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Soil hydraulic properties under different land use types and soil depth at Arjo-Dhiddessa estate sugar factory, Western Ethiopia

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The infiltration process is a significant driver of soil quality and ecological performance that is influenced by several factors, including the soil's hydraulic characteristics, land use types, and soil depth. This study examines the effects of land use types and soil depth on soil hydraulic properties at the Arjo-Dhiddessa Estate Sugar Factory in Western Ethiopia. Composite soil samples were collected from five distinct land-use types (cropland, irrigated land, forest land, shrubland, and fallow land) at three different soil depths (0–30 cm, 30–60 cm, and 60–90 cm). Field infiltration rates were measured using a double-ring infiltrometer to assess variations in soil hydraulic properties. Results revealed significant variations in soil hydraulic properties among land-use types. Forestland exhibited the highest field capacity (51.46%), available water-holding capacity (21.23%), and soil moisture content (23.74%). In contrast, irrigated land demonstrated the lowest infiltration rates (19.6 cm/hr) and sorptivity (75.3 cm/hr), attributed to soil compaction and nutrient depletion. Hydraulic properties also varied with soil depth, showing diminished water retention and infiltration in deeper layers. These findings highlight the necessity for diversified land management strategies to optimize soil health and water resource sustainability. Integrating forest and shrubland conservation practices can enhance soil organic matter and structural integrity. Additionally, adopting techniques such as conservation tillage and reforestation may mitigate soil degradation and compaction, fostering sustainable agricultural productivity. This study underscores the pivotal role of land use in governing soil hydraulic dynamics. The results advocate for management approaches that prioritize soil health and hydrological efficiency, particularly through the preservation of forest and shrubland ecosystems. By implementing these strategies, policymakers and land managers can support long-term agricultural resilience amid ongoing land-use changes.

KEYWORDS

ecosystem services, infiltration, soil hydraulic function, soil physical properties, soil

Highlights

- The study investigates how different land use types, such as farmland, fallow land, forest, and irrigated land, affect soil hydraulic properties.
- The findings reveal that forestlands have superior soil hydraulic properties, including higher field capacity (51.46%) and available water-holding capacity (21.23%).
- The study emphasizes how crucial sustainable farming methods are essential to preserving water supplies and soil health
- The study suggests conservation tillage to enhance water retention and reduce soil erosion.
- According to the study, sorptivity and transmissivity significantly decrease on irrigated land, indicating challenges including nutrient depletion and soil compaction.

1 Introduction

Environmental degradation is largely caused by changes in land use types, which have a major effect on biodiversity, soil health, hydrological cycles, and ecosystem services globally. Land-use activities that drastically change the amount of organic matter, soil structure, and water dynamics include deforestation, agricultural expansion, and urbanization. These changes can lead to soil compaction, reduced infiltration rates, increased surface runoff, and disruption in groundwater recharge processes (1–4). The soil's ability to retain and move water is directly impacted by land management practices, and this ability is critical for plant growth, nutrient cycling, and ecosystem stability (5, 6).

Ethiopia has significant environmental challenges due to rapid LULC changes, as do many developing countries. The expansion of agricultural land, overgrazing, and deforestation have led to increased soil erosion, decreased soil fertility, and disturbed hydrological balances. Large-scale agricultural initiatives, particularly irrigation projects, have made soil degradation and water resource constraints worse (7, 8). The conversion of natural landscapes into agricultural fields without the application of sustainable land management techniques puts long-term agricultural productivity and environmental sustainability at particular risk because it exacerbates soil compaction and reduces infiltration capacity (9, 10).

Ethiopia continues to attempt to encourage economic growth and industrialization through agro-industrial development, particularly through large sugarcane estates such as Arjo-Dhidhessa Sugar Estate. However, there are significant environmental effects associated with the implementation of such extensive irrigation schemes. The production of sugarcane, which demands extensive irrigation and land modification, changes the hydrological processes and soil structure, frequently leading to a reduction in soil permeability and an increased susceptibility to land degradation (11). Despite their economic significance, if soil-

water interactions are not properly managed, these agro-industrial developments may unintentionally jeopardize soil health and water supplies.

Land use has a significant impact on essential soil hydraulic properties such as infiltration rate, water retention capacity, and moisture dynamics that are critical for sustaining agricultural productivity and ecosystem health (12, 65). While most of present-day study is focused on surface-level changes, changes in land cover affect both subsurface and surface soil properties. It is important to understand the depth-specific impacts of different land uses before designing sustainable land and water management plans, especially in intensive agricultural systems like irrigated sugarcane plantations.

Previous studies have evaluated regional hydrological implications (13) and irrigation possibilities (66) in the Dhidhessa River Basin. However, there are still important gaps in the knowledge of how land-use changes brought about by agro-industrial irrigation affect water-holding capacity, field capacity, wilting point, and infiltration rates across different land uses and soil depths under intensive sugarcane cultivation and the empirical relationships between land-use practices, soil compaction, and hydraulic characteristics in Ethiopia's agro-industrial systems. While surface-level consequences are the focus of current study, subsurface differences that are crucial for sustainable land management are overlooked.

This study aims to address these gaps by evaluating certain soil hydraulic characteristics (such as moisture content, water retention, and infiltration rate) at the Arjo-Dhidhessa Sugar Estate under various land use types and soil depths. The study aims to encourage solutions that decrease soil degradation, increase irrigation effectiveness, and improve agricultural resilience in Ethiopia's rapidly changing agro-industrial landscapes by integrating spatial and depth-resolved soil data. Therefore, the main objective of this study is to evaluate selected soil hydraulic properties under varied land use types and soil depths at the Arjo-Dhidhessa Estate Sugar Factory.

2 Materials and methods

2.1 Description of the study area

2.1.1 Study area and location map

Arjo-Dhidhessa Sugar Estate is located in the East Wallaga Zones, Oromia region, 395 km from Addis Ababa and 18 km from Jimma Arjo District (Figure 1). The factory shares boundaries with specific areas of the Buno Bedele and Jimma Zones, which are located in the west of Ethiopia, at 7°36'00" and 9°36'00" North and 35°32'00" and 37°34'00" East. The average altitude of the area is 1,350 m above sea level (a.s.l.). The region experiences a hot and humid climate. The slope distribution in the region shows that approximately 67.2% of the area has slopes greater than 8%, whereas the remaining 32.8% range from mild to less severe (< 8%) (14).

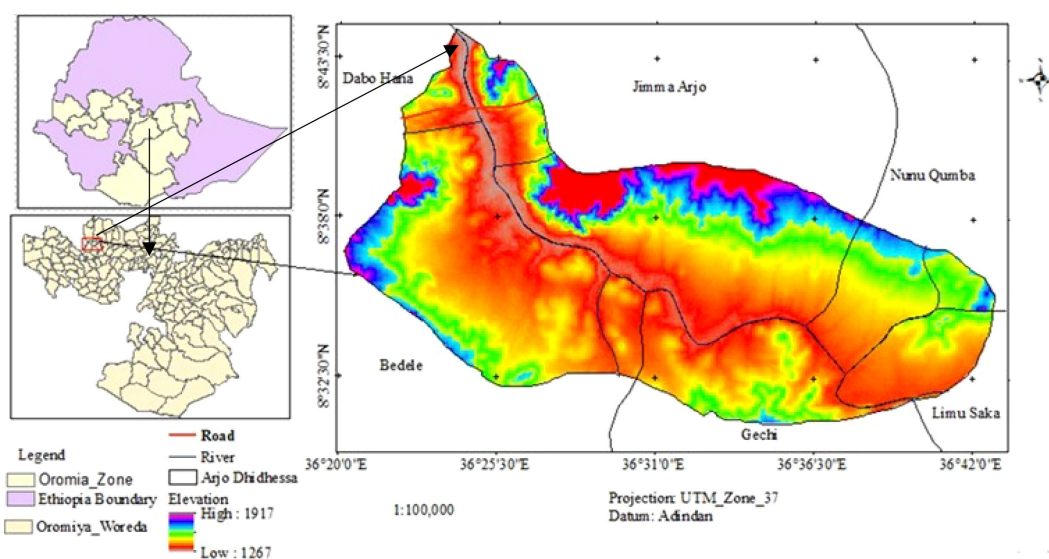


FIGURE 1
Map of the study area.

2.1.2 Soil and geology

The Arjo-Dhidhessa have a variety of soil types that are interconnected to the region's geomorphology. The soil types are mostly black soil and occasionally red and brown soil, which makes it suitable for sugarcane development (15). The soils of the area are well-drained, clay loam-to-clay-textured that characterize the soils of a plateau that are stream-dissected and have flat to mild undulations (16). Precambrian basement rocks, which are high-grade genetic and pre-tectonic granites that are part of the Algae group, comprise the majority of the research area (17).

2.1.3 Climate

The study area receives 1,400 mm of unimodal annual rainfall, with the rainy season dominating from May to October. The rainfall maximum is in July (428.3 mm), and the trough is in January (16.98 mm) (Figure 2). The average monthly temperature is 23.7°C, with monthly extremes ranging from 11.2°C (lowest) to 38.5°C (highest). The annual temperature varies moderately. Monthly highs range from 29 to 29–38.5°C, while monthly lows stay between 11.2 and 11.2–17.1°C, indicating a moderate, seasonally stable climatic regime.

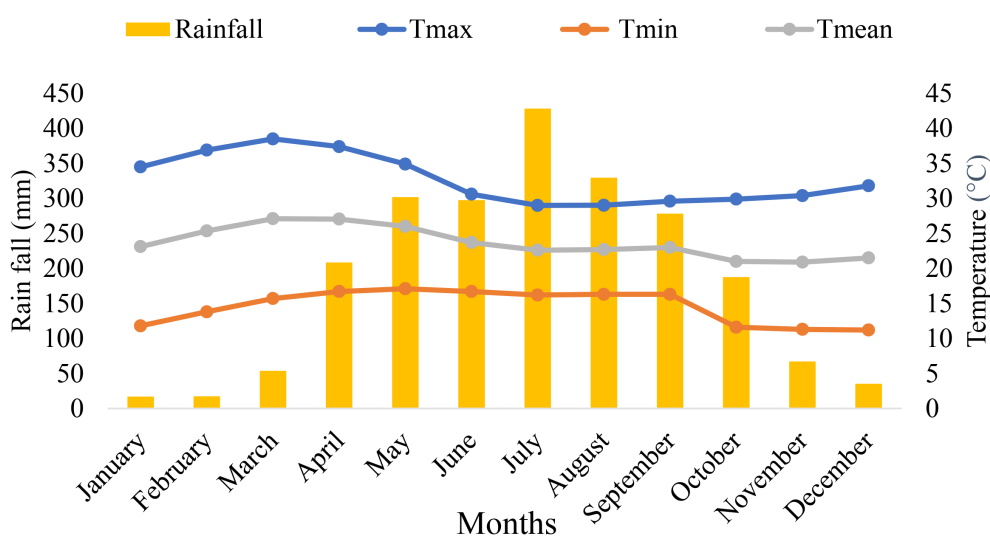


FIGURE 2
Rainfall and temperature distributions in the study area.

2.2 Methodology

2.2.1 Soil sample collection and preparation

To obtain a basic idea of the variances in the study area, an image-based survey was first carried out. To choose sampling sites that are typical of the land use system in Arjo-Dhidhessa Estate Sugar Factory, western Ethiopia, consideration was given to the available land use types. Five main land use types and vegetation categories, cropland, forestland, irrigated land, fallow land, and shrub land, were identified in the study area on the basis of the available land use type histories. The soil was randomly sampled via a soil auger for each land use type. The GPS coordinates of the sampling locations are shown in Figure 3. There were five typical (20 m × 20 m) plots for each form of land use type next to the forest, with a maximum distance of 200 m between them. Subsamples from each of the three depths of soil samples were used to produce a single composite sample, which was then taken from each plot via a basic random technique for each land use type. Each sampling location was cleared of gravel debris, tree roots, and nearby regions before the collection of the soil samples.

For all types of land use, three soil depths were used to collect samples of both disturbed and undisturbed soil. Thus, a total of 15 undisturbed and 15 composite soil samples were collected at three different soil depths (0–30, 30–60, and 60–90 cm).

To determine the bulk density and soil moisture content, undisturbed soil samples were collected from the pits at three distinct depths via a core sampler. Except for total nitrogen (TN) and organic carbon (OC), which were run through a 0.5 mm sieve, packed in a labeled polyethylene bag, authorized, and delivered to the soil testing laboratories of Fincha Sugar Estate and the central soil laboratory of Haromaya University, the collected combined soil samples were dried in the air, carefully mixed, smashed and passed through a 2 mm sieve for each parameter examined.

2.2.2 Analysis and processing of soil samples

The United States Department of Agriculture (USDA) is a visual tool dispersion of the soil particles (sand, silt, and clay) to determine a soil's textural class and is based on the hydrometer methods described by Bouyoucos (18). A gravimetric moisture content was determined as the mass of moisture in the soil sample divided by the mass of the dry soil multiplied by 100 (19).

The core technique was used to determine the bulk density and total porosity of the soil (Equations 1, 2), whereas the gravimetric approach was used to determine the soil water content.

$$\text{Bulk Density}(\rho_b) = \frac{\text{Dry mass of soil sample (DM)}}{\text{Volume of the core sampler (cm}^3\text{)}} \quad (1)$$

Where ρ_b is expressed in (g/cm³), DM is the dry mass in grams, and Vis is the volume of the core sampler in (cm³).

The total porosity was calculated from the measurements of the dry bulk density (ρ_b) of the soil and the soil particle density (ρ_s) as follows:

$$\text{Total porosity (\%)} = \left(1 - \frac{\rho_b}{\rho_s}\right) \times 100 \quad (2)$$

where ρ_b is the bulk density (g cm⁻³) and ρ_s is the particle density, which is assumed to be 2.65 g cm⁻³.

A pressure device apparatus was used to measure the field capacity and permanent wilting point at 33kpa, according to the method described by Klute and Dirksen (20). Available water capacity was measured as the difference between field capacity and permanent wilting point and then multiplied by 1000 to express it in millimeters per meter of soil depth.

A pH potentiometer (model-4070) was used to measure the soil pH (1:2.5) (67). The Walkley and Black method by dichromate oxidation techniques was used to measure the soil organic carbon (SOC) (68) and the organic matter in the soil (SOM) was obtained

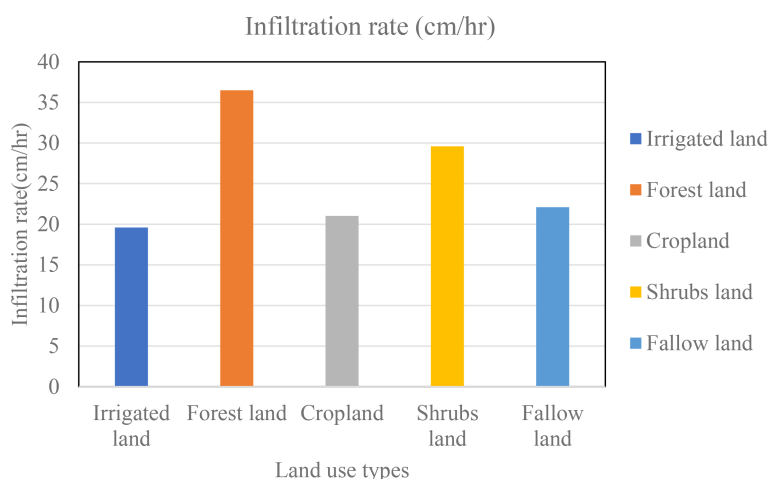


FIGURE 3
Infiltration rate across land use types.

by multiplying the SOC values by 1.724 (organic matter = $1.724 \times \%$ carbon). The Kjeldahl digestion, distillation, and titration methods were used to quantify total nitrogen.

2.2.3 Experimental site and area characterization

2.2.3.1 Measurement of infiltration rates

The soil infiltration rate was measured using a double ring infiltrometer (Humboldt Mfg. Co., Elgin, IL, USA, ASTM D3385-09) in accordance with the ASTM (21) established procedure for field infiltration testing. To assist with the measurements, we also used some basic tools, including a wooden plank, a water-filled jar, a scale and ruler, a timer, a calculator, a cross-shaped galvanized steel plate, and a steel hammer.

The infiltrometer consisted of two concentric rings with inner and outer diameters of 30 and 60 cm, respectively. Both rings were 25 cm in height, composed of 12-gauge steel, and featured sharpened bottom edges for easier insertion into the ground. Making sure that around 5 cm of each ring was above the soil's surface, we hammered the rings into the ground with the steel hammer and galvanized plate.

To reduce extra resistance to water infiltration, we carefully eliminated any grass or vegetation inside the inner ring area before the tests. The outer edges of the ring were carefully tamped to prevent soil disturbance or leaks, and a pad was positioned inside the inner ring to stop puddling as water was being poured.

The infiltration testing procedure involved the following steps:

- ✓ Simultaneously filling both the inner and outer rings with water to a depth of at least 5 cm.
- ✓ Maintain roughly equal water levels in both rings throughout the test to limit lateral flow from the inner ring.
- ✓ Recording the drop in water level inside the inner ring at specific time intervals: 2, 5, 10, 20, 30, 45, and 60 minutes.
- ✓ Calculating cumulative infiltration and infiltration rates based on the recorded measurements.
- ✓ Continue the test until the rate of water level decrease slows significantly, indicating that a steady state has been reached.

The infiltration rate was recorded as the terminal (steady state) infiltration rate once it had stabilized. Measurements were performed between March and May for five different land use types, with 15 replicate samples for each type. All fieldwork was conducted in the same weather situations during the day to maintain consistency. For each land use type, the complete process was repeated in order to provide reliable assessments of the behaviors of soil infiltration.

2.2.4 Sorptivity and transmissivity

Field data were analyzed using the estimated linear infiltration formula of Philip (69) to determine sorptivity and transmissivity, which is a measure of a soil's ability to retain or conduct water flow. The fundamental information consisted of determining

accumulated infiltration (I_c) values as a function of time reported in centimeters (Equation 3).

$$I_c = St^{1/2} + At \quad (3)$$

where I_c (cm) represents the accumulated infiltration at time t (s). The sorptivity of the soil water, $S(\text{cm}/\sqrt{t})$, was determined from the slope of I_c vs. \sqrt{t} , where $A(\text{cm}^{-1})$ is the transmissivity obtained from the intercept of the infiltration rate equation (Equation 4).

$$IR = \frac{1}{2}St^{-1/2} + A \quad (4)$$

2.2.5 Statistical analysis

The statistical analysis was conducted using an Excel spreadsheet and R Software (Version 4.3.2, Boston, MA, USA). To find variations in the soil properties between the various land use categories and soil depths ($P < 0.05$), a test of variance (ANOVA) was employed. LSD tests are used for mean comparisons when ANOVA indicates significant variation ($P < 0.05$) due to LSD's focus on specific comparisons; it can be easier to interpret in certain experimental designs.

3 Results and discussions

3.1 Effects of land use types and soil depth on selected soil hydraulic properties

3.1.1 Particle size distribution (sand, silt, and clay)

The particle size distribution (clay, silt, and sand) varies significantly ($P \leq 0.01$) and is affected by the interaction of land use and soil depth (Table 1). Compared with fallow and irrigated land, the surface layer of forestland had the highest percentages of sand (27.28%) due to the interaction effects of land use and soil depth. Conversely, the bottom surface layer of the cropland had the maximum amount of clay (72.16%), whereas the top layer of fallow land had the minimum amount of clay (54.56%) (Table 1).

The higher sand and silt contents in forestland under the surface layer could be attributed to factors such as organic matter decomposition, leaf litter, and root growth, which can enhance the soil structure and increase sand and silt accumulation. On the other hand, the higher clay content in the subsurface layer of cropland may be due to tillage practices, which can mix and redistribute soil particles, leading to a higher clay content at greater depths (70, 71, 22). The current results are in line with those of Masha et al. (23), who noted that because the soil selectively removes clay fractions from the surface, croplands have lower clay fractions and higher sand fractions. The accumulation of organic matter and vegetation cover under forestland is what causes the highest amount of clay, although significant rainfall in the area may be the cause of the highest sand content (22). While the sand and silt contents reduce the soil depth in the soil profile from the surface to the subsurface, the clay content increases under all land use types (24, 72, 25).

TABLE 1 Effects of different land use types on some soil physicochemical properties.

Land Use	Depth	pH	SOM	TN	ρ_b	Tp	Sand	Silt	Clay	Soil
	(cm)		(%)	(%)	(gm^{-3})	(%)	(%)	(%)	(%)	Texture
FaL	0-30	5.8 ^a	2.16 ^a	0.123 ^a	1.2 ^a	54.72 ^b	27.36 ^a	18.08 ^{cd}	54.56 ^b	Clay
FaL	30-60	5.3 ^a	2.15 ^a	0.123 ^a	1.3 ^a	50.94 ^c	20.32 ^c	17.2 ^{cde}	63.48 ^{de}	Clay
FaL	60-90	5.11 ^a	1.49 ^a	0.112 ^a	1.4 ^a	47.17 ^{de}	17.56 ^{de}	16.44 ^{ghi}	66 ^c	Clay
CL	0-30	5.6 ^a	1.94 ^a	0.124 ^a	1.35 ^a	47.92 ^d	20.08 ^c	15.44 ^{fgh}	58.48 ^{fg}	Clay
CL	30-60	5.4 ^a	1.77 ^a	0.123 ^a	1.38 ^a	46.79 ^{de}	23.4b	14.12 ^{hij}	62.38 ^c	Clay
CL	60-90	5.12 ^a	1.29 ^a	0.101 ^a	1.43 ^a	44.15 ^{fg}	15.36 ^f	12.48 ^{def}	72.16 ^a	Clay
FL	0-30	6.2 ^a	2.45 ^a	0.138 ^a	1.3 ^a	50.94 ^c	27.28 ^a	13.24 ^{ijk}	59.48 ^f	Clay
FL	30-60	5.73 ^a	2.5 ^a	0.127 ^a	1.2 ^a	54.72 ^b	19.04 ^{cd}	14.4 ^{hi}	66.23 ^c	Clay
FL	60-90	5.6 ^a	1.89 ^a	0.114 ^a	1.23 ^a	50.18 ^c	17.44 ^{de}	12.48 ^{jk}	70.16 ^b	Clay
IL	0-30	5.3 ^a	2.15 ^a	0.123 ^a	1.3 ^a	50.9 ^c	22.28 ^b	20.16 ^a	52.56 ^g	Clay
IL	30-60	5.1 ^a	1.89 ^a	0.122 ^a	1.38 ^a	45.66 ^{ef}	20.36 ^c	19.8 ^{bc}	59.84 ^{de}	Clay
IL	60-90	5.73 ^a	1.58 ^a	0.102 ^a	1.34 ^a	50.94 ^c	17.32 ^e	18.44 ^{bc}	62.91 ^{de}	Clay
ShL	0-30	6.1 ^a	2.3 ^a	0.126 ^a	1.2 ^a	54.72 ^b	26.36 ^a	16.08 ^{efg}	57.47 ^{de}	Clay
ShL	30-60	5.8 ^a	2.27 ^a	0.125 ^a	1.32 ^a	50.94 ^c	23.44 ^b	14.48 ^{ghi}	62.08 ^e	Clay
ShL	60-90	5.5 ^a	1.58 ^a	0.12 ^a	1.34 ^a	50.94 ^c	19.36 ^c	16.48 ^{def}	64.16 ^d	Clay
SEM (\pm)		0.57	0.58	0.01	0.63	0.57	0.57	0.42	0.36	
LSD (0.05)		1.63	1.67	0.02	0.96	1.67	1.67	0.96	1.05	
CV (%)		17.9	18.3	7.1	16.76	2	6.9	6.3	1.74	
P-v value		Ns	**	**	***	***	***	***	***	

Mean values followed by different letters are significantly different and the same letters are not significantly different, non-significant (Ns), highly significant at ($P < 0.01$)** and ($P < 0.001$ ***, SEM, Standard Mean Error; CV, Coefficient of Variance; ρ_b , Bulk density; Tp, Total Porosity; SOM, Soil Organic matter; FaL, Fallow land; CL, Cropland; FL, Forestland; IL, Irrigation land; and ShL, Shrub land.

3.1.1 Bulk density

The bulk density (ρ_b) was substantially ($P > 0.05$) not influenced by the interaction between land use and soil depth (Table 1). Considering the main effect of land use and soil depth, subsurface cropland had the highest bulk density (1.43 g/cm^3), and the surface layer of forestland had the lowest bulk density (1.2 g/cm^3) (Table 1). This result is in line with findings of Regassa et al. (26) Tigist et al. (27), and Haile et al. (72), who reported that the cultivated areas in the western Ethiopian region of Abobo presented the lowest bulk densities in the surface soil layer (0–20 cm). Low organic matter content, increased soil disturbance, animal trampling, recurrent tillage operations, and compaction may contribute to croplands having the highest bulk density by eliminating pore space and degrading soil organic matter (8, 22, 28). Because of compaction, reduced organic matter content, less aggregation, and fewer pore spaces in subsurface soil layers, the bulk density (ρ_b) increases with soil depth under all land-use regimes (29, 30).

3.1.2 Total porosity

The total porosity (Moc) content was significantly ($P < 0.001$) affected by the interaction effects of land use and soil depth

(Table 1). Considering the interaction effect of land use and soil depth, the highest total porosity (54.72%) observed on the surface of forestland, whereas the lowest total porosity (45.66%) was recorded under the subsurface of irrigated land (Table 1). The highest total porosity above surface forestland may be attributed to the accumulation of surface litter and decomposing biomass in forest soils. Soil aggregation is encouraged by these organic materials. Stable pore holes result in enhanced porosity (31). The lowest SOM under the subsurface of irrigated land may be a result of continuous tillage, and the low organic matter content in irrigated areas may lead to reduced soil porosity and increased soil compaction. This could be the explanation for why the subsurface of irrigated areas had the lowest total porosity (32, 73). The weight of the soil layer on the surface and the decline in soil organic matter with depth might be the source of the overall reduction in porosity (33).

3.1.3 Soil pH

The soil pH was not significantly ($P > 0.05$) affected by the interaction of land use and soil depth (Table 2). The soil pH data revealed that most land uses fall within the moderately acidic range, with fallow land (pH 5.8), cropland (pH 5.6), forestland (pH 5.62),

TABLE 2 Effects of land use types and soil depth on selected soil hydraulic properties.

LUT	Depth (cm)	FC (%)	PWP (%)	AWHC (%)	SMC (%)
FaL	0-30	35.11 ^h	23.1 ^f	12.03 ^b	10.45 ^{hi}
FaL	30-60	40.63 ^{de}	35.1 ^{df}	15.46 ^c	10.32 ^{df}
FaL	60-90	46.47 ^c	46.72 ^{fh}	13.64 ^{de}	9.45 ^{ij}
CL	0-30	29.04 ^{fg}	15.56 ^{ab}	13.96 ^d	7.97 ^j
CL	30-60	32.29 ^c	16.89 ^{ef}	15.4 ^{de}	14.6 ^{ef}
CL	60-90	33.28 ^a	16.74 ^{cd}	13.31 ^{fg}	23.74 ^a
FL	0-30	43.69 ^f	26.48 ^{ac}	17.22 ^a	13.19 ^{fg}
FL	30-60	47.67 ^c	28.29 ^{gh}	18.54 ^b	23.73 ^{cd}
FL	60-90	51.46 ^b	30.24 ^{ad}	21.23 ^c	15.74 ^{cde}
IL	0-30	34.32 ^g	25.77 ^{ba}	8.52 ^c	11.4 ^h
IL	30-60	38.37 ^{de}	29.12 ^{cd}	13.31 ^{ef}	17.16 ^{bc}
IL	60-90	39.04 ^{de}	35.54 ^{fe}	10.79 ^g	22.77 ^a
ShL	0-30	29.52 ^{de}	10.6 ^{cd}	10.69 ^b	11.69 ^{gh}
ShL	30-60	31.09 ^e	16.56 ^{fh}	14.87 ^c	15.21 ^{de}
ShL	60-90	30.58 ^d	15.54 ^{gh}	14.52 ^c	17.78 ^{bc}
SEM (±)		0.57	0.864	0.4	0.144
LSD (0.05)		1.67	2.49	1.6	0.42
CV (%)		2	3.99	2.79	1.75
P-v value		***	***	***	***

Mean values followed by different letters are significantly different, and the same letters are not significantly different, highly significant at ($P < 0.001$)***, SEM, standard mean error; CV, coefficient of variance; FC, field capacity; PWP, permanent wilting point; AWHC, available water-holding capacity; Moc, soil moisture content; FaL, fallow land; CL, d; FL, forestland; IL, irrigation land; ShL, shrub land.

and shrubland (pH 5.80) categorized as moderately acidic. In contrast, irrigated land, with a pH of 5.1, is classified as “strongly acidic”. These pH values can significantly impact nutrient availability and biological activity within the soil, which are essential factors for plant growth. Therefore, it is advisable to consider soil amendments, such as lime, for irrigated land to increase pH levels and improve nutrient availability, whereas other land uses should implement regular monitoring and management practices to maintain optimal pH levels. The application of inorganic fertilizers is responsible for variations in pH (27). This result corresponds with previous studies conducted in northern Ethiopia (49).

The slight pH increase with depth could be explained by the migration of cations from the top layer of soil to the bottom surface of the soil (28, 34). In the subsurface soil layer, the pH of the soil was greater than that in the surface soil layer. Mulugeta et al. (25) reported that the pH varied between 5.17 and 5.84, which is mildly acidic, in all five land-use groups. This result corresponds with the findings of earlier research carried out in northern Ethiopia (49).

3.1.4 Soil organic matter

The soil organic matter content was substantially ($P \leq 0.01$) influenced by the interaction between land use and soil depth (Table 2). Considering the interaction effect of land use and soil depth, the highest total SOM (2.45%) observed on the surface of forestland, whereas the lowest SOM (1.29%) was recorded under the subsurface of cropland (Table 2). The highest concentration of SOM beneath the surface of forest land may be caused by the natural deposit of SOM in the topsoil by forest ecosystems due to various significant mechanisms. The substantial organic matter that forests contribute through deadwood, leaf litter, and root turnover enriches the surface layer. Similar results have been published by He et al. (35), who pointed out that crop yields are eventually impacted by agricultural methods that result in low SOM levels (below 2%) in croplands. According to these findings, regulating SOM through organic amendments and cover crops is crucial for enhancing soil sustainability and quality in agricultural systems (22, 36, 37). The higher levels of soil organic matter in the topsoil layer across all land-use types can be attributed to the return of biomass, decomposition in the soil surface layer, and deposition of plant remains and animal waste (25, 29).

The lowest SOM in the subsurface of cropland may be the result of long-term degradation brought on by intensive cultivation. Subsurface layers of crop may retain a moderate quantity of SOM from crop remnants, despite the fact that erosion and tillage limit accumulation. Low inputs, compaction, and anaerobic conditions all contribute to the SOM depletion of subterranean layers. This result is consistent with the findings of other Ethiopian studies (38, 39). The result is in line with Bufebo and Elias's (39) findings that soil SOM declines as soil depth increases.

3.1.5 Total nitrogen

Total nitrogen was significantly ($P < 0.001$) influenced by the interaction between land use and soil depth (Table 2). In terms of the relationship between land use and soil depth, total nitrogen was highest (0.138%) in the top layer of forestland, whereas it was lowest (0.101%) in the subsurface layer of cropland (Table 2). The highest total nitrogen observed under the surface of forest land attributed due to the nitrogen released during mineralization and the desirable forest climate conditions that temper soil temperature and thus decrease total nitrogen loss through volatilization, the relatively high total nitrogen content under forestland may be related to the high organic matter content. Organic matter is the primary source of total nitrogen in the soil (22, 27). This result consistent with the result of Chemed et al. (40), who found that forestland yields a higher total nitrogen content than nearby farmed and grazing areas do.

However, the lowest total nitrogen content under irrigation and cropland may be caused by ongoing cultivation, vegetation removal for plows that deplete organic matter residues and expose the surface layer of irrigated and cropland to direct raindrop generation, loss of residue during crop harvest, and inadequate fertilizer replacement (8, 41). This result is in line with Abadeye et al. (42) and Tebekew et al. (74), who found that the decrease in

total nitrogen from the surface to the subsurface is caused by nitrogen materials, such as organic matter on the surface, plant matter, and animal waste.

3.2 Effects of land use types on soil hydraulic properties

3.2.1 Field capacity

The FC was significantly ($P < 0.001$) influenced by land use and soil depth (Table 1). The maximum FC (51.46%) was observed in the subsurface layer (60–90 cm) of forestlands, while the lowest capacity (29.04%) was found in the surface layer (0–30 cm) of cropland (Table 1). These findings align with Assefa et al. (43) and Garedew et al. (44), who demonstrated that forested areas had significantly higher moisture retention across all depths compared to adjacent croplands. The highest soil FC on forest land and the lowest under cropland could be due to forest land being more able to retain moisture content compared to cropland, likely due to forest land having greater vegetative cover, organic matter content, deeper root systems, improved soil structure, and higher water retention and infiltration rates, whereas the FC in cropland due to reduced SOM, agricultural residue removal, and intensive tillage deteriorates soil structure by lowering pore connectivity and increasing surface-layer compaction (23, 45). This finding aligns with those of Wang et al. (46), who reported similar patterns across various land uses. Subsurface layers show higher field capacity than surface layers, indicating that deeper soil layers may contain more clay and possess a better structure for water retention (47). This observation is consistent with Hu et al. (48), who noted a higher water storage capacity in deeper soil layers due to increased porosity and reduced evaporation.

3.2.2 Permanent wilting point

The PWP was significantly ($P < 0.001$) influenced by land-use type and soil depth (Table 1). The highest percentage of PWP (46.72%) was observed in the subsurface layer (60–90 cm) of fallow land, while the lowest percentage (10.6%) was found in the surface layer (0–30 cm) of shrublands (Table 1). The higher PWP in subsurface fallow land may be attributed to deeper root penetration, increased organic matter content, and improved soil structure, leading to greater water-holding capacity (24, 49). Conversely, surface shrublands have reduced PWP, which is linked to shorter roots, coarser textures, and less organic matter, all of which limit the quantity of water that is available during droughts (8). Forests help PWP by retaining soil moisture, lowering evaporation, and capturing rainfall (10). Despite surface restrictions, shrublands may reduce water scarcity by improving moisture retention through root-mediated mechanisms (45).

3.2.3 Available water holding capacity

The AWHC was significantly ($P < 0.001$) influenced by the interaction between land use and soil depth (Table 1). Forestland in the subsurface layer (60–90 cm) exhibited the highest AWHC at 21.23% (Table 1). The highest available water-holding capacity

(AWHC) was found in forestland subsurface soils (60–90 cm) (Table 1), most likely due to the buildup of organic matter and the retention-enhancing effects of well-structured soils (50). This is consistent with findings by Terefe et al. (51), who reported that forest ecosystems promote the development of stable soil aggregates and organic carbon retention at deeper layers, enhancing moisture retention. The lowest AWHC (10.69%) was found in surface shrublands (0–30 cm), which are linked with shallow roots and low organic inputs that decrease moisture storage (11). The findings are consistent with wider studies indicating that forest ecosystems are better at maintaining soil water reserves than shrublands due to their deeper root systems and ecologically dense subsurface layers (52).

3.2.4 Soil moisture content

The SMC was significantly ($P < 0.001$) influenced by land use and soil depth (Table 1). Forestland exhibited the highest SMC at 23.74%, while the cropland surface layer (0–30 cm) had the lowest at 7.97% (Table 1). The higher SMC (23.74%) in forestland is attributed to its dense vegetation, organic matter accumulation, deep root systems that enhance water retention, and reduced evaporation (45). Conversely, the lowest SMC (7.97%) was found in cropland surface layers (0–30 cm), most likely due to increased crop water demand, soil compaction from cultivation, and reduced organic inputs that restrict water-holding capacity (53). Soil moisture's tendency to increase with depth was made worse by higher clay content in subsurface layers, which improves retention (38). These findings align with agroecological studies carried out in Ethiopia, which emphasize the significance of vegetation type, land management, and soil depth in regulating moisture dynamics (29).

3.3 Effects of different land use types on infiltration rate

3.3.1 Infiltration rate and cumulative infiltration

Land use types significantly influenced infiltration rates and cumulative infiltration (Figures 3, 4). Forest land showed the highest average infiltration rate (36.5 cm/hr) and cumulative infiltration (12.8 cm) (Figures 3, 4), attributed to organic matter enrichment and deep root systems that stabilize soil structure and enhance porosity (5, 54). These results align with global evidence linking forests to superior hydrological function

In contrast, irrigated land had lower performance on infiltration rate and cumulative (19.6 cm/hr; 12.4 cm) (Figures 3, 4), likely due to soil compaction from frequent irrigation and machinery use, which reduces permeability (55, 56). Cropland exhibited the lowest infiltration rate and cumulative (21.03 cm/hr; 9.1 cm), reflecting compaction and organic matter depletion from intensive tillage (57).

Shrubland demonstrated strong water management with an average infiltration rate and a cumulative infiltration (29.6 cm/hr; 12.3 cm) (Figures 3, 4), as shrub roots mitigate erosion and sustain moderate porosity, though less effectively than forests (58, 59). Fallow land showed intermediate values of infiltration rate and

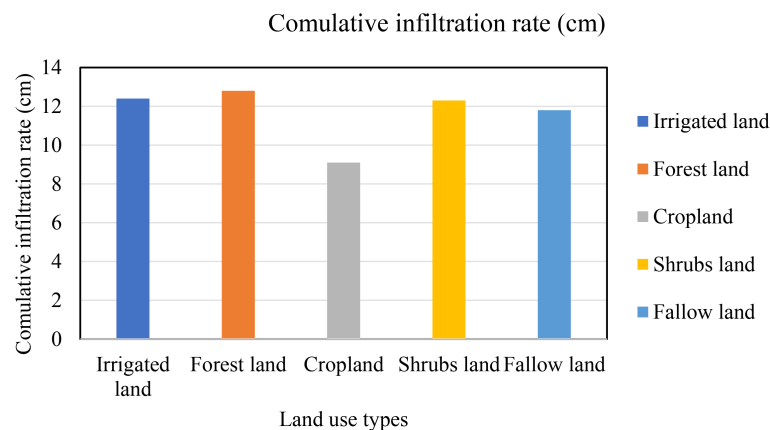


FIGURE 4
Cumulative infiltration across land use types.

cumulative (22.1 cm/hr; 11.8 cm), suggesting partial soil recovery during rest periods but insufficient biological activity to match vegetated systems (75). These findings underscore the critical role of vegetation and land management in soil hydrology. Forests and shrublands outperform agricultural systems due to organic inputs and stable structure, while irrigation and tillage degrade infiltration capacity. Prioritizing agroforestry and reduced tillage could mitigate water scarcity in vulnerable ecosystems (5, 55).

3.3.2 Sorptivity

Shrubland had the highest average sorptivity at (146.5 cm/hr), while croplands exhibit significantly lower sorptivity values at (75.3 cm/hr) (Figure 5). The highest sorptivity under shrubland may be due to the increased soil organic matter and structural porosity that vegetation fosters, which encourages water infiltration. These findings are in line with trends that were shown to be dependent on land use

by Debebe et al. (60). On the other hand, the lower sorptivity in croplands may be due to soil being packed down and losing organic matter from regular tilling, which agrees with Miller et al. (4) and Agbai Williams et al. (57), who point out that farming methods significantly affect soil water properties. The pattern of sorptivity rates is as follows: shrubland (146.5 cm/hr) > fallow land (113.9 cm/hr) > forest land (113.4 cm/hr) > irrigated land (90.2 cm/hr) > cropland (75.3 cm/hr) (Figure 5). This pattern supports previous research by Failache and Zuquette (61), which found that sorptivity is influenced by different land use systems.

3.3.3 Transmissivity (A)

Forest land exhibited the highest transmissivity at (1.01 cm/hr), while, in contrast, irrigated land showed lower transmissivity at (0.3 cm/hr) (Figure 6). Forest land had the highest soil transmissivity, likely due to their organic matter and well-

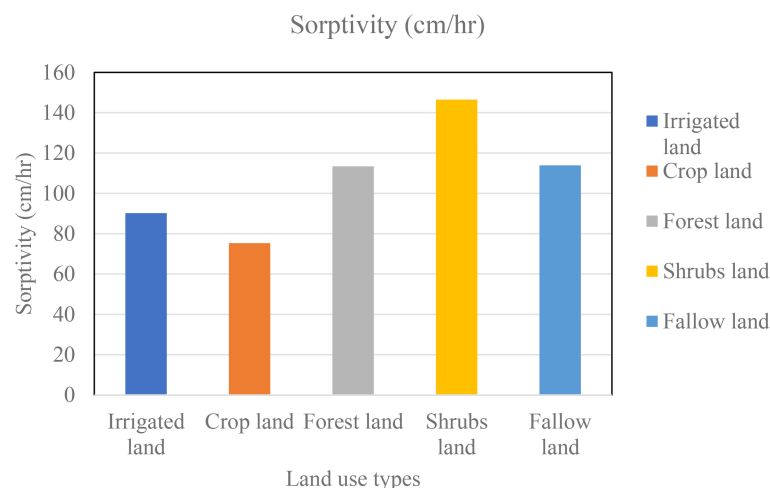


FIGURE 5
Average sorptivity across land use types.

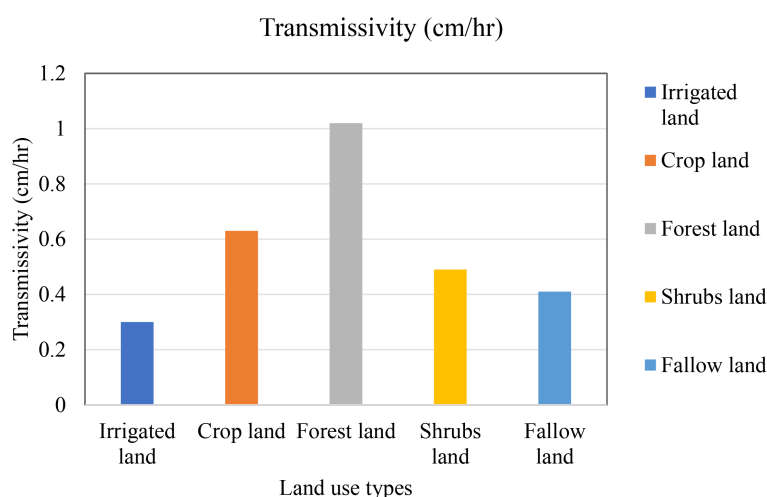


FIGURE 6
Average soil transmissivity across land use types.

developed soil structure, which allowed water to move easily. In contrast, irrigated lands had the lowest, maybe due to compaction and decreased porosity from frequent irrigation, which increased the risk of waterlogging (62). These findings are consistent with those of Karahan and Yalim (5) and Agbai Williams et al. (57), who connected hydraulic features to land-use practices. They are also supported by Zhang et al. (63) and Müller (64), who pointed out that extensive irrigation breaks down soil stability. The results underscore how important land management is to preserve the hydrological function of soil, especially in agricultural settings where sustainable practices may reduce waterlogging and improve permeability.

3.4 Practical implications of the study

The study on soil hydraulic properties under varied land use types at the Arjo-Dhidhessa Sugar Estate in Western Ethiopia presents several practical implications for agriculture and land management:

3.4.1 Sustainable agricultural practices

The findings indicate that relying solely on agricultural practices may not be sustainable for maintaining soil health. This suggests that integrating diverse land use practices, such as incorporating forest and shrubland, can enhance soil health and water retention, which is crucial for sustainable agriculture.

3.4.2 Water resource management

The research highlights the complex interactions between land use, soil depth, and hydraulic properties. This information is valuable for developing effective farming practices that support water resource management in the region. Policymakers and land

managers can utilize these insights to promote practices that enhance water retention and soil quality.

3.4.3 Impact of land use changes

The study identifies the lasting effects of land use changes on hydraulic soil characteristics. This underscores the need for further research to develop effective water conservation strategies that can be applied in similar agricultural contexts, thereby improving water resource management.

3.4.4 Soil management techniques

The research suggests that specific land management techniques, such as conservation tillage, replanting, and reducing soil compaction, are essential for maintaining soil health. These practices can help mitigate issues like soil compaction and nutrient depletion observed in irrigated lands, which showed lower sorptivity and infiltration rates.

3.4.5 Vegetation protection

The study emphasizes the importance of protecting vegetation, particularly in forestlands, which exhibited superior soil moisture content and hydraulic properties. This highlights the role of vegetation in maintaining soil quality and water retention, suggesting that land management should prioritize the conservation of natural vegetation.

3.4.6 Policy recommendations

The findings provide essential insights for policymakers, advocating for the integration of diverse land use practices to improve soil health and water retention. This can lead to more effective agricultural policies that support long-term sustainability in the face of ongoing land transformation.

4 Conclusions and recommendations

4.1 Conclusions

The study conducted at Arjo-Dhidhessa Sugar Estate underscores the significance soil depth and land use have in influencing hydraulic properties. The higher soil moisture retention and sorptivity (146.5 cm/hr in shrublands) and vegetation-driven organic matter buildup in forest and shrubland systems have been attributed to structural porosity and vegetation. In contrast, irrigated lands exhibited significant decreases in transmissivity (0.3 cm/hr) and sorptivity (75.3 cm/hr), which were attributed to nutrient depletion and compaction from intensive activities. The permanent wilting point (PWP) was highest in deeper fallow layers (60–90 cm) and lowest in shrubland topsoil (0–30 cm), suggesting that subsurface moisture reserves are essential for drought resilience. This suggests that soil depth further influenced moisture dynamics.

4.2 Recommendations

To mitigate degradation in irrigated systems, farmers could adopt conservation tillage, precision irrigation, and organic matter restoration strategies. Governments and organizations should prioritize vegetation-based strategies (e.g., agroforestry, shrubland preservation) to enhance soil organic matter accumulation, porosity, soil infiltration and water retention, especially in regions that have been degraded or heavily farmed and are affected by semi-arid or arid conditions. Farmers should optimize irrigation strategies to reduce compaction and nutrient depletion in irrigated lands and convert to precision irrigation systems (such as drip irrigation systems) and integrate conservation tillage in land preparation.

4.3 Limitations

- ✓ Geographic specificity: Findings originate from a single estate; validation across different soil types and climates is essential for broader relevance.
- ✓ Temporal constraints: Since the data only cover a single period, they cannot provide valuable information about seasonal variability or long-term trends.
- ✓ Socioeconomic factors: Labor and cost barriers to implementing suggested practices were not assessed.

4.4 Future research direction

- ✓ Multi-regional studies: Investigate hydraulic characteristics in a range of agroecological zones to determine general compared to situation-specific management recommendations.

- ✓ Long-term research: Evaluate the long-term effects of methods of conservation (such as agroforestry and reduced tillage) on soil resilience and health.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

WG: Writing – original draft, Writing – review & editing. FF: Writing – original draft, Writing – review & editing. AB: Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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