

Comparative Performance Evaluation of Tractor-Drawn Mouldboard and Disc Plows under Varying Soil Conditions in Rwanda

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Abstract

This study was conducted at Gishari College Demonstration Farm to investigate the performance evaluation of tractor-drawn mouldboard and disc plows, the spatial variability of soil properties, and the economic efficiency of tillage operations. The research aimed to optimize tillage practices by providing insights into how different plows perform under varying soil conditions and their associated operational costs. To achieve these objectives, a Completely Randomized Design (CRD) was employed over a 3,600 m² area. Treatments combined two types of plows (Mouldboard and Disc) with three plowing depths (10 cm, 15 cm, and 20 cm), resulting in six treatment combinations replicated across the farm. Data on fuel consumption, soil resistance, weed count, cutting width, field capacity, field efficiency, and wheel slippage were collected and analyzed using descriptive statistics. The study revealed that the soil texture across the farm was predominantly sandy loam, characterized by an average sand content of 62.13%, silt at 28.75%, and clay at 9.12%. Bulk density was found to increase with soil depth, from 1.015 g/cm³ at 0 - 10 cm to 1.338 g/cm³ at 0 - 20 cm, while moisture content also increased from 21.01% to 26.09% within the same depth range. Spatial analysis identified distinct zones of compaction and moisture retention, highlighting the importance of targeted soil management practices to enhance soil health and productivity. The performance evaluation showed that the mouldboard plow achieved superior results in terms of cutting width, effective field capacity, and soil inversion. Specifically, it recorded a cutting width of 0.654 m and an effective field capacity of 0.334 ha/hr at 0 - 10 cm depth. However, it also exhibited higher wheel slippage, reaching 22.35% at 0 - 20 cm depth, and required more operational time

compared to the disc plow. The disc plow, although having a narrower cutting width and lower field capacity, demonstrated higher field efficiency (up to 93.684%) and lower wheel slippage (16.60% at 0 - 10 cm), making it more suitable for shallow tillage and harder soils. Both plows showed comparable soil inversion capabilities, with no significant differences in weed burial effectiveness. Therefore, the disc plow presents a preferable option for operations where cost sensitivity and fuel efficiency are critical, whereas the mouldboard plow remains essential for tasks requiring thorough soil inversion and deeper plowing. The mouldboard plow is recommended for deep tillage and effective soil turnover, particularly in fields with high weed pressure, while the disc plow is better suited for routine, cost-efficient operations in fields where traction and operational speed are prioritized. The findings advocate for a balanced approach to tillage selection, considering both soil management and economic sustainability to optimize agricultural productivity under varying field conditions.

Keywords

Performance, Disc Plow, Mouldboard Plow, ANOVA, T-Test

1. Introduction

Agricultural mechanization has become a cornerstone of global food production, significantly enhancing productivity, efficiency, and sustainability in farming practices. The extent and adoption of mechanization, however, vary widely across regions due to differences in economic development, infrastructure, policy frameworks, and the availability of resources. In developed countries such as the United States, Canada, and much of Europe, agricultural mechanization is highly advanced. The use of precision farming technologies, autonomous machinery, GPS-guided equipment, and robotics is widespread. These advancements have enabled farmers to optimize input usage, reduce labor dependency, and improve yields. The availability of high-capacity tractors, harvesters, and irrigation systems has further revolutionized large-scale farming. Mechanization in these regions often focuses on sustainability, including energy-efficient machinery and reduced environmental impact. Agricultural mechanization is essential for increasing productivity and efficiency in food production, particularly as the global population is projected to rise significantly, necessitating a 60% increase in food production by 2050 [1] [2]. Current estimates indicate that mechanization could reduce the global agricultural labor force from 286 million to as low as 19 million full-time equivalent workers, depending on the speed of mechanization adoption [3]. The draft force required for a given implement will also be affected by the soil conditions, geometry of the tillage implement [4], operating depth and travel speed [5]. [6] evaluated the effects of tillage depth and forward speed on draft of moldboard, disk and chisel plows on sandy loam soil. The results showed that draft increased

with increasing of forward speed and tillage depth for all the implements and the moldboard and chisel plow had highest draft force. [7] found that draft force increased by 33.41% when the forward speed increased from 0.75 to 1.70 m sec⁻¹. [8] noted that draft force of offset disk harrow increased with increasing the operating depth or/and tractor speed. Soil type had considerable effect on draft force, whereas [9] found that draft force increased from 19.73 KN in sandy soil to 20.35 KN in clay soil for disk plow. The field efficiency is one of the important factors to evaluate performance of the tillage implements. The field performance of agricultural machinery is influenced by several factors, including the condition of the power unit, operating speed, working depth, and the geometry of the tillage implement. Studies [10]-[12] have shown that field efficiency is also significantly affected by soil type and the type of tillage implement used. For instance, it was observed that chisel and ridger plows performed better in sandy clay soils, achieving field efficiencies of 74.33% and 74.37%, respectively, compared to 71.94% and 72.90% in clay soils. These findings highlight the importance of matching tillage equipment to specific soil conditions to optimize performance. While the disc harrow recorded the highest field efficiency compared to other implements, which was 79.90%. The field capacity of a machine is the number of unit, which it can process or cover in a specific time and it may be expressed as the area covered per hour. It is affected by soil conditions, surface roughness of soil, tractor wheels slippage and failure to utilize the full operating width of the machine [13]. The study conducted by [14] indicated that disc harrow had effective capacity higher than of the disc plough and ridger at same work conditions. As well as they found that effective field capacity increased by 25.41% when the operating speed for disc harrow increased from 6.58 to 6.71 km hr⁻¹ respectively.

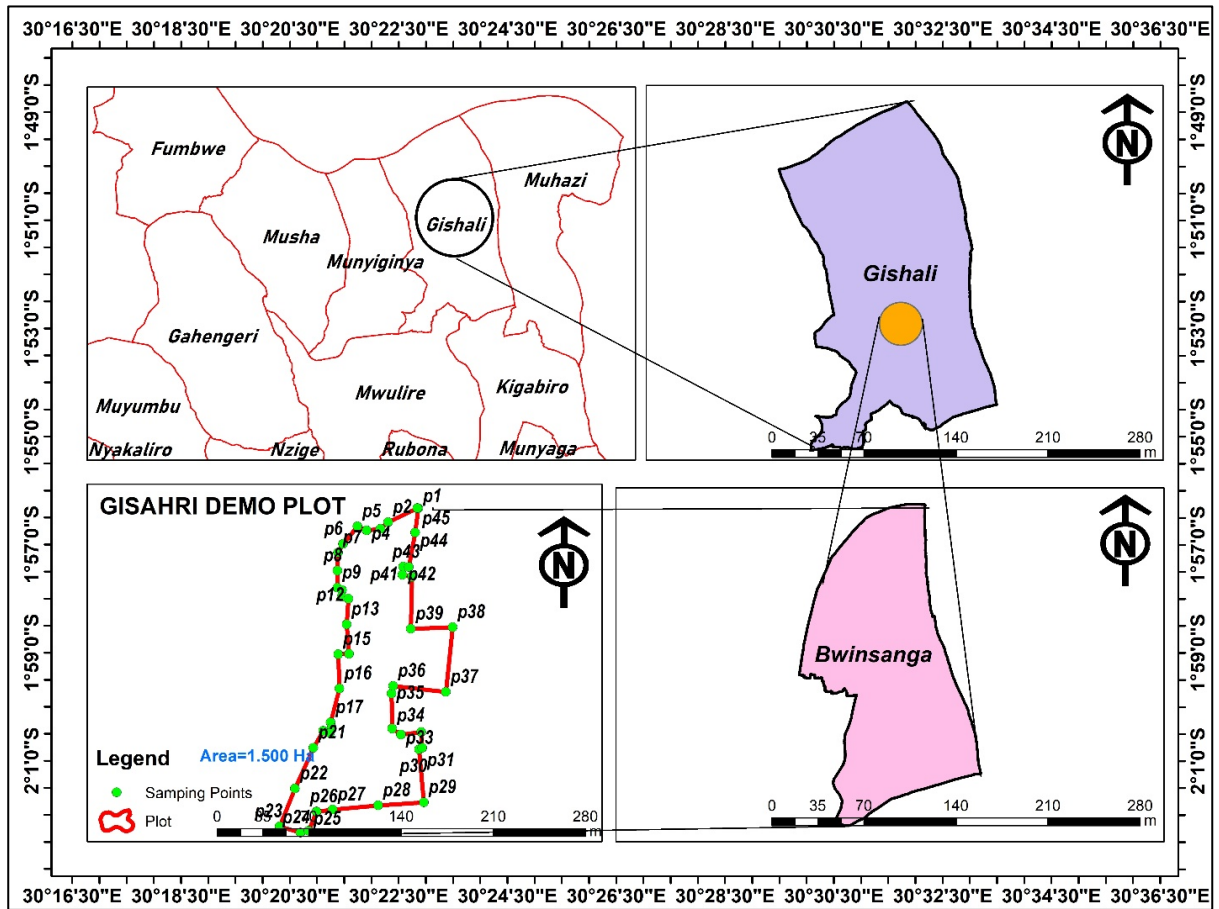
Agricultural mechanization adoption in Africa remains relatively low, with significant regional disparities. In sub-Saharan Africa, including Rwanda, mechanization levels are among the lowest globally. Across the continent, less than 30% of agricultural activities are mechanized, with many farmers relying on manual labor and animal power. Tractor density in sub-Saharan Africa averages fewer than five tractors per 1,000 hectares of arable land, compared to the global average of 20 tractors per 1,000 hectares. In Rwanda, the situation mirrors the broader regional trend, with mechanization adoption remaining modest. Approximately 25% of land preparation in the country is mechanized, while the majority of farming activities are still performed manually or with the help of draft animals. Tractor density in Rwanda is estimated to be around one to two tractors per 1,000 hectares, highlighting significant room for improvement. This low level of mechanization is attributed to small and fragmented landholdings, limited financial resources among smallholder farmers, and insufficient access to machinery and spare parts. Despite these challenges, Rwanda has made strides in promoting agricultural mechanization through government initiatives and partnerships with international organizations. Programs aimed at subsidizing machinery, providing access to mechanization services, and supporting cooperatives have been implemented

to encourage adoption. Mechanization hubs and rental services have also been introduced to improve access for small-scale farmers who cannot afford to purchase equipment outright. While progress has been made, the pace of mechanization in Rwanda remains slow, and further investment in infrastructure, financing options, and farmer training is needed to accelerate adoption and boost agricultural productivity. Soil tillage is a critical agricultural operation that influences soil structure, water retention, aeration, and overall crop productivity. Tractor-drawn implements such as mould board plows and disc Plows are commonly employed for tillage operations. However, their performance is strongly affected by soil properties, including texture, moisture content, bulk density, and compaction, as well as the desired soil cutting depths. Numerous studies have demonstrated that these variables directly impact soil pulverization efficiency, fuel consumption, draft force, and energy requirements. For instance, previous research highlights that heavier, compacted soils increase draft forces and energy demand, while excessively moist soils can lead to clogging and uneven tillage [15] [16]. Despite these insights, localized data on the performance of tillage implements under specific soil conditions is limited. At Gishari College demonstration farm, diverse soil conditions, coupled with varying operational demands, present challenges in selecting the most effective tillage equipment and optimizing cutting depths for sustainable land preparation. Empirical studies from similar environments have emphasized the importance of tailoring tillage practices to soil properties to enhance efficiency and reduce costs [17] [18]. However, there remains a gap in understanding how mould board plows and disc plows perform under these conditions in the context of Rwandan agricultural systems. This study aims to bridge this gap by evaluating the performance of tractor-drawn mould board plows and disc plows under varying soil conditions and cutting depths at Gishari College Demonstration Farm. Field experiments will measure soil parameters, such as texture, moisture content, and bulk density, before and after tillage operations. Performance metrics, including draft force, fuel consumption, working depth, and soil pulverization quality, were assessed to close the knowledge gaps.

2. Materials and Methods

2.1. Description of the Study Area

This study was conducted in Gishari Sector of Rwamagana District at RP Gishari College demo farm and its serves as an essential agricultural training and demonstration center. It is designed to enhance agricultural productivity and promote modern farming practices, benefiting both farmers and the broader community. The farm integrates several key initiatives and programs aimed at fostering innovation, education, and economic development in agriculture. The geographical coordinates are of $1^{\circ}57'12.65''S$ and a longitude of $30^{\circ}26'19.12''E$ or -1.953513 and 30.438644 respectively. With an even altitude varies from 1480 - 1550 m above sea level. The total of 45 soil sampling points covering the total area of 1.478 Ha were considered. The Map of Gishari College demo farm is shown in **Figure 1**.



Source: Researcher, 2025 (Application of GIS 10.8.1).

Figure 1. Map showing the study area (Gishari college demonstration farm).

2.2. Experimental Design

The experimental design for the performance evaluation of tractor-drawn mould-board and disc plows at Gishari College Demonstration Farm utilized a completely randomized design (CRD) across a total sampled area of 3,600 m², divided into three (3) Blocks with equal 18 experimental treatments. Each block represented distinct soil conditions, such as dry, moist, and compacted soils, ensuring a diverse range of testing environment as the soil physical properties have been tested in the laboratory and the spatial interpolation was done to the entire field of the college of 1.5 hectares. The design of experiment consists of two (2) independent parameters: Plow with two (2) levels namely MBP (P1) and DP (P2); and Depth with three (3) levels namely D1 = 10 cm, D2 = 15 cm and D3 = 20 cm). The study involved three (3) replications distributed evenly across the demo farm and six treatments have been done to each block to enhance statistical reliability and minimize errors. The treatments are as followed such as P1D1, P1D2, P1D3, P2D1, P2D2, P2D3. The data for dependent parameters or response parameter are collected and recorded systematically such as Fuel consumption, Soil resistance, weed count, cutting width, theoretical field capacity,

actual field capacity, field efficiency, slippage. The treatments are represented in **Figure 2**.

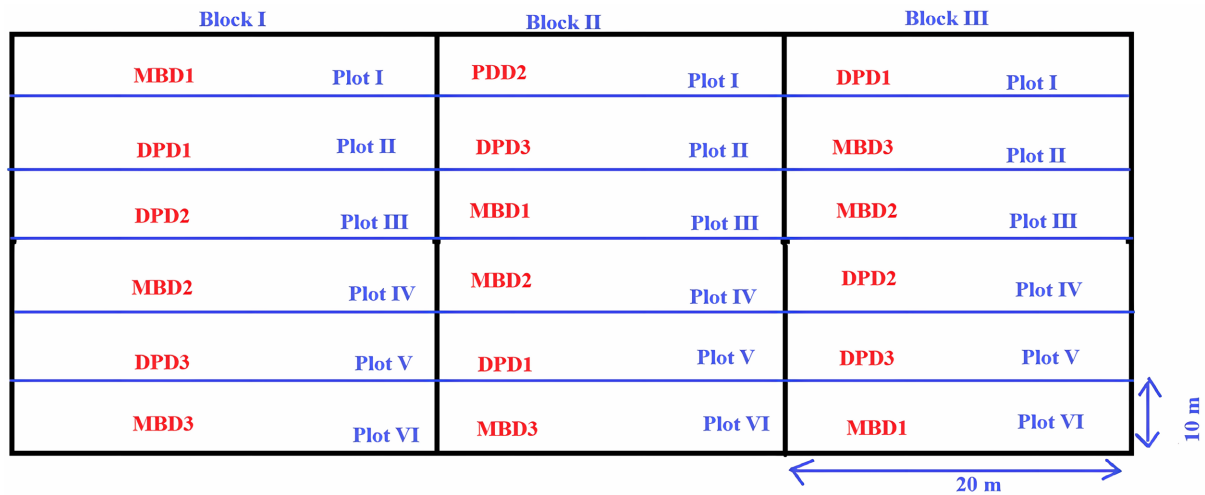


Figure 2. Experimental design for the performance evaluation of tractor-drawn mouldboard and disc plows (Completely randomized design).

2.2.1. Tractor Model and Settings

A detailed specification of tractor and implement settings for the experimental treatments involving mouldboard and disc plows under varying soil conditions in Rwanda. These settings ensure consistency, accuracy, and replicability of the performance evaluation (**Table 1**).

Table 1. Tractor model and settings.

Parameter	Specification
Tractor Model	TYM 60 (or equivalent 60 HP 4 WD tractor)
Ballast	Front: 4 × 40 kg weights Rear: 2 × 50 kg wheel weights
Tyre Pressure	Front: 1.8 bar (26 psi) ≈ 1.828 kg/cm² Rear: 1.4 bar (20 psi) ≈ 1.406 kg/cm²
Speed and Gear Selection	Field work: Medium Speed, 1 st Gear, low range (approx. 4 - 5 km/h)
PTO Setting	Not engaged (plows are ground-driven)
Hydraulic Control	Position control for depth regulation; draft control used in heavy soils

2.2.2. Plows Settings by Type

Proper plow settings are essential for achieving optimal performance, efficiency, and durability in various agricultural and snow management tasks. Plows come in different types such as moldboard, and disc plows and each type requires specific settings tailored to its function, terrain, and operating conditions. These settings can include depth, angle, pitch, and speed, all of which directly influence the quality of the plowing, fuel consumption, and soil or surface impact (**Table 2**).

Table 2. Plows specifications and settings.

1. Mouldboard Plow (3 - bottoms)		Disc Plow (3 - discs)	
Setting	Specification	Setting	Specification
Working Width	60 cm (20 cm per bottom) Shallow: 15 cm	Working Width	75 cm (25 cm per disc) Shallow: 12 cm
Tillage Depths	Medium: 20 cm Deep: 25 cm	Tillage Depths	Medium: 18 cm Deep: 22 cm
Tilt Angle	20° - 25° (adjusted for full soil inversion)	Disc Angle	42° (standard for moderate penetration and soil throw)
Draft Control	Enabled in medium and heavy soils	Tilt Adjustment	Adjusted to match soil resistance and maintain uniform depth
Plow Angle	Adjusted to maintain vertical alignment and reduce side draft	Draft Control	Enabled in heavy soils to maintain consistent depth

2.3. Soil Sampling and Laboratory Analysis

The study area was divided into experimental plots of 10 m × 15 m per each plot, corresponding to the test conditions. Soil samples were collected from each plot to ensure uniformity and representativeness of soil properties across treatments. Sampling was done systematically to account for spatial variability. Differential Global Positioning System (DGPS) was used to map soil sampling points, which will allow the research to spatially represent the sampled points. A zigzag pattern was used within each plot, ensuring coverage of the entire area. The soil samples were collected at depths of 0 - 10 cm to indicate the Surface layer for evaluating soil structure and compaction and 10 - 20 cm to show the subsurface layer relevant for root zone and plow depth. At each depth, at least three subsamples were collected and combined to create a composite sample for analysis.

2.3.1. Data Analysis

The collected soil samples were analyzed by using the sieve analysis method to classify soil as sandy, loamy, or clayey to come up with soil texture classification. The soil bulk Density, was calculated from undisturbed core samples to determine soil compactness. The soil Moisture Content was confirmed by oven-drying the samples at 105°C for 24 hours. In the comparative performance evaluation of tractor-drawn mouldboard and disc plows under varying soil conditions in Rwanda, a range of soil physical properties and field performance indicators were measured to assess the effectiveness and efficiency of each plowing method. These variables are essential for understanding how different plow types interact with soil under diverse conditions, and how they influence operational efficiency, energy consumption, and soil quality outcomes. **Table 3** below presents a concise summary of the key variables used in the study. For each variable, the table outlines its name, the formula used for its computation (where applicable), and the rationale for its inclusion in the research.

Table 3. Summary table of performance metrics measured.

SN	Variable Name	Formula and Why is it Needed
1	Moisture Content	Gravimetric method: Moisture content helps assess soil condition and its impact on plow performance.
2	Bulk Density	$BD = \text{Mass of dry soil} / \text{Total volume}$; indicates soil compaction and suitability for tillage.
3	Porosity	$\text{Porosity} = 1 - (BD / \text{Particle Density})$; shows air/water movement potential in soil.
4	Penetration Resistance	$PR = \text{Force} / \text{Cone base area}$; measures soil strength and resistance to tillage.
5	Soil Adhesion	Qualitative measure; affects how soil sticks to plow surfaces, influencing energy use.
6	Soil Cohesion	Qualitative measure; relates to soil shear strength and plowability.
7	Pulverization Ratio	% of soil <25 mm after plowing; evaluates soil breakdown efficiency.
8	Soil Inversion	% of buried weeds; assesses effectiveness of plow in turning soil.
9	Trench Formation	Depth and width measurements; indicates soil disruption and plow depth control.
10	Fuel Consumption	$FC = (\text{Fuel used} \times 10,000) / \text{Area}$; measures energy efficiency of plowing.
11	Effective Field Capacity	$EFC = (\text{Area} \times 0.36) / (\text{Productive time} + \text{Delay time})$; actual work rate of plow.
12	Theoretical Field Capacity	$TFC = \text{Width} \times \text{Speed} \times 0.36$; ideal work rate under perfect conditions.
13	Field Efficiency	$FE = (EFC / TFC) \times 100$; compares actual vs. theoretical performance.

Source: Researcher, 2025.

2.3.2. Data Analysis Techniques

After data collection, Descriptive analysis first was performed to get general overview of measured parameters by comparing both disc plow and Mouldboard plow. Secondary Analysis of Variance (ANOVA) tests were carried to investigate effects driving speed and plowing depth. Results were recorded using SPSS statistical software Version 27 and STATA 15.0. The Two-Way ANOVA (Analysis of Variance), which is a statistical method used to determine the effect of two independent variables (factors) on a dependent variable, and whether there is any interaction effect between the two factors. In this study, the objective was to evaluate how different plow types (Mouldboard vs. Disc) perform under different soil conditions at different soil cutting depths. During the data analysis, The Tukey test is essential in two-way ANOVA for identifying specific group differences after finding a significant effect. In the context of evaluating the comparative performance of tractor-drawn mouldboard and disc plows under varying soil conditions in Rwanda, its use is justified for several reasons. After two-way ANOVA confirms that there are statistically significant differences due to factors like plow type, cutting depth, or their interaction, the Tukey Honest Significant Difference (HSD) test was used to pinpoint exactly which pairs of means differ. This post-hoc analysis is especially important when dealing with multiple levels of a factor in this case, three soil cutting depths (10 cm, 15 cm, and 20 cm). Tukey's test controls the overall Type I error rate during multiple comparisons, ensuring that the likelihood of falsely detecting a difference remains low. In this study, the Tukey test helps determine whether the performance of the mouldboard and disc plows differs significantly at each of the three depths, and whether changes in depth significantly affect performance within each plow type. It provides clear, statistically sound conclusions for comparing every pair of

treatments, aiding in decision-making and recommendations for optimal plow type and depth combination under specific Rwandan soil conditions.

3. Results and Discussion

3.1. Descriptive Characteristics of Measured Parameters

Descriptive analysis involves summarizing and presenting key characteristics of a dataset, providing an overview and understanding of its main features. This type of analysis is often the first step in data exploration and is essential for gaining insights into the distribution, central tendency, and variability of variables. From this view, **Table 4** indicates the summary of categorical variables of each measured parameters.

Table 4. Descriptive characteristics of measured soil properties.

Depths	Soil Characteristics	Sand	Silt	Clay	MC	BD	Porosity
	Units	%	%	%	%	g/cm ³	%
0 - 10 cm	Obs	6	6	6	6	6	6
	Mean	61.4	29.1	9.5	21.013	1.015	44.267
	SE (mean)	0.292	0.155	0.221	1.579	0.025	1.901
	SD	0.716	0.379	0.542	3.867	0.061	4.657
	Min	60.6	28.5	8.75	16.07	0.957	35.5
	Max	62.2	29.4	10	26.05	1.126	48
	CV	0.012	0.013	0.057	0.184	0.06	0.105
	0 - 15 cm	Obs	6	6	6	6	6
Mean		62.221	28.8	8.979	23.275	1.203	45.5
SE (mean)		0.198	0.219	0.203	1.708	0.024	0.796
SD		0.484	0.537	0.496	4.183	0.058	1.949
Min		61.475	28.2	8	19.85	1.102	44
Max		62.675	29.4	9.375	28.8	1.248	49
CV		0.008	0.019	0.055	0.18	0.048	0.043
0 - 20 cm		Obs	6	6	6	6	6
	Mean	62.775	28.35	8.875	26.095	1.338	45.617
	SE (mean)	0.516	0.353	0.315	1.793	0.009	1.563
	SD	1.263	0.864	0.771	4.392	0.023	3.829
	Min	61.275	27	7.5	21.45	1.311	39.5
	Max	64.3	29.4	9.625	31.2	1.374	49.7
	CV	0.02	0.03	0.087	0.168	0.017	0.084
	Total of the experimental site	Obs	18	18	18	18	18
Mean		62.132	28.75	9.118	23.461	1.185	45.128
SE (mean)		0.239	0.158	0.151	1.049	0.034	0.823
SD		1.013	0.669	0.642	4.449	0.144	3.493
Min		60.6	27	7.5	16.07	0.957	35.5
Max		64.3	29.4	10	31.2	1.374	49.7
CV		0.016	0.023	0.07	0.19	0.122	0.077

Source: Researcher, 2025.

The dataset presented in **Table 4** offers a detailed statistical summary of various soil physical properties measured at different soil depths (0 - 10 cm, 0 - 15 cm, and 0 - 20 cm) at the Gishari Demonstration Farm. The variables considered include sand, silt, clay content, moisture content (MC), bulk density (BD), and porosity.

3.1.1. Change in Soil Texture by Soil Depths

At the shallowest depth of 0 - 10 cm, the mean sand content was recorded at 61.4%, which is relatively high and indicates a sandy texture. The minimum and maximum sand contents were 60.6% and 62.2%, respectively with a standard deviation of 0.716% and a CV of 0.012. These values suggest a relatively uniform sand distribution at this depth. The low CV implies minimal variation among the samples, which is typical in surface layers due to uniform exposure to similar environmental and anthropogenic influences such as tillage and erosion. Silt content averaged 29.1%, ranging from a minimum of 28.5% to a maximum of 29.4%, with a standard deviation of 0.379% and a CV of 0.013. This again reflects a fairly homogeneous distribution of silt particles. The consistency in silt content may be due to the stable deposition environment at the surface. Clay content, with a mean of 9.5%, showed slightly more variability with an SD of 0.542% and a CV of 0.057. This indicates a minor degree of heterogeneity, possibly resulting from differential weathering and micro-scale soil mixing processes.

At the 0 - 15 cm depth, the mean sand content increased slightly to 62.221%, with a narrow range between 61.475% and 62.675%. The standard deviation was 0.484%, and the CV was 0.008, indicating even less variability than in the 0 - 10 cm layer. This suggests a consistent sandy composition in the upper subsoil layer, possibly due to consistent particle size distribution from parent material or uniform agricultural practices. Silt content slightly decreased to 28.8%, with a broader variation range (28.2% to 29.4%), an SD of 0.537%, and a CV of 0.019. This indicates a marginal increase in heterogeneity, possibly due to varying levels of finer material deposition or mixing from below. Clay content at this depth averaged 8.979%, with a minimum of 8% and a maximum of 9.375%, SD of 0.496%, and a CV of 0.055. The clay content variation is still minor but slightly more pronounced than in the 0 - 10 cm layer, reflecting gradual changes in particle size distribution with depth.

At the 0 - 20 cm depth, representing the full plow layer, the sand content further increased to a mean of 62.775%. The range was broader (61.275% to 64.3%), SD 1.263%, and CV 0.02, indicating higher variability than the shallower layers. This could be due to mixing of materials from both surface and subsurface during plowing, which introduces heterogeneity. Silt content dropped slightly to 28.35%, with a wider range (27% to 29.4%), SD 0.864%, and CV of 0.03. The increase in variation may be due to the influence of subsurface materials being incorporated into the sampling depth. Clay content showed a slight decrease to 8.875%, with more variability (range: 7.5% to 9.625%, SD 0.771%, CV 0.087). This variability indicates mixing of finer particles from deeper horizons or uneven weathering processes.

When data from all depths (0 - 10 cm, 0 - 15 cm, and 0 - 20 cm) are aggregated, the general soil texture is dominated by sand, with a mean of 62.132%, indicating a sandy loam texture that is consistent across the site. The sand content varied from 60.6% to 64.3%, with an SD of 1.013% and a CV of 0.016, showing low variability and implying homogeneity in the parent material or long-term uniform management practices. Silt content had a mean of 28.75%, ranging from 27% to 29.4%, with an SD of 0.669% and a CV of 0.023, also suggesting uniformity across the plots. These consistent values are characteristic of soils developed under similar pedogenic conditions and land use. Clay content averaged 9.118%, showing slightly more variability (range: 7.5% to 10%, SD: 0.642%, CV: 0.07). This increase in variation is expected given the finer nature of clay particles, which are more sensitive to soil-forming processes and differential movement through the soil profile.

3.1.2. Change in Bulk Density by Soil Depths

At 0 - 10 cm soil cutting depths, the bulk density (BD) at this depth averaged 1.015 g/cm³, with values ranging from 0.957 to 1.126 g/cm³. The SD was 0.061 and the CV stood at 0.06. These figures indicate moderate variability. The lower bulk density values may be attributed to loose soil structure often found in surface soils due to tillage and organic matter incorporation. At 0 - 15 cm cutting depths, the Bulk density increased to 1.203 g/cm³, with a range between 1.102 and 1.248 g/cm³. The SD was 0.058 and the CV was 0.048, indicating a tighter clustering of values. The higher bulk density in this layer may reflect compaction due to reduced organic matter and limited biological activity compared to the surface. Furthermore, at 0 - 20 cm soil cutting depths, Bulk density was highest at this depth (1.338 g/cm³), ranging from 1.311 to 1.374 g/cm³. The low SD (0.023) and CV (0.017) denote minimal variation, suggesting uniform compaction or soil structure, possibly from repeated plowing to the same depth over time. When data from all depths (0 - 10 cm, 0 - 15 cm, and 0 - 20 cm) are aggregated, the Bulk density had a mean of 1.185 g/cm³, with values from 0.957 to 1.374 g/cm³, an SD of 0.144, and a relatively high CV of 0.122. The variability in BD is closely linked to differences in compaction, organic matter, and soil structure across the plots.

3.1.3. Soil Moisture Content by Soil Cutting Depths

At 0 - 10 cm depth, the Moisture content (MC) showed greater variability with a mean of 21.013%, a minimum of 16.07%, a maximum of 26.05%, an SD of 3.867%, and a CV of 0.184. The relatively high variation in moisture content suggests inconsistent water retention capacity among the samples, likely influenced by micro-topography and organic matter content that can differ significantly at the micro-scale. At 0 - 15 cm depth, the Moisture content increased to a mean of 23.275%, ranging from 19.85% to 28.8%. The SD rose to 4.183% and CV to 0.18, indicating significant variability. This can be attributed to differences in drainage, infiltration rates, and root water uptake, which become more apparent at deeper layers. While at 0 - 20 cm plowing depth, Moisture content increased substantially to a mean of

26.095%, with values ranging from 21.45% to 31.2%. The SD was 4.392% and the CV was 0.168. Increased moisture at this depth is expected due to reduced evaporation and potentially higher water-holding capacity associated with fine particles and organic matter. When data from all depths (0 - 10 cm, 0 - 15 cm, and 0 - 20 cm) are aggregated, the Moisture content across all samples averaged 23.461%, with a wide range (16.07% to 31.2%), SD of 4.449%, and CV of 0.19. This considerable variability can be attributed to spatial differences in organic matter content, porosity, and micro-topography that affect water retention and movement.

3.1.4. Soil Porosity (%) by Soil Depths

During the analysis, at 0 - 10 cm soil cutting depths, the Porosity had a mean of 44.267%, with a wide range from 35.5% to 48%, an SD of 4.657%, and a CV of 0.105. The substantial variation in porosity correlates with the variability observed in bulk density and moisture content, both of which are directly influenced by soil structure and organic matter. When the cutting depths shifted to 0 - 15 cm, Porosity averaged 45.5%, with a tighter range (44% to 49%), SD of 1.949% and CV of 0.043. This consistency in porosity suggests a uniform soil structure likely formed through consistent tillage and cropping activity across the plot, which minimizes variability. At deeper plowing depths of 0 - 20 cm, Porosity averaged 45.617%, ranging from 39.5% to 49.7%. The SD was 3.829% and the CV was 0.084, indicating moderate variability. This variation is likely influenced by changes in bulk density and moisture, as well as compaction differences across the field. When data from all depths (0 - 10 cm, 0 - 15 cm, and 0 - 20 cm) are aggregated, the Porosity averaged 45.128%, ranging from 35.5% to 49.7%, with an SD of 3.493% and a CV of 0.077. This moderate variability reflects changes in soil compaction and structure, which are directly influenced by bulk density and organic matter content.

3.1.5. Variations across All Soil Plowing Depths

The observed variation in soil properties across depths is primarily due to natural soil formation processes and anthropogenic factors such as tillage, cropping patterns, and management history. The topsoil (0 - 10 cm) is typically more influenced by organic matter addition, biological activity, and farming practices, resulting in lower bulk density, higher porosity, and more uniform texture. As depth increases, the influence of these factors diminishes, and the properties tend to reflect the characteristics of the underlying parent material and long-term soil-forming processes. The increasing variability in moisture content with depth is due to changes in water retention capabilities, which are influenced by texture and structure. Similarly, the increase in bulk density with depth is a natural consequence of soil compaction, reduced root penetration, and less organic matter. Variations in porosity directly reflect the interplay between texture, structure, and compaction. To sum up, despite some variations, the soil across the Gishari Demonstration Farm is relatively homogeneous in texture and structure, suggesting consistent land use and management prac-

tices. However, the variability in moisture content and bulk density highlights the need for site-specific management to optimize water use and maintain soil health.

3.1.6. Comparative Statistical Analysis of Soil Properties by Two Way ANOVA

To evaluate whether the differences in soil properties (Sand, Silt, Clay, Moisture Content, Bulk Density, and Porosity) across three plowing depths (0 - 10 cm, 0 - 15 cm, and 0 - 20 cm) are statistically significant, the pairwise independent sample t-tests between the groups were conducted. These tests assess whether the observed differences in mean values are due to random chance or represent true differences in the population. Below is the resulting comparative table with Mean Difference, t-statistic, and P-values, including significance notations: *p < 0.1, **p < 0.05, ***p < 0.001. The two-way ANOVA analysis presented in section 4.2.6 assesses the statistical significance of variations in several soil properties sand, silt, clay content, moisture content, bulk density, and porosity across different plough types and three soil depths (0 - 10 cm, 0 - 15 cm, and 0 - 20 cm). The evaluation is based on F-values and significance (p-values), with statistical thresholds indicated as: *p < 0.1 (marginal significance), **p < 0.05 (significant), and ***p < 0.001 (highly significant).

1) Variation of Sand Soil by across all depths and plows

This section investigates whether the percentage of sand in the soil varies significantly with ploughing depth, plough type, or their interaction. Sand, being a large and stable particle, is expected to show limited changes due to tillage unless significant mixing of soil horizons occurs.

Table 5. Variation of sand soil across all depths and plows.

Tests of Between-Subjects Effects						
Dependent Variable:		% Sandy soil				
Source		Type III Sum of Squares	Df	Mean Square	F	Sig.
Intercept	Hypothesis	69486.813	1	69486.813	24198.844	0.000
	Error	5.743	2	2.871 ^a		
Ploughs Types	Hypothesis	1.240	1	1.240	1.802	0.312
	Error	1.377	2	0.688 ^b		
Depth	Hypothesis	5.743	2	2.871	4.171	0.193
	Error	1.377	2	0.688 ^b		
Ploughs Types X Depth	Hypothesis	1.377	2	0.688	0.908	0.429
	Error	9.097	12	0.758 ^c		

a. MS (Depth); b. MS (Ploughs Types X Depth) and c. MS (Error)

*p < 0.1, **p < 0.05, ***p < 0.001. Source: Researcher, 2025.

The two-way ANOVA results for sand content from **Table 5** reveal that the main effect of plough types has an F-value of 1.802 with a p-value of 0.312, which is statistically insignificant. Similarly, the effect of depth on sand content yielded an F-value of 4.171 and a p-value of 0.193, which also does not reach the threshold for significance. The interaction between plough types and depth shows an F-value of 0.908 and a p-value of 0.429, indicating no significant interaction effect. From this analysis, it can be inferred that neither ploughing depth nor plough type nor their interaction significantly affects the percentage of sand in the soil. The high F-value for the intercept (24198.844, $p < 0.001$) is expected and indicates that the overall model is meaningful, but this does not translate into significant variation due to the independent variables studied. These findings are consistent with studies by [19] and [20], who found that sand content typically remains unchanged under various tillage methods due to its inert and heavy nature. Sand tends not to move vertically or laterally in the soil profile as easily as finer particles like silt or clay.

2) Variation of Silt Soil across all depths and plows

This section evaluates whether the proportion of silt in soil is significantly influenced by either ploughing depth or type, or their interaction. Silt particles are smaller than sand but larger than clay and can be moderately affected by tillage.

Table 6. Variation of silt soil across all depths and plows.

Tests of Between-Subjects Effects						
Dependent Variable:		% Silt soil				
Source		Type III Sum of Squares	DF	Mean Square	F	Sig.
Intercept	Hypothesis	14878.125	1	14878.125	17401.316	0.000
	Error	1.710	2	0.855 ^a		
Ploughs Types	Hypothesis	0.245	1	0.245	0.476	0.562
	Error	1.030	2	0.515 ^b		
Depth	Hypothesis	1.710	2	0.855	1.660	0.376
	Error	1.030	2	0.515 ^b		
Ploughs Types X Depth	Hypothesis	1.030	2	0.515	1.338	0.299
	Error	4.620	12	0.385 ^c		

a. MS (Depth); b. MS (Ploughs Types X Depth) and c. MS (Error)

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.001$. Source: Researcher, 2025.

The analysis for silt content from **Table 6** similarly demonstrates non-significant effects for all sources of variation. The F-value for plough types is 0.476 ($p = 0.562$), for depth is 1.660 ($p = 0.376$), and for the interaction term is 1.338 ($p = 0.299$). None of these values suggest statistical significance at any level. This suggests a homogenous distribution of silt content across the different depths and ploughing practices. The absence of significant variation implies that silt content is primarily influenced by inherent soil characteristics rather

than agricultural intervention through tillage or depth variations. The results align with [21] and [22], who noted minimal changes in silt proportions following tillage, particularly in short-term experiments. Silt may redistribute slightly in highly disturbed systems but tends to remain relatively stable under normal ploughing conditions.

3) Variation of clay Soil across all depths and plows

Clay particles are the finest of the three soil textures and are highly responsive to tillage because they are easily translocated within the profile. This section examines the extent to which ploughing depth and type influence clay content.

Table 7. Variation of clay soil across all depths and plows.

Dependent Variable:		Tests of Between-Subjects Effects				
		% Clay				
Source		Type III Sum of Squares	DF	Mean Square	F	Sig.
Intercept	Hypothesis	1496.501	1	1496.501	2224.476	0.000
	Error	1.345	2	0.673 ^a		
Ploughs Types	Hypothesis	0.383	1	0.383	7.000	0.118
	Error	0.109	2	0.055 ^b		
Depth	Hypothesis	1.345	2	0.673	12.302	0.075
	Error	0.109	2	0.055 ^b		
Ploughs Types X Depth	Hypothesis	0.109	2	0.055	0.127	0.882
	Error	5.177	12	0.431 ^c		

a. MS (Depth); b. MS (Ploughs Types X Depth) and c. MS (Error)

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.001$. Source: Researcher, 2025.

In the case of clay content from **Table 7**, slightly more variation is observed. The effect of plough type has an F-value of 7.000 and a p-value of 0.118, which approaches marginal significance ($*p < 0.1$) but does not cross the threshold. The depth effect yields an F-value of 12.302 with a p-value of 0.075, indicating marginal significance ($*p < 0.1$), suggesting that clay content may be somewhat influenced by soil depth. However, the interaction term is again not significant ($F = 0.127$, $p = 0.882$). These findings suggest that while clay content shows some sensitivity to depth, the influence of plough type and its interaction with depth is minimal. Clay particles, being the finest, often exhibit stronger vertical distribution patterns due to percolation and compaction, which may explain the observed depth-wise variation. These results reflect findings by [23] and [24], who concluded that clay content often increases in surface layers after deep tillage due to horizon mixing. It implies that farmers practicing deep tillage may experience more compacted or sticky soil surfaces as a result of increased clay exposure.

4) Variation of Moisture Content (%) across all depths and plows

This section explores how soil moisture content responds to variations in

ploughing depth and plough type. Since moisture is affected by soil structure and porosity, changes in these physical properties due to tillage can influence retention.

Table 8. Variation of moisture content (%) across all depths and plows.

Dependent Variable:		Tests of Between-Subjects Effects				
		Moisture Content (%)				
Source		Type III Sum of Squares	DF	Mean Square	F	Sig.
Intercept	Hypothesis	9907.627	1	9907.627	254.755	0.004
	Error	77.782	2	38.891 ^a		
Ploughs Types	Hypothesis	0.047	1	0.047	0.016	0.911
	Error	5.953	2	2.977 ^b		
Depth	Hypothesis	77.782	2	38.891	13.066	0.071
	Error	5.953	2	2.977 ^b		
Ploughs Types X Depth	Hypothesis	5.953	2	2.977	0.141	0.870
	Error	252.696	12	21.058 ^c		

a. MS (Depth); b. MS (Ploughs Types X Depth) and c. MS (Error)

*p < 0.1, **p < 0.05, ***p < 0.001. Source: Researcher, 2025.

Moisture content (%) analysis from **Table 8** reveals that, a depth effect with an F-value of 13.066 and a p-value of 0.071, indicating marginal significance (*p < 0.1). The plough type (F = 0.016, p = 0.911) and interaction effect (F = 0.141, p = 0.870) are statistically insignificant. This result suggests that soil depth plays a more critical role in influencing moisture retention compared to the type of ploughing. This aligns with the understanding that deeper soil layers tend to retain more moisture due to reduced evaporation and higher organic matter content. This is consistent with the work of [25] and [26], who reported improved soil moisture retention following deep tillage. These authors noted that tillage can break hardpans and increase porosity, allowing greater water absorption and storage.

5) Variation of Bulk density (g/cm³) across all depths and plows

Bulk density is a key indicator of soil compaction. High bulk density limits root penetration and water movement. This section evaluates the extent to which plough type and depth influence this critical soil parameter.

The analysis of bulk density from **Table 9** shows significant variation with respect to depth, with an F-value of 1845.183 and a p-value of 0.001, indicating a highly significant effect (***p < 0.001). The effect of plough type has an F-value of 8.895 with a p-value of 0.096, which is marginally significant (*p < 0.1). The interaction term is not significant (F = 0.028, p = 0.973). These results imply that both depth and, to a lesser extent, ploughing type influence bulk density. This is consistent with literature that identifies tillage and compaction as key factors affecting soil density. Soil compaction tends to increase with depth due to the weight

of overlying soil and machinery. Similar findings were reported by [27] and [28], who found that different tillage tools and depths can significantly reduce soil bulk density by disrupting compacted layers. The observed effects in this study suggest that appropriate tillage can improve root zone conditions.

Table 9. Variation of bulk density (g/cm^3) across all depths and plows.

Tests of Between-Subjects Effects						
Dependent Variable:		Bulk density (g/cm^3)				
Source		Type III Sum of Squares	DF	Mean Square	F	Sig.
Intercept	Hypothesis	25.283	1	25.283	160.260	0.006
	Error	0.316	2	0.158 ^a		
Ploughs Types	Hypothesis	0.001	1	0.001	8.895	0.096
	Error	0.000	2	8.550E-5 ^b		
Depth	Hypothesis	0.316	2	0.158	1845.183	0.001
	Error	0.000	2	8.550E-5 ^b		
Ploughs Types X Depth	Hypothesis	0.000	2	8.550E-05	0.028	0.973
	Error	0.037	12	0.003 ^c		

a. MS (Depth); b. MS (Ploughs Types X Depth) and c. MS (Error)

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.001$. Source: Researcher, 2025.

6) Variation of Soil Porosity (%) across all depths and plows

Table 10. Variation of soil porosity (%) by two way ANOVA.

Tests of Between-Subjects Effects						
Dependent Variable:		Porosity (%)				
Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	Hypothesis	36657.294	1	36657.294	10918.936	0.000
	Error	6.714	2	3.357 ^a		
Ploughs Types	Hypothesis	0.045	1	0.045	0.009	0.934
	Error	10.363	2	5.182 ^b		
Depth	Hypothesis	6.714	2	3.357	0.648	0.607
	Error	10.363	2	5.182 ^b		
Ploughs Types X Depth	Hypothesis	10.363	2	5.182	0.327	0.728
	Error	190.333	12	15.861 ^c		

a. MS (Depth); b. MS (Ploughs Types X Depth) and c. MS (Error)

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.001$. Source: Researcher, 2025.

Soil porosity affects air and water movement and is inversely related to bulk

density. This section investigates whether tillage treatments significantly influence porosity.

For porosity (%), none of the factors showed significant effects as shown in **Table 10**. Plough type ($F = 0.009$, $p = 0.934$), depth ($F = 0.648$, $p = 0.607$), and their interaction ($F = 0.327$, $p = 0.728$) were all statistically insignificant. This may suggest that porosity, being closely related to bulk density and organic matter, is less sensitive to the short-term effects of depth or ploughing type. Long-term soil management practices may be required to significantly alter porosity. These results differ from [29], who found increased porosity under deep tillage. However, they are more in line with [30], who observed no significant change in porosity in the short term, suggesting that such transformations may require extended tillage periods to be observable.

3.2. Performance of Mouldboard and Disc Plow across All Depths and Plows

Tillage implements such as mouldboard and disc ploughs play a crucial role in soil preparation and directly influence soil physical properties, crop establishment, and ultimately, agricultural productivity. Understanding how these plough types perform under varying conditions is essential for selecting the most effective tillage method, especially in mechanized and semi-mechanized farming systems. To evaluate their effectiveness, statistical tools such as Two-Way Analysis of Variance (ANOVA) can be employed to assess how plough type (mouldboard vs. disc plough) and ploughing depth (e.g., 0 - 10 cm, 0 - 15 cm, 0 - 20 cm) independently and interactively influence key soil physical parameters including soil texture (sand, silt, and clay), moisture content, bulk density, and porosity. This analysis used two-way ANOVA to determine the effect of plough type and depth of ploughing on various performance indicators: cutting width, time used, effective and theoretical field capacity, wheel slip, soil inversion, and fuel consumption. Interpretation is based on the significance levels: $p < 0.1$ (*), $p < 0.05$ (**), and $p < 0.001$ (***) respectively.

3.2.1. Average Cutting Width across All Depths and Plows

Cutting width determines the working width covered by a plough in one pass. It directly influences efficiency and fuel use and their findings are now summarized and presented in **Table 11**.

Plough type significantly influenced cutting width ($F = 53.271$, $p = 0.018^{**}$), indicating different tools cover varying widths. However, ploughing depth ($F = 2.277$, $p = 0.305$) and the interaction term ($F = 0.526$, $p = 0.604$) were not significant. These findings are supported by [31], who found that disc ploughs generally have a wider effective width due to their angular configuration. [20] also noted significant differences in implement width among tillage tools, with disc ploughs covering larger widths in a single pass compared to mouldboard ploughs.

Table 11. Average cutting width across all depths and plows.

Dependent Variable:		Average Cutting Width (m)				
Source		Type III Sum of Squares	DF	Mean Square	F	Sig.
Intercept	Hypothesis	5.501	1	5.501	1644.535	0.001
	Error	0.007	2	0.003 ^a		
Ploughs Types	Hypothesis	0.078	1	0.078	53.271	0.018
	Error	0.003	2	0.001 ^b		
Depth	Hypothesis	0.007	2	0.003	2.277	0.305
	Error	0.003	2	0.001 ^b		
Ploughs Types X Depth	Hypothesis	0.003	2	0.001	0.526	0.604
	Error	0.034	12	0.003 ^c		

a. MS (Depth), b. MS (Ploughs Types X Depth) and c. MS (Error)

$p < 0.1$ (*), $p < 0.05$ (**), and $p < 0.001$ (***)).

3.2.2. Variation of Average Time Used across All Depths and Plows

The time required to complete tillage is a key operational efficiency metric and reflects the working speed and maneuverability of the implement. The findings from two way ANOVA are presented in **Table 12** below.

Table 12. Variation of average time used across all depths and plows.

Tests of Between-Subjects Effects						
Dependent Variable:		Total Field Time (sec)				
Source		Type III Sum of Squares	DF	Mean Square	F	Sig.
Intercept	Hypothesis	10137543.883	1	10137543.883	276.556	0.004
	Error	73312.722	2	36656.361 ^a		
Ploughs Types	Hypothesis	134604.391	1	134604.391	35.093	0.027
	Error	7671.348	2	3835.674 ^b		
Depth	Hypothesis	73312.722	2	36656.361	9.557	0.095
	Error	7671.348	2	3835.674 ^b		
Ploughs Types X Depth	Hypothesis	7671.348	2	3835.674	0.362	0.704
	Error	127253.526	12	10604.460 ^c		

a. MS (Depth), b. MS (Ploughs Types X Depth) and c. MS (Error)

$p < 0.1$ (*), $p < 0.05$ (**), and $p < 0.001$ (***)).

Time use was significantly affected by plough type ($F = 35.093$, $p = 0.027^{**}$) and depth ($F = 9.557$, $p = 0.095^*$), while the interaction term was not significant ($F = 0.362$, $p = 0.704$). Mouldboard ploughs required more time, especially at deeper settings. According to [32], mouldboard ploughs have higher soil engagement and resistance, resulting in slower operation. [33] also reported that disc ploughs are faster due to lower draft force, which supports the findings of this study.

3.2.3. Variation of Effective Field Capacity across All Depths and Plows

Effective field capacity (EFC) reflects the actual area tilled per unit time, accounting for operational inefficiencies such as turning and adjustments, and the summary of findings are now presented in **Table 13**.

Table 13. Variation of effective field capacity across all depths and plows.

Dependent Variable:		Tests of Between-Subjects Effects				
		Effective Field Capacity (Ha/Hr)				
Source		Type III Sum of Squares	DF	Mean Square	F	Sig.
Intercept	Hypothesis	1.363	1	1.363	305.315	0.003
	Error	0.009	2	0.004 ^a		
Ploughs Types	Hypothesis	0.018	1	0.018	314.635	0.003
	Error	0.000	2	5.617E-5 ^b		
Depth	Hypothesis	0.009	2	0.004	79.508	0.012
	Error	0.000	2	5.617E-5 ^b		
Ploughs Types X Depth	Hypothesis	0.000	2	5.617E-05	0.042	0.959
	Error	0.016	12	0.001 ^c		

a. MS (Depth), b. MS (Ploughs Types X Depth) and c. MS (Error)

$p < 0.1$ (*), $p < 0.05$ (**), and $p < 0.001$ (***)

Based on findings presented in **Table 14** below, It was found that Plough type ($F = 314.635$, $p = 0.003^{***}$), and depth ($F = 79.508$, $p = 0.012^{**}$) were statistically significant, while the interaction was not ($F = 0.042$, $p = 0.959$). Disc ploughs provided higher effective capacity, especially at shallower depths. This is consistent with [34], who found that effective capacity is higher in disc ploughs because of reduced soil adhesion. [35] also found significant gains in EFC when plough width and forward speed were optimized, similar to the findings here.

3.2.4. Variation of Theoretical Field Capacity across All Depths and Plows

Theoretical field capacity (TFC) is a function of working width and travel speed, providing an ideal performance value under perfect field conditions, and the summary of key findings are known presented in **Table 14**.

Table 14. Variation of theoretical field capacity across all depths and plows.

Dependent Variable:		Tests of Between-Subjects Effects				
		Theoretical Field Capacity (Ha/Hr)				
Source		Type III Sum of Squares	DF	Mean Square	F	Sig.
Intercept	Hypothesis	2.023	1	2.023	4222.331	0.000
	Error	0.001	2	0.000 ^a		
Ploughs Types	Hypothesis	0.033	1	0.033	356.951	0.003
	Error	0.000	2	9.372E-5 ^b		

Continued

Depth	Hypothesis	0.001	2	0.000	5.111	0.164
	Error	0.000	2	9.372E-5 ^b		
Ploughs Types X Depth	Hypothesis	0.000	2	9.372E-05	0.159	0.855
	Error	0.007	12	0.001 ^c		

a. MS (Depth), b. MS (Ploughs Types X Depth) and c. MS (Error)

p < 0.1 (*), p < 0.05 (**), and p < 0.001 (***)

Plough type was highly significant (F = 356.951, p = 0.003***), whereas depth (F = 5.111, p = 0.164) and the interaction term (F = 0.159, p = 0.855) were not significant. This indicates that implement design is the main contributor to TFC. [36] and [37] noted that disc ploughs, due to their broader working width, offered higher theoretical capacity. [38] reinforced that TFC variations are mainly tied to machine geometry, confirming that depth alone has minimal impact.

3.2.5. Variation of Wheel Slip (%) across All Depths and Plows across All Depths and Plows

Wheel slip refers to loss of traction by the tractor wheels, influenced by soil type, ploughing depth, and draft force. Excessive slip reduces fuel efficiency and increases wear, and the summary of key findings are now presented in **Table 15**.

Table 15. Variation of wheel slip (%) across all depths and plows.

Tests of Between-Subjects Effects						
Dependent Variable:		Wheel slip (%)				
Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	Hypothesis	6404.479	1	6404.479	275.806	0.004
	Error	46.442	2	23.221 ^a		
Ploughs Types	Hypothesis	16.340	1	16.340	13.026	0.069
	Error	2.509	2	1.254 ^b		
Depth	Hypothesis	46.442	2	23.221	18.511	0.051
	Error	2.509	2	1.254 ^b		
Ploughs Types X Depth	Hypothesis	2.509	2	1.254	1.977	0.181
	Error	7.614	12	0.635 ^c		

a. MS (Depth), b. MS (Ploughs Types X Depth) and c. MS (Error)

p < 0.1 (*), p < 0.05 (**), and p < 0.001 (***)

Both plough type (F = 13.026, p = 0.069*) and depth (F = 18.511, p = 0.051*) were marginally significant at 10% level of probability. The interaction effect was not (F = 1.977, p = 0.181). Wheel slip increased with depth and was higher for mouldboard ploughs. Abubakar *et al.* (2013) observed that disc ploughs typically induce less wheel slip due to their smoother penetration and rolling action. [39]

similarly found that deeper tillage significantly increased wheel slip, confirming both main effects found here.

3.2.6. Variation of Soil Inversion across All Depths and Plows

Soil inversion reflects the degree to which soil is flipped, affecting residue management, aeration, and weed control. It is particularly relevant in comparing primary tillage implements. **Table 16** presents the key findings related to soil inversion or weeds counts.

Table 16. Variation of soil inversion across all depths and plows.

Dependent Variable:		Tests of Between-Subjects Effects				
		Soil Inversion Or weed Count (%)				
Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	Hypothesis	115392.080	1	115392.080	3691.169	0.000
	Error	62.523	2	31.262 ^a		
Ploughs Types	Hypothesis	6.969	1	6.969	3.907	0.187
	Error	3.568	2	1.784 ^b		
Depth	Hypothesis	62.523	2	31.262	17.524	0.054
	Error	3.568	2	1.784 ^b		
Ploughs Types X Depth	Hypothesis	3.568	2	1.784	0.030	0.970
	Error	711.980	12	59.332 ^c		

a. MS (Depth), b. MS (Ploughs Types X Depth) and c. MS (Error)

$p < 0.1$ (*), $p < 0.05$ (**), and $p < 0.001$ (***)

Depth was significant ($F = 17.524$, $p = 0.054^*$), but plough type ($F = 3.907$, $p = 0.187$) and the interaction term ($F = 0.030$, $p = 0.970$) were not. Greater depths increased inversion irrespective of plough type. These results are supported by [40], who found that deeper tillage enhanced residue burial. Furthermore, the study conducted by [41] also noted that inversion is depth-dependent and more pronounced at 20 cm depth, supporting the observed trends.

3.2.7. Variation of Fuel Consumption (L) across All Depths and Plows

Fuel consumption is a major operational cost in mechanized tillage. It is affected by soil resistance, plough geometry, working depth, and wheel slip. The summary of key findings was presented and summarized in **Table 17**.

Based on findings shown in **Table 17**, it was found that none of the factors showed a significant effect: plough type ($F = 0.090$, $p = 0.793$), depth ($F = 1.530$, $p = 0.395$), and interaction ($F = 0.970$, $p = 0.407$). These results suggest fuel usage remained consistent across treatments. Contrary to [42], who found mouldboard ploughs to consume more fuel, this study's results indicate minimal differences in fuel consumption, potentially due to uniform field conditions or tractor efficiency. [43] similarly found negligible differences when tillage was performed on uni-

formly moist soils.

Table 17. Variation of Fuel consumption (L) across all depths and plows.

Tests of Between-Subjects Effects						
Dependent Variable:		Fuel Consumption (L)				
Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	Hypothesis	10411.245	1	10411.245	2487.753	0.000
	Error	8.370	2	4.185 ^a		
Ploughs Types	Hypothesis	0.245	1	0.245	0.090	0.793
	Error	5.470	2	2.735 ^b		
Depth	Hypothesis	8.370	2	4.185	1.530	0.395
	Error	5.470	2	2.735 ^b		
Ploughs Types X Depth	Hypothesis	5.470	2	2.735	0.970	0.407
	Error	33.840	12	2.820 ^c		

a. MS (Depth), b. MS (Ploughs Types X Depth) and c. MS (Error)

$p < 0.1$ (*), $p < 0.05$ (**), and $p < 0.001$ (***)

The performance of mouldboard and disc ploughs at different depths, as evaluated through Two-Way ANOVA, reveals nuanced insights based on F-values and p-values across several operational parameters. Cutting width was significantly influenced by plough type ($F = 53.271$, $p = 0.018$), with disc ploughs covering a wider swath, while depth ($F = 2.277$, $p = 0.305$) and the interaction between plough type and depth ($F = 0.526$, $p = 0.604$) were not significant, indicating that width differences are inherent to the implement design rather than depth settings. Time used for tillage was significantly affected by both plough type ($F = 35.093$, $p = 0.027$) and depth ($F = 9.557$, $p = 0.095$), suggesting that mouldboard ploughs, especially at deeper settings, are slower due to higher soil resistance. However, the interaction effect was not significant ($F = 0.362$, $p = 0.704$), implying that the time difference is consistent across depths. Effective field capacity (EFC) showed strong significance for both plough type ($F = 314.635$, $p = 0.003$) and depth ($F = 79.508$, $p = 0.012$), with disc ploughs performing better, particularly at shallower depths. The interaction was not significant ($F = 0.042$, $p = 0.959$), reinforcing that the advantages of disc ploughs are consistent regardless of depth.

Theoretical field capacity (TFC) was significantly influenced by plough type ($F = 356.951$, $p = 0.003$), but not by depth ($F = 5.111$, $p = 0.164$) or the interaction ($F = 0.159$, $p = 0.855$), indicating that the implement's geometry, rather than operational depth, dictates theoretical efficiency. Wheel slip was marginally significant for both plough type ($F = 13.026$, $p = 0.069$) and depth ($F = 18.511$, $p = 0.051$), with mouldboard ploughs and deeper tillage causing more slip. The interaction was not significant ($F = 1.977$, $p = 0.181$), suggesting independent effects of type and depth on traction loss. Soil inversion was significantly affected by depth ($F = 17.524$, $p =$

0.054), but not by plough type ($F = 3.907$, $p = 0.187$) or their interaction ($F = 0.030$, $p = 0.970$), indicating that deeper tillage enhances inversion regardless of the implement used. Fuel consumption showed no significant differences across plough type ($F = 0.090$, $p = 0.793$), depth ($F = 1.530$, $p = 0.395$), or interaction ($F = 0.970$, $p = 0.407$), suggesting uniform energy use under the tested conditions.

4. Conclusion and Recommendations

The study assessed soil physical properties which affect tractor plow performance and economic viability of tillage operations at Gishari Demonstration Farm, Rwanda. The following conclusions were drawn based on the study's specific objectives and results findings. The study at Gishari Demonstration Farm revealed critical insights into soil properties under different tillage conditions. Soil texture remained predominantly sandy loam across all depths (0 - 10 cm, 0 - 15 cm, 0 - 20 cm), with sand content averaging 62.132% showing minimal variation ($CV = 0.016$). While sand and silt content showed no significant variation with depth or plow type ($p > 0.05$), clay content exhibited marginal sensitivity to depth ($F = 12.302$, $p = 0.075$), Bulk density increased significantly with depth ($F = 184.5183$, $p = 0.001$), ranging from 1.015 g/cm^3 at 0 - 10 cm to 1.338 g/cm^3 at 0 - 20 cm, indicating natural compaction. Moisture content showed depth-dependent variation ($F = 13.066$, $p = 0.071$), increasing from 21.013% at surface to 26.095% at deeper layers. Porosity remained relatively stable (45.128% average) with no significant treatment effects ($p > 0.05$). Spatial analysis confirmed these patterns, showing homogeneous texture distribution but variability in bulk density ($1.2 - 1.6 \text{ g/cm}^3$) and moisture (10% - 30%) across the farm. The comparative evaluation of Mouldboard (MB) and Disc Plows (DP) revealed distinct operational characteristics. MB plows demonstrated superior soil inversion (78% - 83.5%) but required 15% - 25% more operational time and showed higher wheel slip (17.5% - 22.4%). DP plows exhibited better field efficiency (93.7% at 0 - 10 cm) and lower wheel slip (16.6% - 19.6%), though with slightly reduced inversion capability (78% - 81.5%). Statistical analysis confirmed plow type significantly affected cutting width ($F = 53.271$, $p = 0.018$) and time use ($F = 35.093$, $p = 0.027$), while depth primarily influenced wheel slip ($F = 18.511$, $p = 0.051$) and bulk density ($F = 1845.183$, $p = 0.001$). Fuel consumption differences were negligible ($p > 0.05$), averaging 23 - 25 liters across treatments. In swift disc plough operations, disc ploughs demonstrated superior performance over mouldboard ploughs in terms of working width, operational speed, and overall field capacity. However, ploughing depth emerged as a more influential factor in achieving effective soil inversion and minimizing wheel slip. The study therefore concludes that the Interaction effects were consistently non-significant, indicating that the performance trends of each implement are stable across different depths at the site.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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