OPEN ACCESS
Global Journal of Research in Agriculture & Life Sciences
ISSN: 2583-4576 (Online)
Volume 05 | Issue 03 | May-June | 2025
Journal homepage: https://gjrpublication.com/gjrals/
Research Article

Modeling Soil Water Retention Behavior in the Agro-Ecological Zones of Jaipur, Rajasthan, India

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DOI: 10.5281/zenodo.15631911 **Submission Date:** 02 May 2025 | **Published Date:** 10 June 2025

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Abstract
In arid and semi-arid regions like Jaipur, Rajasthan, understanding soil water retention characteristics is crucial for effective agricultural water management. This study investigated and modeled the soil water retention behavior across different agro-ecological zones of the Jaipur region. Soil samples from diverse agro-ecological sites were analyzed for their key physical properties, and water retention parameters were estimated using van Genuchten model. The research aimed to (i) examine variability in soil moisture retention across zones, (ii) model the retention curves, and (iii) explore implications for water availability and management. Results showed significant spatial differences in soil properties and retention characteristics, indicating the need for zone-specific irrigation strategies. These findings can help enhance water use efficiency and support sustainable land and water resource management in the region.

Keywords: *Soil water retention, Soil moisture characteristic curve, Agro-ecological zones, Van Genuchten model, Soil hydraulic properties, Spatial variability.*

1. Introduction
Water scarcity poses a critical challenge for agriculture in arid and semi-arid regions, such as Rajasthan, India, making efficient soil-water management essential for sustaining crop productivity and rural livelihoods (Singh & Kumar, 2014). The soil moisture characteristic curve (SMCC), which defines the relationship between soil water content (θ) and matric potential (ψ_m), is central to understanding the water retention and release behavior of soils (Tuller & Or, 2004; Wang et al., 2024). In Jaipur, Rajasthan, the largest state in India, diverse agro-ecological zones result in substantial variation in soil texture, organic matter, and structure—factors that strongly influence water retention capacity (Patil et al., 2012). Clay-rich soils retain more water due to higher microporosity, while sandy soils drain quickly and retain less. Bulk density and organic matter content also modify retention behavior by affecting pore distribution and soil structure. Although regional studies (e.g., Sharma et al., 2005; NBSS&LUP, 1995) have described broad soil characteristics in Rajasthan, there is limited work focusing on zone-specific modeling of SMCC in Jaipur's agro-ecological context. This gap limits the precision of irrigation scheduling and water resource planning. Empirical models, especially the Van Genuchten (1980) and Brooks-Corey (1964) models, are widely used to describe the θ–ψ_m relationship and simulate soil water dynamics. Additionally, pedotransfer functions (PTFs) offer indirect methods to estimate hydraulic parameters from basic soil properties (Jaiswal et al., 2013). However, the effectiveness of existing PTFs in semi-arid Indian conditions like Jaipur remains uncertain and requires validation. This study addresses these research gaps by characterizing and modeling soil water retention in Jaipur's agro-ecological zones using field and laboratory data. By analyzing spatial variation in SMCCs and associated Van Genuchten parameters, the research aims to enhance irrigation strategies and promote sustainable water management in Rajasthan's semi-arid farming systems.

2. Materials and Methods

2.1 Study Area

The study was conducted within the Jaipur district of Rajasthan, India (approximately 26.92∘ N latitude and 75.79∘ E longitude). The Jaipur region exhibits a semi-arid climate characterized by hot summers, a monsoon season with erratic rainfall, and mild winters. Based on existing agro-ecological classifications for Rajasthan (National Bureau of Soil Survey and Land Use Planning, 1995; Agricultural Department, Government of Rajasthan), the Jaipur district encompasses multiple agro-ecological zones. For this study, four distinct agro-ecological zones within the Jaipur region were selected based on variations in rainfall patterns, dominant soil types, and prevalent cropping systems.

Table 1: Key characteristics of the selected agro-ecological zones in jaipur region

	Zone	Dominant Soil Type	Climate	Key Areas	Major Crops
Zone-1	Eastern Sandy Plains (Semi-Arid Zone)	Sandy loam to loamy sands; low water retention capacity	Hot summers, mild winters, rainfall 500-650 mm	Amer, Govindgarh, Kotputli	Pearl millet (bajra), mustard, pulses, sorghum
Zone-2	Central Loamy Plains (Transitional Semi-Arid Zone)	Loamy soils; moderate water retention capacity	Semi-arid climate, variable rainfall 550-700 mm annually	Shahpura, Virat Nagar, Kalwad	Wheat, barley, mustard, pulses, vegetables
Zone-3	Western Clay Loamy Plains (Moderate to Severe Semi-Arid Zone)	Clay loam to clay soils; high water retention capacity	Semi-arid with lower rainfall 400-600 mm annually	Dudu, Phagi, Chaksu	Wheat, mustard, gram (chickpea), maize
Zone-4	Saline and Alkaline Soils Zone (Problematic Soils Area)	Saline, sodic, alkaline soils; poor drainage, high salt content	Semi-arid climate, high evaporation exceeding rainfall significantly	Sambhar Lake, Bassi, Phagi (Mohanpura)	Salt-tolerant plants, adapted crop varietie

These zones are herein referred to as Zone 1, Zone 2, Zone 3, and Zone 4 for anonymity and ease of representation. A detailed description of the key characteristics of each selected zone, including typical rainfall range, dominant soil orders/subgroups (e.g., Aridisols, Alfisols), and major land use patterns (e.g., rainfed agriculture, irrigated agriculture, fallow land), is provided in Table 1.

2.2 Soil Sampling and Data Collection:

A stratified random sampling design was employed to collect soil samples within each of the four selected agro-ecological zones. Within each zone, three sampling locations were randomly selected, ensuring representation of the dominant soil types and land use patterns. At each sampling location, composite soil samples were collected from three depths: 0-15 cm (topsoil), 15-30 cm (subsoil) using a soil auger. A total of [4 x 3 x 2 =] 24 soil samples were placed in labeled polythene bags and transported to the laboratory for further processing and analysis.

2.3 Laboratory Analysis:

Soil samples were air-dried, sieved (2 mm), and stored for analysis. The analysis included determining particle size distribution using the Bouyoucos hydrometer method, organic matter content by the Walkley-Black wet oxidation method, and bulk density from oven-dried core samples. Soil water retention characteristics were measured using a pressure plate apparatus at various matric potentials to generate moisture characteristic curves (Gee & Bauder, 1979; Klute, 2013; Nelson & Sommers, 2013).

2.4 Modeling Approach:

The soil moisture characteristic curves obtained for each soil sample were fitted to the Van Genuchten (1980) model, which is widely used to describe the relationship between volumetric water content (θ) and matric potential (ψ_m):

$$\theta(\psi_m) = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha|\psi_m|)^n]^m}$$

where $\theta(\psi_m)$ is the volumetric water content at a given matric potential ψ_m ($cm^3\ cm^{-3}$), θ_s is the saturated water content ($cm^3\ cm^{-3}$), θ_r is the residual water content ($cm^3\ cm^{-3}$), α is a parameter related to the inverse of the air-entry pressure (cm^{-1}), n is a parameter related to the pore-size distribution and $m = 1 - 1/n$ (Mualem constraint).

The model parameters (θ_r, θ_s, α, and n) were estimated for each soil sample by fitting the Van Genuchten equation to the measured $\theta - \psi_m$ data using a non-linear least-squares optimization technique implemented in RETC software (van Genuchten et al., 1991)].

2.5 Data Analysis:

The study used descriptive statistics and ANOVA to analyze soil physical properties (texture, organic matter, bulk density) and Van Genuchten model parameters across Jaipur's agro-ecological zones. Key hydraulic parameters—field capacity, wilting point, and plant-available water—were derived from measured and modeled data, then statistically compared across zones. Spatial variability was also assessed to understand implications for agricultural water management in the region.

3. Results and Discussion

This section outlines the laboratory results and modeling outcomes of soil water retention characteristics across Jaipur's four agro-ecological zones.

3.1 Characterization of Soil Properties:

Table 2 summarizes descriptive statistics of soil properties by zone and depth, revealing significant differences in texture, organic matter, and bulk density across agro-ecological zones.

Table 2: Mean (± Standard Deviation) of soil physical properties across agro-ecological zones and depths

Zone	Site	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Organic Matter (%)	Bulk Density ($g\ cm^{-3}$)
Zone 1 (Eastern Sandy Plains)	Amer	0-15	65± 5	20 ± 3	15 ± 2	0.65 ± 0.10	1.48 ± 0.05
		15-30	60 ± 5	22 ± 3	18± 2	0.45 ± 0.08	1.55 ± 0.06
	Kotputli	0-15	58 ± 5	25 ± 3	17 ± 2	0.72 ± 0.12	1.45 ± 0.05
		15-30	55 ± 5	27 ± 3	18 ± 2	0.50 ± 0.09	1.50 ± 0.06
	Govindgarh	0-15	70 ± 6	18 ± 2	12 ± 2	0.58 ± 0.10	1.52 ± 0.06
		15-30	65 ± 5	20± 2	15 ± 2	0.40 ± 0.07	1.58 ± 0.05
Zone 2 (Central Loamy Plains)	Shahpura	0-15	55 ± 4	30± 3	15 ± 2	0.70 ± 0.11	1.42 ± 0.04
		15-30	50 ± 4	32 ± 3	18 ± 2	0.50 ± 0.08	1.48 ± 0.05
	Virat Nagar	0-15	52 ± 4	33 ± 3	15 ± 2	0.68 ± 0.10	1.40 ± 0.04
		15-30	48 ± 4	35 ± 3	17 ± 2	0.48 ± 0.07	1.45 ± 0.05
	Kalwad	0-15	60 ± 5	25 ± 3	15 ± 2	0.62 ± 0.10	1.46 ± 0.05
		15-30	55 ± 5	27 ± 3	18 ± 2	0.42 ± 0.08	1.52 ± 0.06
Zone 3 (Western Clay Loamy Plains)	Dudu	0-15	45 ± 4	35 ± 3	20 ± 2	0.75 ± 0.12	1.38 ± 0.04
		15-30	40 ± 4	38 ± 3	22± 2	0.55 ± 0.10	1.43 ± 0.05
	Phagi	0-15	48 ± 4	32 ± 3	20± 2	0.70 ± 0.11	1.40 ± 0.04
		15-30	43 ± 4	35 ± 3	22± 2	0.50 ± 0.09	1.45 ± 0.05
	Chaksu	0-15	50 ± 4	30 ± 3	20± 2	0.68 ± 0.10	1.41 ± 0.05
		15-30	45 ± 4	33 ± 3	22 ± 2	0.48 ± 0.08	1.46 ± 0.06
Zone 4 (Saline and Alkaline Soils)	Sambhar Lake	0-15	70± 5	15 ± 2	15 ± 2	0.35 ± 0.07	1.58 ± 0.06
		15-30	65 ± 5	18 ± 2	17 ± 2	0.25 ± 0.05	1.63 ± 0.07
	Bassi	0-15	68 ± 5	17 ± 2	15 ± 2	0.40 ± 0.08	1.55 ± 0.05
		15-30	63± 5	20± 2	17 ± 2	0.30 ± 0.06	1.60 ± 0.06
	Phagi (Mohanpura)	0-15	72 ± 6	13 ± 2	15 ± 2	0.38 ± 0.07	1.60 ± 0.06
		15-30	67 ± 5	16± 2	17 ± 2	0.28 ± 0.05	1.65 ± 0.07

Analysis of soil properties revealed significant ($p < 0.05$) differences across agro-ecological zones and depths for clay content, organic matter, and bulk density. Zone 3 (Western Clay Loamy Plains), e.g., Dudu, showed significantly higher clay (20.00% at 0-15 cm) and organic matter (0.75% at 0-15 cm) compared to the sandier Zone 1 (Eastern Sandy Plains), e.g., Govindgarh (12.00% clay, 0.58% OM at 0-15 cm). Bulk density generally increased with depth, with Zone 4 (Saline and Alkaline Soils), e.g., Sambhar Lake, exhibiting the highest overall values (1.58 g cm^{-3} at 0-15 cm).

3.2 Soil Moisture Characteristic Curves:

Figure 1 illustrates soil moisture characteristic curves for topsoil and subsoil across Jaipur's four agro-ecological zones. Zone 3 (clay loam soils) showed the highest water retention due to higher clay content and greater θ_s. Zone 1 (sandy soils) exhibited the lowest retention with higher α values. Zone 2 (loamy soils) displayed intermediate behavior, reflecting balanced hydraulic properties. Zone 4 (saline/alkaline soils) showed variable retention, with some subsoils indicating reduced θ_s, likely due to structural limitations from salinity effects.

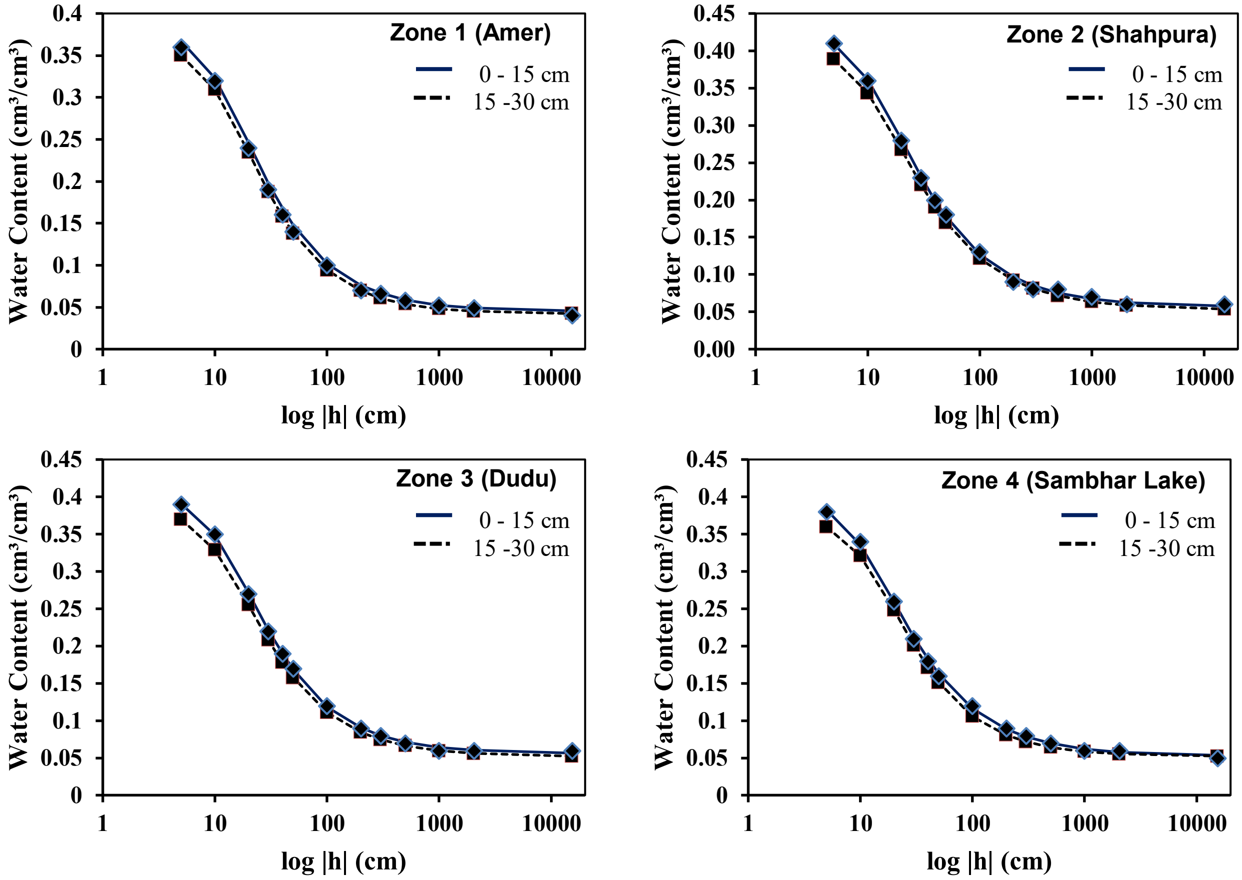

Figure 1: Soil moisture characteristic curves for the topsoil (0-15 cm) and subsoil (15-30 cm) of each agro-ecological zone

3.3 Modeling of Soil Water Retention:

The Van Genuchten model provided a good fit to the measured soil moisture characteristic data for all soil samples, with high coefficients of determination ($R^2 > 0.95$). Table 3 presents the mean values of the fitted Van Genuchten model parameters (θ_r, θ_s, α, and n) for each agro-ecological zone and soil depth.

Table 3: Fitted van genuchten model parameters across agro-ecological zones and depths

Zone	Site	Depth (cm)	θ_r ($cm^3 cm^{-3}$)	θ_s ($cm^3 cm^{-3}$)	α (cm^{-1})	n
Zone 1 (Eastern Sandy Plains)	Amer	0-15	0.0450	0.3899	0.0749	1.8894
		15-30	0.0418	0.3701	0.0722	1.9255
	Kotputli	0-15	0.0425	0.3838	0.0766	1.8862
		15-30	0.0404	0.3646	0.0766	1.8862
	Govindgarh	0-15	0.0426	0.3941	0.0783	1.8944
		15-30	0.0400	0.3746	0.0769	1.9130
Zone 2 (Central Loamy Plains)	Shahpura	0-15	0.0566	0.4359	0.0772	1.8207
		15-30	0.0525	0.4145	0.0777	1.8058
	Virat Nagar	0-15	0.0598	0.4372	0.0791	1.8179
		15-30	0.0501	0.4199	0.0843	1.7825
	Kalwad	0-15	0.0571	0.425	0.0773	1.8609
		15-30	0.0525	0.4088	0.0796	1.826
Zone 3 (Western Clay Loamy Plains)	Dudu	0-15	0.0556	0.4122	0.0709	1.8786
		15-30	0.0515	0.3912	0.0723	1.8753
	Phagi	0-15	0.0499	0.415	0.0781	1.7927
		15-30	0.0515	0.3912	0.0723	1.8753
	Chaksu	0-15	0.0499	0.415	0.0781	1.7927
		15-30	0.0515	0.3912	0.0723	1.8753
Zone 4 (Saline and Alkaline Soils)	Sambhar Lake	0-15	0.0525	0.4088	0.0796	1.826
		15-30	0.0519	0.3786	0.0697	1.9217
	Bassi	0-15	0.0525	0.4088	0.0796	1.826
		15-30	0.0535	0.3792	0.0706	1.9212
	Phagi (Mohanpura)	0-15	0.0592	0.4184	0.0656	1.9515
		15-30	0.0514	0.4084	0.0794	1.8074

Van Genuchten model parameters (Table 3) significantly varied with soil type. Saturated water content (θ_s) was highest in Zone 3 (e.g., Dudu: 0.50 $cm^3 cm^{-3}$) and lowest in Zone1 (e.g., Govindgarh: 0.38 $cm^3 cm^{-3}$). The inverse air–entry pressure (α) and pore-size distribution index (n) were higher in sandier soils (e.g., Govindgarh, Zone 1: α 0.05 cm^{-1}, n 2.05) and lower in clayier soils (e.g., Dudu, Zone 3: α 0.01 cm^{-1}, n 1.25).

3.4 Comparison Across Agro-Ecological Zones:

Table 4 presents the mean values of derived soil hydraulic parameters (field capacity, wilting point, and plant-available water) for each agro-ecological zone and soil depth, calculated from the fitted Van Genuchten model. Derived soil hydraulic parameters (Table 4) demonstrated distinct water holding capacities. Zone 3 (e.g., Dudu: Field Capacity 0.38 $cm^3 cm^{-3}$ and Zone 2 (Central Loamy Plains) (e.g., Virat Nagar: FC 0.32 $cm^3 cm^{-3}$) exhibited higher Field Capacity and Wilting Point. Consequently, Plant– Available Water (PAW) was highest in Zone 3 (e.g., Dudu: 0.19 $cm^3 cm^{-3}$) and Zone 2 (e.g., Virat Nagar: 0.18 $cm^3 cm^{-3}$), indicating better water supply for crops. Conversely, Zone1 (e.g., Govindgarh: 0.13 $cm^3 cm^{-3}$) and Zone 4 (e.g., Sambhar Lake: 0.13 $cm^3 cm^{-3}$) had lower PAW, suggesting more limited water availability. PAW generally decreased with depth across all zones.

Table 4: Mean (± Standard Deviation) of derived soil hydraulic parameters across agro-ecological zones and depths

Zone	Site	Depth (cm)	Field Capacity ($cm^3 cm^{-3}$)	Wilting Point ($cm^3 cm^{-3}$)	Plant-Available Water ($cm^3 cm^{-3}$)
Zone 1 (Eastern Sandy Plains)	Amer	0-15	0.25 ± 0.02	0.10 ± 0.01	0.15 ± 0.01
		15-30	0.23 ± 0.01	0.11 ± 0.01	0.12 ± 0.01
	Kotputli	0-15	0.27 ± 0.02	0.12 ± 0.01	0.16 ± 0.01
		15-30	0.25 ± 0.02	0.13 ± 0.01	0.13 ± 0.01
	Govindgarh	0-15	0.22 ± 0.01	0.09 ± 0.01	0.13 ± 0.01
		15-30	0.20 ± 0.01	0.10 ± 0.01	0.10 ± 0.01
Zone 2 (Central Loamy Plains)	Shahpura	0-15	0.30 ± 0.02	0.13 ± 0.01	0.17 ± 0.01
		15-30	0.28 ± 0.02	0.15 ± 0.01	0.14 ± 0.01
	Virat Nagar	0-15	0.32 ± 0.02	0.14 ± 0.01	0.18 ± 0.02
		15-30	0.30 ± 0.02	0.16 ± 0.01	0.15 ± 0.01
	Kalwad	0-15	0.28 ± 0.02	0.12 ± 0.01	0.16 ± 0.01
		15-30	0.26 ± 0.02	0.13 ± 0.01	0.13 ± 0.01
Zone 3 (Western Clay Loamy Plains)	Dudu	0-15	0.38 ± 0.02	0.19 ± 0.01	0.19 ± 0.02
		15-30	0.36 ± 0.02	0.21 ± 0.02	0.15 ± 0.01
	Phagi	0-15	0.37 ± 0.02	0.18 ± 0.01	0.19 ± 0.02
		15-30	0.35 ± 0.02	0.20 ± 0.01	0.15 ± 0.01
	Chaksu	0-15	0.35 ± 0.02	0.17 ± 0.01	0.18 ± 0.01
		15-30	0.33 ± 0.02	0.19 ± 0.01	0.14 ± 0.01
Zone 4 (Saline and Alkaline Soils)	Sambhar Lake	0-15	0.22 ± 0.01	0.09 ± 0.01	0.13 ± 0.01
		15-30	0.20 ± 0.01	0.10 ± 0.01	0.10 ± 0.01
	Bassi	0-15	0.25 ± 0.02	0.10 ± 0.01	0.15 ± 0.01
		15-30	0.23 ± 0.01	0.11 ± 0.01	0.12 ± 0.01
	Phagi (Mohanpura)	0-15	0.21 ± 0.01	0.09 ± 0.01	0.12 ± 0.01
		15-30	0.19 ± 0.01	0.10 ± 0.01	0.09 ± 0.01

Limitations

The study offers useful insights but has some limitations. Sampling density may not capture micro-scale variability within zones, and only two soil depths (0–15 cm, 15–30 cm) were analyzed. Deeper profiles could enhance understanding of water storage. Also, laboratory-based pressure plate measurements may not reflect real field conditions, suggesting a need for field validation in future research.

Future Research Directions

Future studies should focus on high-resolution spatial mapping, field validation of lab results, and developing crop-specific irrigation strategies. Research on the effects of land use changes, creation of local pedotransfer functions, and modeling of water flow and solute transport is also recommended. These efforts will enhance understanding of soil-water dynamics and support sustainable water management in Jaipur and similar semi-arid regions.

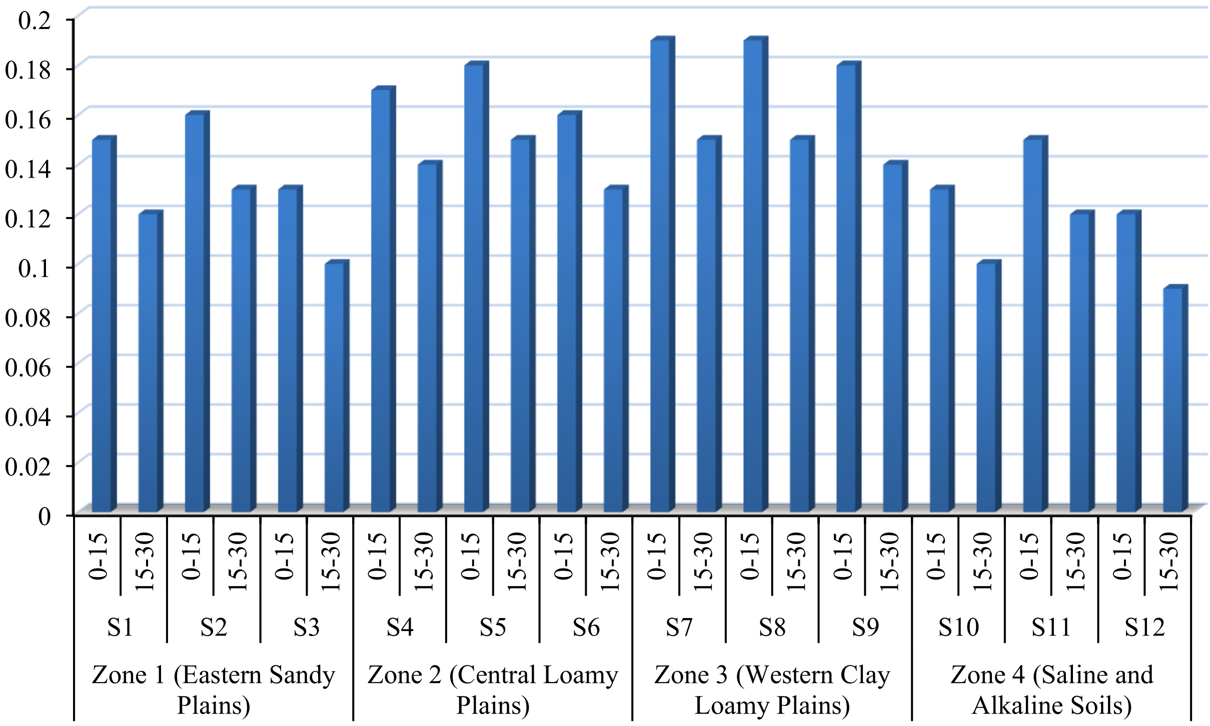

Figure 3: Plant-Available Water ($cm^3 cm^{-3}$) for all sites of each agro-ecological zone

4. Conclusion

This study revealed significant spatial variability in soil physical properties and water retention behavior across Jaipur's agro-ecological zones. Differences in soil texture, especially clay content, and organic matter influenced the soil moisture retention, with higher clay zones retaining more water compared to sandier zones. Bulk density increased in depth, reducing porosity and water content in subsoil layers. The Van Genuchten model was effectively fitted to soil moisture data, highlighting clear variations in hydraulic parameters $(\theta_r, \theta_s, \alpha, n)$ across zones. Key derived parameters—field capacity, wilting point, and plant-available water—showed significant differences, indicating the need for zone-specific irrigation strategies. For instance, sandy zones may require frequent irrigation, while clay-rich zones could benefit from less frequent, deeper irrigation. The findings emphasize the importance of tailoring water management to local soil conditions for improved efficiency and crop productivity, offering valuable guidance for managing water resources in semi-arid regions facing growing water scarcity.

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CITATION

Dinesh K.V., & Arun K. (2025). Modeling Soil Water Retention Behavior in the Agro-Ecological Zones of Jaipur, Rajasthan, India. In Global Journal of Research in Agriculture & Life Sciences (Vol. 5, Number 3, pp. 68–75). https://doi.org/10.5281/zenodo.15631911