil physical and mechanical behaviors under different tillage depths for agrotechnical operation in Bukito, Sidama, Ethiopia

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Tillage operation aims to create a favorable environment for seed germination of agricultural crop production practices. Physio-mechanical properties of soil directly affecting soil behaviors and determinants in initial conditions affecting soil failure. An absence in understanding how soil physio-mechanical properties affect agrotechnical operations at different tillage depths, especially in study area, and lacks insights into their associations and practical implications for optimizing tillage and soil health. This study presents an experimental investigation of the physio-mechanical properties of agricultural soil in Bukito Kebele, Loka Abaya woreda of Sidama Regional state, Ethiopia. The objective was to identify these properties under varying agro-technical soil depth conditions. Randomized Complete Block Design (RCBD) field experimental design was spotted to take soil samples using appropriate sample equipment and further lab analysis was conducted. Loka Abaya farm soil is loam, offering balanced texture for drainage, water retention, and nutrient availability. Moisture content reaches a maximum of 24.36%, with a linear relationship between soil depth and moisture content. The Atterberg limits of the soil (LL: 37.5–40%, PL: 25–27.5%, PI: 10–15%) indicate low plasticity and low clay content, consistent with loamy or silty soils. The results also show that soil cohesion is low in the topsoil (surface layers) but increases significantly at depths of 10–15 cm. Soil resistance decreases with depth due to reduced compaction and increased pore space in subsurface layers. Bulk density peaks at 1.28 g/cm^3 at 10 cm depth due to high organic matter decomposition, then decreases to 1.20 g/cm^3 at 15–20 cm, likely from reduced organic matter and root activity in subsurface layers. Correlations analysis reveals that soil moisture strongly increases with depth ($r = 0.99$, $p < 0.01$), indicating that deeper tillage may be necessary in arid regions to access moist soil layers. Sandy soils, which show a strong link between plastic limit and sand percentage ($r = 0.97$, $p < 0.01$), require adequate moisture during tillage to prevent erosion. Moist, cohesive soils are less compacted ($r = -0.92$, $p < 0.05$) and easier to till, while cohesive soils resist penetration ($r = -0.90$, $p < 0.05$), highlighting the need for efficient tillage equipment to minimize energy use. Overall, soil moisture, texture, and cohesion are critical factors for optimizing tillage practices and enhancing soil health. The study's site-specific nature limits its broader applicability, its focus on physical properties few mechanical property, overviews chemical and biological aspects, and further research is required to understand the long-term impacts of tillage on soil structure and productivity.

Keywords Depths , Physio-mechanical, Soil failure, Soil tool interaction, Tillage

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Soil tillage requires an interaction of soil and tools to create a favorable environment for crop cultivation. Understanding soil behaviors enables to description of different components that influence workable conditions related to crop production[1,2]. Physio-mechanical characteristics; soil textural class, bulk density, dry density, natural moisture contents, con indexes and soil Atterberg limits[3], cohesion and frictional angle are some of the determining factors of soil failure in tillage[4]. Preparing to suitable seed bed with minimum energy requirement of soil disturbance[5]. An investigation into the mechanical behavior of drier soils during cutting, influenced by their consistency limits, provides valuable insights, particularly in clarifying soil failure patterns and draft forces. Understanding these dynamics in the context of soil recasting is considered acceptable[6,7]. Tidy changes to these surfaces with moisture content and two soil microstructural states have been distinguished[8]. The verdicts are conferred and used as the basis for the agro-technical operations of fairly principally different soil types of soil failure characterized at initial soil conditions. This depiction suggests that it could serve as a theoretical framework for understanding the complex processes involved in soil loosening and compaction. A straightforward experimental approach to measuring the behavior of field soils and their primary structure is necessary to evaluate the typical interactions between soil and tools, which are key to practical soil performance.

Thoughtful properly pulverizing and preparing suitable seed beds with minimum energy requirement is a custom to agricultural mechanization. The operational parameters and shape of the implement determine the degree of soil deformation or type failure[9]. The potential constituents of soil's physical and mechanical properties affect either positively or negatively its failure[10]. Variations in soil surfaces due to soil moisture percentage and soil microstructural states have been identified[11], as a foundation for developing a typical relationship concerning soil strength. Consistency limit can provide evidence of soil resistance to failure in its level of moisture content[7]. A critical investigation of soil loosening nature requires hard work considering how tillage tool geometry and varying soil properties influence these processes across different points[12,13].

As bulk density drops, the shear strength of soil aggregates weakens, creating a looser, more workable soil structure[14]. Evaluations of soil physical properties, including bulk density and cone index, yielded significant findings. In the upper soil layer, all trial variants showed a noticeable reduction in cone index compared to the control, regardless of manure treated sol effect[4]. Based on theoretical analysis and experimental measurements, in soil failure Soil Properties and Behavior[15].

Dry density (γd) is the ratio of the weight of solids (Ws) to the total volume of soil (V)[16]. Soil natural water content[16,17]. Mechanical behavior is characterized by cohesion, structure, angle of internal friction, and con index dry density. Atterberg limits are largely influenced by various soil properties, with organic matter and clay content playing the most significant roles[18]. The liquid and plastic limits of mountain soils are influenced by the specific soil types and the characteristics of different horizons, reflecting how these factors interact to shape the soil's physical properties[18].

Soil physio-mechanical properties are essential metrics for assessing the mechanical behavior of soils under varying conditions related to soil and tools, particularly in terms of disturbance patterns during tillage[19]. Research has identified the influence of soil resistance on tillage depth, which varies based on initial conditions[20]. Additionally, moisture content is the ratio of the weight of water (Ww) to the weight of solid particles (Ws), expressed as a percentage[15].

This study aims to investigate the physio-mechanical properties of soil under varying conditions to understand their influence on soil behavior and tillage efficiency. The specific objectives include analyzing soil physical properties such as soil texture, moisture content, and bulk density to determine their impact on soil structure, compaction, and workability. It also evaluates mechanical properties including shear strength, cohesion, and plasticity indices to understand their role in soil failure mechanisms and tillage efficiency. Additionally, the study examines how soil moisture fluctuations affect tillage resistance and soil-tool interaction and seeks to optimize tillage practices by providing recommendations based on soil behavior analysis.

This study contributes to soil science and agricultural engineering by establishing a comprehensive relationship between soil physio-mechanical properties and tillage efficiency. It provides insights into soil failure mechanisms under different moisture conditions, enhances the understanding of tillage tool-soil interaction to optimize soil disturbance with minimal energy input, and develops region-specific recommendations for sustainable tillage practices, particularly in the Sidama Region, where soil management plays a critical role in crop productivity.

The findings of this study have significant implications for tillage operations and soil management. Deeper tillage in arid regions can improve seed germination by accessing moist soil layers while reducing irrigation needs. Moist soils with lower bulk density enhance workability and prevent compaction. Proper moisture management in cohesive soils facilitates tillage, while sandy soils require optimal moisture levels to reach their plastic limit, minimizing erosion risks.

By integrating these insights, farmers can optimize tillage timing, depth, and equipment selection, leading to improved soil health, energy conservation, and increased crop yields. Furthermore, this study provides valuable guidance for tillage equipment design and the development of sustainable soil management practices to prevent soil degradation and erosion. This research advances the understanding of soil physio-mechanical properties and their implications for tillage operations. By bridging theoretical analysis with practical applications, it offers actionable recommendations for improving agricultural mechanization, ensuring sustainable land use, and optimizing tillage efficiency. The results provide a solid foundation for future research in soil behavior and mechanized tillage systems.

Materials and methodology

Description of the study area

The field experiment was carried out in Bukito Burra Kebele, located in the Loka Abaya woreda, along the western border of the Sidama region. This area is approximately 89 km southwest of Hawassa and 337 km from Addis Ababa. The woreda spans latitudes 6°26′0″ to 6°48′0″ N and longitudes 38°00′0″ to 38°21′0″ E, as illustrated in Fig. 1.

Covering a total area of 1190 km^2, it features a moist kola agro-ecology with altitudes ranging from 1170 to 1500 m above sea level. The annual rainfall in Loka Abaya varies between 670 and 1050 mm. The selected farmland area was highly affected by heavy agricultural machinery density. Due to the density of agricultural machinery, the soil's physical and mechanical properties are affected. Based on the related research work and pilot test done on three farm fields related to the soil's physical, mechanical, and soil resistance the intended farmland was selected as a representative.

Experimental design and lab test procedures

Soil samples for the physio-mechanical investigation were collected from a 60 m × 100 m farmland using a stratified random sampling method to ensure representativeness as shown on Fig. 2. The sampling grid was established at 0.05 m intervals across the cultivation layer, covering the entire farmland. Samples were collected at five distinct depth ranges corresponding to tillage depths (TD): 0–0.05 m, 0.05–0.10 m, 0.10–0.15 m, 0.15–0.20 m, and 0.20–0.25 m below the target cultivation depth. To ensure statistical reliability, three replications were taken for each depth range at every sampling point, resulting in a total of 15 samples per sampling location (5 depths × 3 replications). This replication strategy was applied across the entire farmland to account for spatial variability and ensure robust data. The collected samples were transported to Hawassa University Geotechnical Laboratory and Hawassa Soil Laboratory for detailed analysis of their physical and mechanical properties, including texture, moisture content, bulk density, shear strength, cohesion, and plasticity indices. This methodical approach ensured precise characterization of the soil's behavior and suitability for agricultural practices.

The farm field that was chosen for the analysis was plowed for a long time using a traditional tillage system, and a portion of the soil was taken from the field that was plowed by a tractor. A Randomized Complete Block Design (RCBD) was employed for field sampling to ensure unbiased and representative data collection. Laboratory analyses were conducted on key soil parameters, including textural classes (sand, silt, and clay percentages), natural moisture content (water content under natural conditions), dynamic cone penetration (soil resistance to penetration), bulk density (mass of soil per unit volume), shear strength (resistance to shear stress), cohesion (internal strength of soil particles), plasticity indices (plastic limit, liquid limit, and plasticity index), and the angle of friction (resistance to sliding between soil particles). The results revealed critical insights into the soil's physical properties, such as its textural composition, moisture distribution, resistance to penetration, and strength characteristics. These findings provide a comprehensive understanding of the soil's behavior under different conditions, which is essential for optimizing agricultural practices, improving soil management, and ensuring sustainable land use.

Instrument used

Sieve analysis tests, following ASTM D422, were conducted to evaluate the particle size distribution[21]. The amount of soil retained on each sieve was calculated and presented as a percentage of the total sample mass. Fine materials were analyzed through hydrometer testing. Atterberg limits for cohesive soil samples were determined in line with ASTM D4318. Standard tests, such as the Casagrande test for determining the liquid limit (LL),

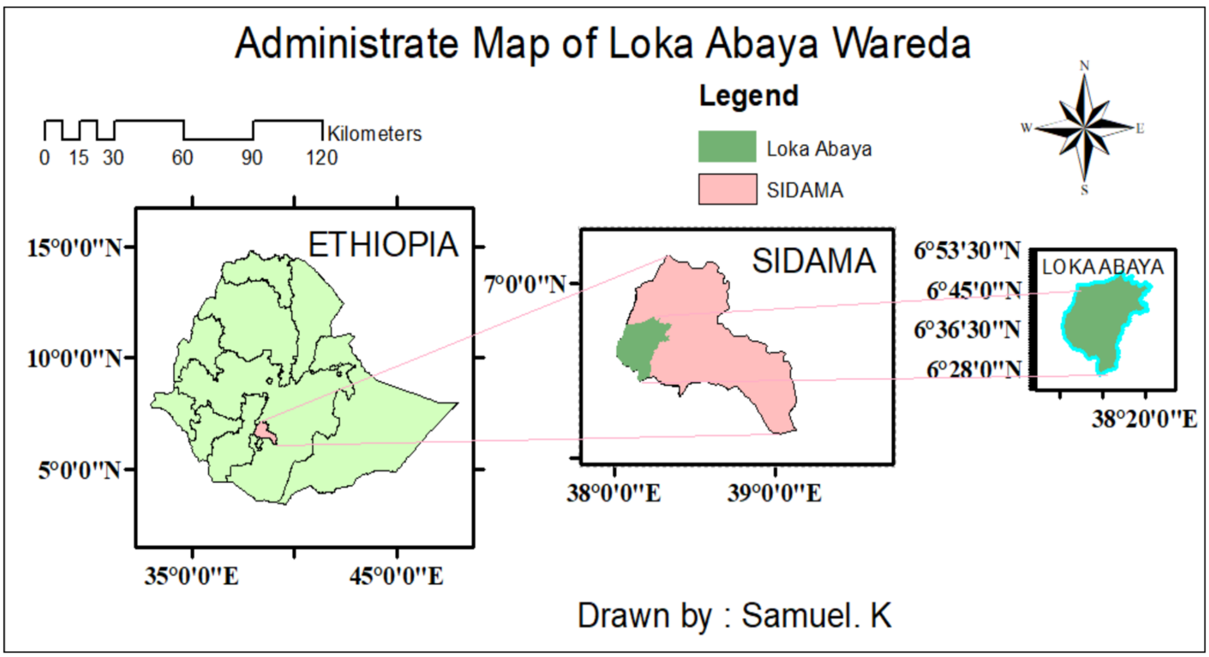

Fig. 1. Map of the study area, Loka Abaya woreda.

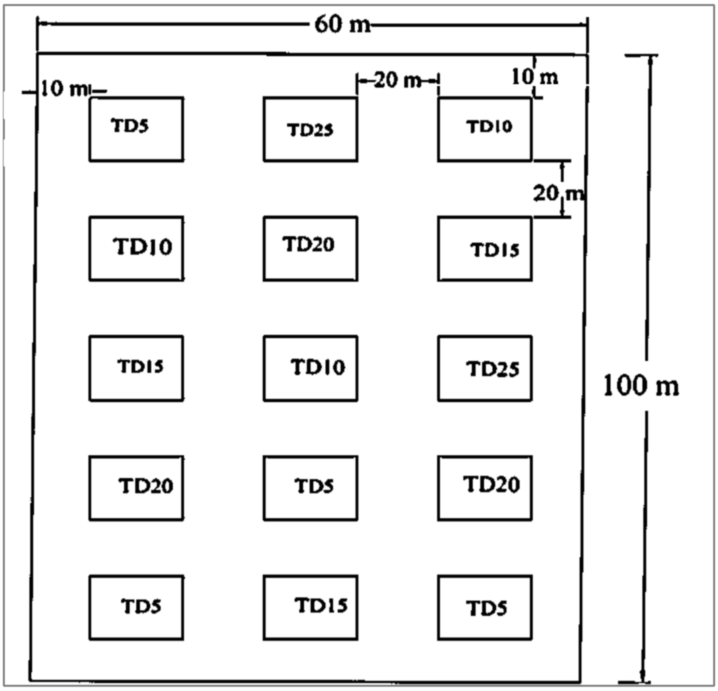

Fig. 2. Experimental sampling layout in field of LokaAbaya woreda bukito kebele.

Nos.	Name of instrument	Function	Specification
1	DHG series drying ovens	To analyze moisture content	DHG—9055 A Power supply: AC220 V ± 5%, 50 Hz Temperature range: Rt + 10–300 °C Temperature accuracy: ± 1 °C Heating power: 110 W
2	Electronic balance scale	For weighting soil sample	Model: TC30K-H Capacity: 30 kg Resolution(d):1 g S/N:41,301,711,098
3	Dynamic Cone Penetrometer	To measure soil compaction	The hammer weight 8 ± 0.1 kg Drop distance 575 ± 1 mm Diameter of the cone 20 ± 0.25 mm The cone tip 60° ± 1° Rod effective length 1000 mm
4	Shear machine	Measure shear strength of a soil	Model:5277–10 S/N:5277–10/AB/0003 V = 230 ph-1 50/60HZ, 100W
5	Glenammer	Particle analysis and material separation	S.N:810,492
6	A060-01 Sieve shaker		A060-24,048 Italy It accepts sieves having diameter 200 Power supply: 230 V Size 350 × 400 × 950 mm Weight: 24 kg

Table 1. List of Scientific Instruments used for soil Physic0- mechanical analysis with their specifications[22].

were performed to assess the soil's consistency and its deformation behavior under varying moisture conditions. Water content was determined using the oven-drying method (ASTM D2216), in which wet soil samples were dried at a consistent temperature of 105 °C for 18–24 h. The moisture content was then calculated by dividing the mass of the water by the mass of the solid particles. A detailed summary of the instruments utilized for both field and laboratory measurements are provided in Table 1.

Results and discussions

Soil texture

The soil texture triangle for the farmland is presented in Fig. 3 and further detailed in Table 2, aiding in the classification of soil texture. According to the soil texture triangle[23,24], the soil in the Loka Abaya farm field is identified as loam, comprising 43.7% silt, 18.3% clay, and 38% sand as indicated on Fig. 3. This classification

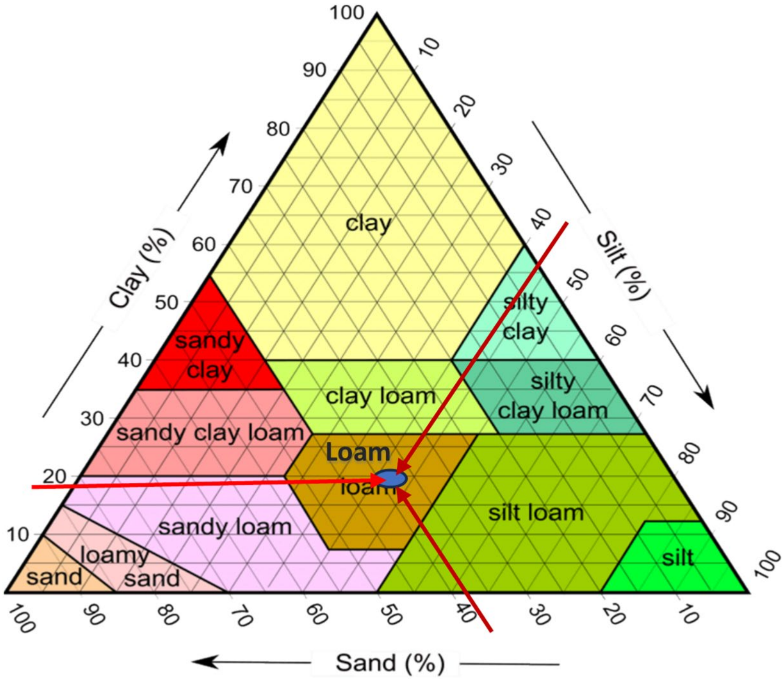

Fig. 3. Soil texture triangle.

Depth (m)	Altitude (m.a.s[a])	Soil pH	EC (d/m)	Carbon (%)	OM (%)	CEC (meq/100)	Total N (%)	Available *p* (%)	Available K (%)	OC (%)	Soil texture Clay (%)	Silt (%)	Sand (%)	Soil texture class
0–0.25	1170	7.28	0.04	0.75	1.33	34.9	0.072	4.6	35.5	2.7	18.3	43.7	38	Loam

Table 2. Soil Physio Chemical Characteristics Bukito Bura Kebele of Loka Abaya.

indicates a balanced mixture of soil particles, which contributes to good drainage and nutrient retention. Recent studies confirm that loam soils are highly productive due to their balanced texture, which supports root growth, water infiltration, and nutrient availability[25].

Moisture content

The moisture content percentages were analyzed in the soil laboratory, revealing that the Loka Abaya farm field has a maximum moisture content of 24.36%. Figure 4, presents the relationship between soil depth and moisture content as linear, indicating that as the depth increases, the percentage of soil moisture content also rises. According to Ahmadi and Mollazade (2009), also the tillage depth of loam soil increases, so does the moisture content. Recent studies suggest that integrating precision agriculture technologies, such as soil moisture sensors and variable-depth tillage, can optimize tillage operations and enhance soil health[26]. Additionally, adopting conservation tillage practices, such as reduced tillage and cover cropping, can mitigate soil erosion and improve water retention, particularly in sandy soils[27].

Atterberg limits

The Liquid Limit, or upper plastic limit, is the moisture content at which soil shifts from a liquid to a plastic state, indicating the minimum level at which it begins to flow with minimal shear force. This can be measured using the Casagrande cup method or a cone penetrometer. The Plastic Limit, also known as the lower plastic limit, is the moisture content at which soil transitions from a plastic state to a semi-solid state. The test for the Plastic Limit involves rolling a small, ellipsoidal mass of soil on a non-porous surface until it crumbles at a diameter of 3 mm, as defined by Casagrande.

The Plasticity Index, which is the difference between the Liquid Limit and the Plastic Limit, is a crucial factor in soil classification. In terms of texture, dry loamy, and silty soils produce fine, powdery dust when disturbed, while clayey soils do not. Silty soil is especially powdery due to its low clay content. Wet loam feels soapy and less plastic, leaving a dust residue when rubbed, whereas clay does not. When ploughed, slightly moist clay has a shiny surface, in contrast to loam.

The outcomes of consistency or Atterberg limits; Liquid limit signified at a 37.5–40% water content interims of depth as shown in Fig. 5. The plastic limit of the soil ranged at 25% and 27.5% when the depth varied from 5 cm deep and the plasticity index ranged at 15% declining after its pick reached 10–15 range between 0 and

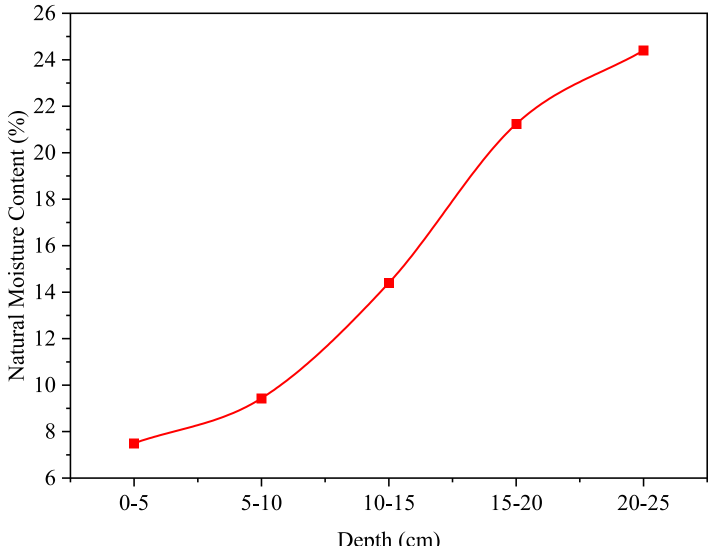

Fig. 4. Moisture content.

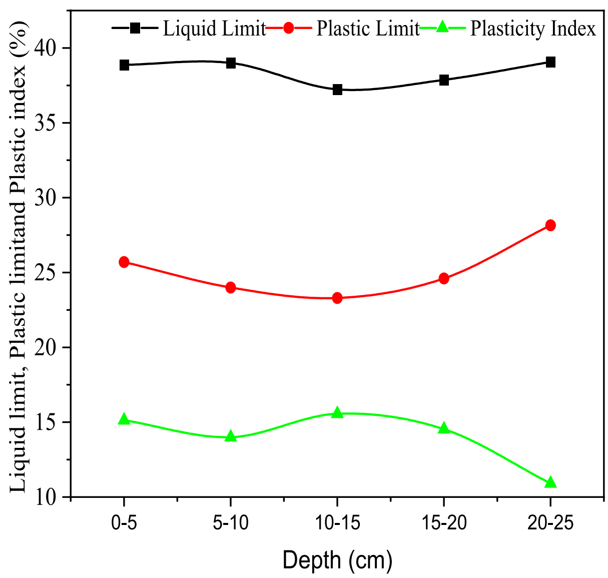

Fig. 5. Atterberg limits of soil.

25 cm depth. As a result, the soil under examination did not exhibit plasticity as indicated by the plastic limit or liquid limit and plasticity index since it had a very low clay concentration[28].

Bulk density

Bulk density is a crucial indicator of soil compaction, impacting various soil functions. It influences water infiltration, root growth depth, water retention capacity, porosity and aeration, nutrient availability for plants, and the activity of soil microorganisms[29]. Each of these factors plays a vital role in sustaining healthy soil processes and ensuring overall productivity. Generally, bulk density is higher in fertile regions of the soil. The agro-technical range of tillage depths in cultivation bulk density effect on loams: < 1–1.41 g/cm^3 satisfying in terms of compaction[30].

As depth increases, the layer 0–5 cm to its peak of 10 cm depths and indicates high organic matter decomposition resulted in maximum bulk density of 1.28 g/cm^3 occurs at a depth of 10 cm, Fig. 6, and at the increased depths 15–20 cm the reverse effect Therefore, as, lower Bulck density 1.20 g/cm^3 at less organic matter decomposition. Subsurface layers typically exhibit lower levels of organic matter, reduced aggregation, and less root penetration compared to surface layers, resulting in decreased pore space[31]. Additionally, subsurface layers are subjected to the compacting weight of the overlying soil.

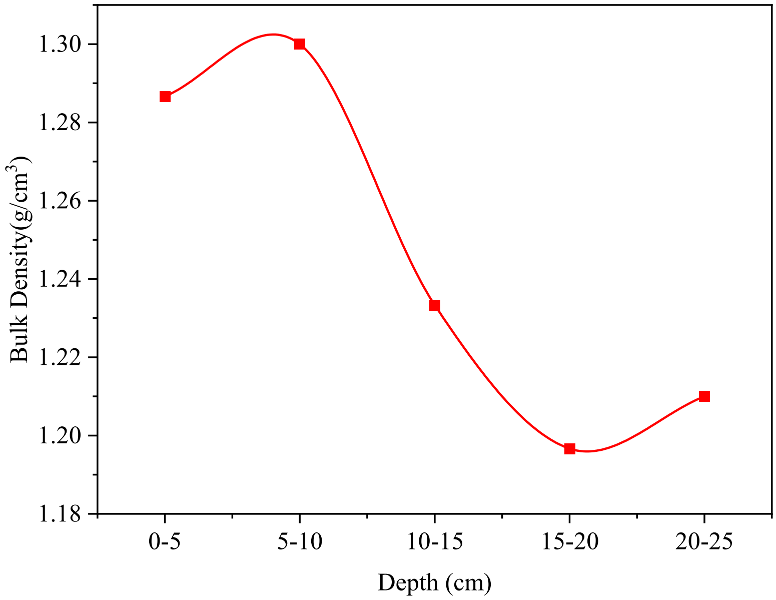

Fig. 6. Soil bulk density.

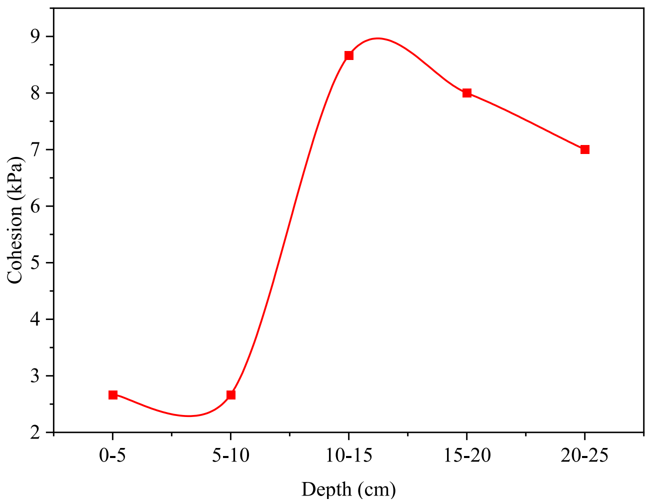

Fig. 7. Soil cohesion.

Soil cohesion

Cohesive soils are fine-grained, weak, and easily deformable, with particles that tend to stick together[32]. A soil is considered cohesive if more than 50% of its composition by weight consists of fine particles, such as silt and clay[33]. As indicated on Fig. 7 the soil cohesion is high at the depth range from 10 to 15 cm. Generally based on the finding of this research work the soil cohesion is low at the top part of fertile soil and when it goes deep the soil cohesion increased up to 15 cm. Research by[34] found that cohesion increases with depth in many soils, as surface layers are often richer in organic matter and have better structure, reducing cohesion. Subsurface layers, with higher clay content and less organic matter, tend to be more cohesive, supporting the findings of this study.

The effect of soil resistance

Soil resistance values effect generally decreases with depth due to several factors. As you move deeper into the soil profile, the compaction effect of above layers on the underlying soil leading to lower resistance as indicated on Fig. 8. This effect resulted in the loos soil particles separately, increased pore space and decreased bulk density[35–39].

Moreover, surface layers often contain more organic matter, roots, and biological activity, which can help create a looser structure. In contrast, deeper layers typically have less organic material and root penetration, resulting in denser, more compacted soil. This increased compaction can affect water infiltration, root growth, and nutrient availability, ultimately impacting soil health and agricultural productivity.

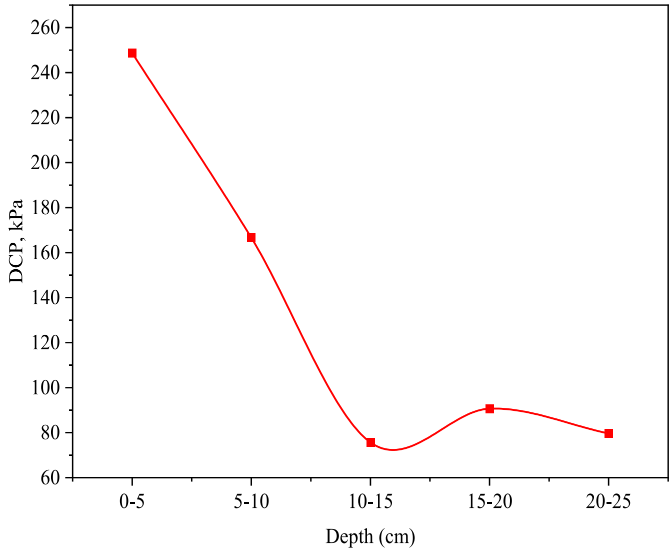

Fig. 8. Soil dynamic cone penetrometer.

Correlation	d	LL	PL	PI	Gravel	Sand	Fines	BD	MC	Coh	DCP
d	1.00	–0.14	0.46	–0.68	0.06	0.28	–0.30	–0.88	0.99**	0.76	–0.87
LL		1.00	0.65	–0.60	–0.27	0.80	–0.51	0.46	–0.14	–0.74	0.53
PL			1.00	–0.85	–0.47	0.97**	–0.47	–0.28	0.51	–0.05	–0.01
PI				1.00	0.32	–0.80	0.46	0.33	–0.65	–0.07	0.33
Gravel					1.00	–0.40	–0.52	–0.19	0.10	0.11	–0.13
Sand						1.00	–0.57	–0.08	0.34	–0.28	0.20
Fines							1.00	0.23	–0.39	0.17	–0.08
BD								1.00	–0.92*	–0.90*	0.82
MC									1.00	0.75	–0.81
Coh										1.00	–0.90*
DCP											1.00

Table 3. Correlation analysis of soil mechanical properties (n = 11).
*Significant at the 0.05 level, ** Significant at the 0.01 level.

Correlation analysis

The correlation analysis of soil properties reveals significant relationships with practical implications for tillage and soil management. A strong positive correlation between soil moisture and depth ($r = 0.99$, $p < 0.01$)[40] suggests deeper tillage may be needed in arid regions to access moist soil, while the link between plastic limit and sand percentage ($r = 0.97$, $p < 0.01$) indicates sandy soils require adequate moisture for tillage to prevent erosion. Negative correlations, such as between soil moisture and bulk density ($r = -0.92$, $p < 0.05$) and soil cohesion and bulk density ($r = -0.90$, $p < 0.05$), highlight that moist, cohesive soils are less compacted and easier to till. Additionally, the resistance of cohesive soils to penetration (DCP, $r = -0.90$, $p < 0.05$) underscores the need for appropriate tillage equipment to minimize energy use. Overall, the findings in Table 3 emphasize the importance of considering soil moisture, texture, and cohesion to optimize tillage practices and enhance soil health.

Regression and ANOVA analysis

The regression analysis provided critical insights into the relationships between various soil parameters. The analysis revealed a strong negative correlation between Natural Moisture Content (%) and Dry Density (g/cc), with an R^2 value of 0.840 and a highly significant p-value of less than 0.001. This indicates that as moisture content increases, dry density decreases, a trend commonly observed in soil mechanics. Higher moisture levels tend to fill soil voids, reducing the overall dry density due to lower compaction efficiency. On the other hand, the relationship between the Plasticity Index (%) and Liquid Limit (%) was found to be weak, with an R^2 value of only 0.044 and an insignificant p-value of 0.451. This suggests that the plasticity index does not significantly influence the liquid limit, implying that other factors, such as mineral composition and soil structure, play a

Analysis	Variables	R^2 / F- Statistic	*P*-value	Conclusion
Regression	Natural moisture content versus dry density	0.840	< 0.001	Strong negative correlation, significant
	Plasticity index versus liquid limit	0.044	0.451	Weak correlation, not significant
	Bulk density versus dry density	Moderate	< 0.05	Positive correlation, significant
	Cohesion versus friction angle	Low	> 0.05	No significant relationship
	DCP versus dry density	Weak	> 0.05	Minimal correlation, not significant
ANOVA	Natural moisture content across depths	90.42 (F)	< 0.0001	Significant variation across depths
	Dry density across depths	High variation	< 0.05	Significant changes with depth
	Liquid limit across depths	Low variation	> 0.05	No significant difference
	Plasticity index across depths	Low variation	> 0.05	No significant difference
	Cohesion and friction angle across depths	No major changes	> 0.05	No significant depth-related variation

Table 4. Regression and ANOVA analysis.

more dominant role in determining the liquid limit. Similarly, Bulk Density (g/cc) showed a moderate positive correlation with Dry Density (g/cc), meaning that as bulk density increases, dry density also increases, which is expected as higher bulk density reflects a more compact soil structure. The analysis between Cohesion (kPa) and Friction Angle (°) showed no significant relationship, indicating that cohesion does not strongly predict friction angle for these soil samples. Additionally, the correlation between Dynamic Cone Penetrometer (DCP) strength and Dry Density was weak, suggesting that soil stiffness is influenced by other factors such as particle arrangement, compaction history, and cementation as shown on Table 4.

The ANOVA analysis was conducted to determine whether various soil parameters, including Natural Moisture Content, Dry Density, Liquid Limit, and Plasticity Index, significantly vary across different depth ranges. The results indicated that Natural Moisture Content (%) exhibits a statistically significant variation across depths, with an F-statistic of 90.42 and a *p*-value of less than 0.0001. This confirms that deeper layers retain more moisture due to reduced evaporation and different soil water retention properties. Likewise, Dry Density (g/cc) also exhibited significant variations across depths, suggesting differences in soil compaction at varying depths. However, the Liquid Limit (%) and Plasticity Index (%) showed no significant variations across depth ranges, implying that the plasticity characteristics of the soil remain relatively consistent throughout the profile. Furthermore, both Cohesion (kPa) and Friction Angle (°) exhibited no substantial depth-dependent variations, indicating that soil shear strength properties do not change drastically with depth in this particular dataset.

These findings have significant geotechnical implications. The strong inverse relationship between Natural Moisture Content and Dry Density highlights the importance of moisture control during soil compaction processes, which is critical for construction and foundation stability. The lack of correlation between Plasticity Index and Liquid Limit suggests that different soil compositions exhibit similar plastic behavior despite variations in their plasticity indices. Additionally, the significant variation in Natural Moisture Content with depth implies that deeper soil layers are more stable in terms of moisture retention, which is an important factor in foundation engineering. The weak correlation between DCP strength and Dry Density suggests that field penetration resistance is influenced by multiple factors, necessitating a more comprehensive approach when evaluating soil strength for engineering applications. Overall, the study provides valuable insights into the behavior of soil under different conditions, which is essential for making informed decisions in geotechnical and construction projects.

Conclusion

The study provided a comprehensive analysis of the physical and mechanical properties of soil under varying conditions, revealing significant correlations between soil composition, moisture content, and mechanical stability. The soil in the study area was classified as loam, consisting of 43.7% silt, 18.3% clay, and 38% sand, which contributed to a balanced texture supporting water retention and drainage. Moisture content demonstrated a direct relationship with depth, reaching a maximum of 24.36%, with statistical analysis showing a strong correlation between moisture content and depth ($r = 0.99$, $p < 0.01$). This finding suggests that deeper tillage may be required in arid regions to access moisture-rich soil layers for improved crop growth. The Atterberg limits indicated low plasticity, with a liquid limit ranging from 37.5 to 40%, a plastic limit between 25 and 27.5%, and a plasticity index of 10–15%, highlighting the soil's low clay content and reduced susceptibility to excessive shrinkage or swelling.

Bulk density exhibited depth-dependent variations, peaking at 1.28 g/cm^3 at 10 cm depth due to organic matter decomposition, before decreasing to 1.20 g/cm^3 in the 15–20 cm layer, where lower organic content reduced soil aggregation. The dry density followed a similar trend, showing a strong negative correlation with natural moisture content ($R^2 = 0.840$, $p < 0.001$), confirming that increased moisture reduces soil compactness. Soil cohesion values increased with depth, reaching a maximum at 10–15 cm, as finer particles and reduced organic matter contributed to higher resistance. This was further supported by ANOVA results, which confirmed significant variations in natural moisture content and dry density across depths ($F = 90.42$, $p < 0.0001$), reinforcing the role of depth in determining soil stability.

The mechanical properties of the soil were also analysed in relation to tillage efficiency. The Dynamic Cone Penetrometer (DCP) test showed that soil resistance to penetration decreased with depth, with penetration strength dropping from 414 kPa at 0–5 cm to 74 kPa at 20–25 cm, indicating reduced compaction and increased pore space in the subsurface layers. Correlation analysis revealed that soil cohesion was negatively associated with bulk density ($r = -0.90$, $p < 0.05$), emphasizing the need for precise moisture control during tillage to optimize soil workability. Furthermore, friction angle measurements remained relatively constant at 30–32°, suggesting that shear resistance was primarily governed by particle interlocking rather than depth-dependent changes in cohesion.

Overall, the findings underscore the importance of soil moisture, bulk density, and cohesion in determining soil behaviour, with implications for tillage optimization and soil conservation strategies. The strong influence of depth on moisture retention and dry density suggests that targeted tillage practices could improve soil aeration and root penetration while reducing compaction. Future research should explore long-term tillage impacts on soil structure, particularly in relation to seasonal changes in moisture content and organic matter decomposition.

Data availability
The data used to support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

S.K. developed the study methodology, analysed the samples, and prepared the manuscript. G.G, K.P.K and M.D, conceptualized and supervised the study. Y.S and M.M prepared the manuscript and edit the manuscript. All authors reviewed the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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