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Seasonal Dynamics of Soil Physicochemical Properties beneath *Acacia nilotica* in the Arid Zone of Rajasthan

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***Abstract*— Seasonal variability in soil physicochemical properties is a key determinant of nutrient cycling, soil fertility and carbon dynamics in arid ecosystems. This study characterized seasonal and depth-wise variation in soil pH, electrical conductivity (EC), soil organic carbon (SOC) and bulk density (BD) beneath Acacia nilotica in Sardarshahar, Churu District, Rajasthan. Soil properties were assessed at two depths (0–15 and 15–30 cm) across four seasons: winter, spring, summer and rainy. Soil pH ranged from 7.50 to 8.10, EC from 0.45 to 0.63 dS m^{-1} and SOC from 0.32 to 0.58%, with overall means of 7.78, 0.53 dS m^{-1} and 0.44%, respectively. The surface layer exhibited lower pH (7.68) but higher EC (0.57 dS m^{-1}) and SOC (0.5%) than the 15–30 cm layer, which recorded corresponding means of 7.87, 0.49 dS m^{-1} and 0.38%. Seasonally, pH and EC reached their highest mean values during summer (8.0 and 0.59 dS m^{-1}, respectively), whereas SOC was highest during the rainy season (0.51%) and lowest during summer (0.37%). Surface SOC was approximately 30.7% higher than subsurface SOC, indicating a pronounced vertical gradient in organic carbon. Bulk density increased from 1.48 g cm^{-3} in the 0–15 cm layer to 1.54 g cm^{-3} at 15–30 cm depth. Overall, the observed patterns demonstrate pronounced seasonal variability in SOC and EC, relatively stable soil pH and bulk density, and greater organic carbon accumulation in the surface soil beneath A. nilotica. These findings highlight the potential importance of A. nilotica-dominated microsites for maintaining soil organic matter and associated soil functions under the strongly seasonal conditions of the Rajasthan arid zone.*

***Keywords*—Acacia nilotica, arid soil, bulk density, electrical conductivity, soil organic carbon, soil pH, seasonal variation, Sardarshahar**

I. INTRODUCTION

Soil is a fundamental component of dryland ecosystems, providing the physical and chemical medium necessary for plant growth, water storage, nutrient cycling and carbon sequestration (Yadav et al., 2021). In arid and semi-arid regions, however, soil processes are strongly constrained by limited and highly variable precipitation, high temperatures, intense evaporative demand and prolonged dry periods. These climatic constraints interact with vegetation cover, litter accumulation, root activity, soil texture and land-use history to regulate the distribution and availability of soil resources. Consequently, even relatively small changes in vegetation structure can produce substantial spatial and temporal differences in soil properties within dryland landscapes. Rajasthan encompasses extensive arid and semi-arid ecosystems where low and erratic rainfall and high atmospheric demand can limit organic matter inputs and decomposition dynamics. Previous studies from Rajasthan have demonstrated that soil carbon pools vary considerably with soil type, rainfall regime, canopy cover and land use, while soil organic carbon (SOC) is generally concentrated in the upper soil layers and declines with increasing depth (Singh et al., 2007; Singh et al., 2022).

Woody vegetation can substantially modify the physical and chemical environment of soils in drylands by creating localized zones of enhanced resource availability beneath their canopies. Tree canopies influence near-surface microclimatic conditions, litter deposition, root distribution, soil moisture retention and nutrient cycling, potentially resulting in distinct soil conditions beneath trees compared with surrounding open areas. Such vegetation-mediated patches, often described as islands of fertility, are particularly important in water-limited ecosystems where resources are spatially heterogeneous. In arid Rajasthan, studies have reported measurable differences in soil pH, electrical conductivity (EC) and organic carbon beneath tree canopies, demonstrating the capacity of woody vegetation to modify soil properties at relatively small spatial scales (Raina, 2003). Among these properties, SOC is particularly important because it represents a major terrestrial carbon reservoir and contributes to soil aggregation, nutrient retention, water-holding capacity and biological activity. Changes in SOC can consequently influence several other aspects of soil functioning. Bulk density, in turn, is closely associated with soil porosity, compaction and organic matter content, and increases in soil organic matter are frequently associated with reductions in bulk density. Supporting this relationship, a study from Rajasthan reported a negative association between SOC and bulk density across different land-use systems (Sharma, 2022).

Although vegetation can influence soil properties spatially, these effects may also vary considerably through time. Seasonal changes in temperature, precipitation, evaporative demand, soil moisture and biological activity can alter the rates of litter decomposition, organic matter accumulation, nutrient transformation and salt redistribution. The transition from the dry season to the monsoon period is particularly important in arid environments because even a relatively short period of rainfall can substantially modify soil moisture availability and associated biogeochemical processes. Conversely, the prolonged hot and dry conditions preceding the monsoon can promote surface drying and concentration of soluble constituents through evaporation. Consequently, assessment of soil properties at different times of the year provides a more comprehensive understanding of soil functioning than measurements from a single season.

These seasonal processes are particularly relevant in the Sardarshahar region of Rajasthan, which is characterized by a hot and dry arid climate and a highly seasonal rainfall regime. Government groundwater information describes Sardarshahar as having a hot and dry arid climate with average annual rainfall of approximately 258 mm, while local environmental assessments characterize the soils largely as sandy to loamy-sand and report pronounced seasonal temperature variation. Such environmental conditions provide a useful setting for examining seasonal changes in soil properties associated with woody vegetation. The combination of low annual rainfall, high evaporative demand, sandy soil conditions and strong seasonality can influence both the accumulation of organic matter and the movement and concentration of soluble soil constituents. Therefore, seasonal assessment of soil physicochemical characteristics is important for understanding tree–soil interactions and the role of woody vegetation in maintaining soil quality under arid conditions.

Acacia nilotica is an ecologically and socioeconomically important tree species in dryland regions and has characteristics that may promote soil development and resource retention beneath its canopy. Its extensive root system and substantial biomass production provide pathways for organic matter inputs through litter deposition, root turnover and associated biological activity. The species can therefore contribute to the development of localized nutrient-rich soil microsites and potentially influence soil physical properties. In Rajasthan, *A. nilotica* should be contributed significantly to SOC through the addition and turnover of organic matter derived from leaf litter and roots like *Prosopis cineraria* (Pareek et al., 2024). Beyond its ecological importance, the species has considerable socioeconomic value in rural landscapes. Its wood is widely used for fuelwood and charcoal and is particularly valued for cooking and domestic heating (Pareek et al., 2024). Rural communities also continue to depend on local and nearby trees for fuelwood and fodder, highlighting the importance of woody vegetation not only for ecosystem functioning but also for sustaining rural livelihoods (Yadav et al., 2022).

Despite the ecological and socioeconomic importance of *A. nilotica* in Rajasthan, information on how soil physicochemical properties beneath this species vary across seasons and soil depths remains comparatively limited, particularly under the strongly seasonal conditions of the arid zone. Understanding these temporal and vertical patterns is important for evaluating the capacity of *A. nilotica* to influence soil organic matter dynamics, salinity-related properties and soil physical condition under water-limited environments. Such information can also contribute to a better understanding of tree-mediated resource redistribution and the role of native or widely established woody vegetation in maintaining soil quality in arid landscapes.

Therefore, the present study evaluated the seasonal and depth-wise variation in selected soil physicochemical properties, including pH, electrical conductivity, soil organic carbon and bulk density, beneath *Acacia nilotica* in the arid region of Rajasthan. The study specifically aimed to characterize seasonal changes in soil chemical properties, assess vertical differences between surface and subsurface soil layers, and examine the relative variability of these properties across the annual seasonal cycle. The findings provide baseline information on soil conditions associated with *A. nilotica* and contribute to understanding vegetation–soil interactions in the arid ecosystems of Rajasthan.

II. MATERIALS AND METHODS

2.1 Study area

The study was conducted in Sardarshahar, a town located in the Churu district of Rajasthan, India (Figure: 1). Sardarshahar is situated in the northwestern part of the state and falls within the arid region of the Thar Desert (Wikipedia contributors, 2024). The geographical coordinates of the study area are approximately 28.44° N latitude and 74.49° E longitude, with an average elevation of about 312 meters above sea level. The region experiences extreme climatic conditions characterized by high temperatures, low and erratic rainfall, and significant variations in day and night temperatures (Wikipedia contributors, 2024).

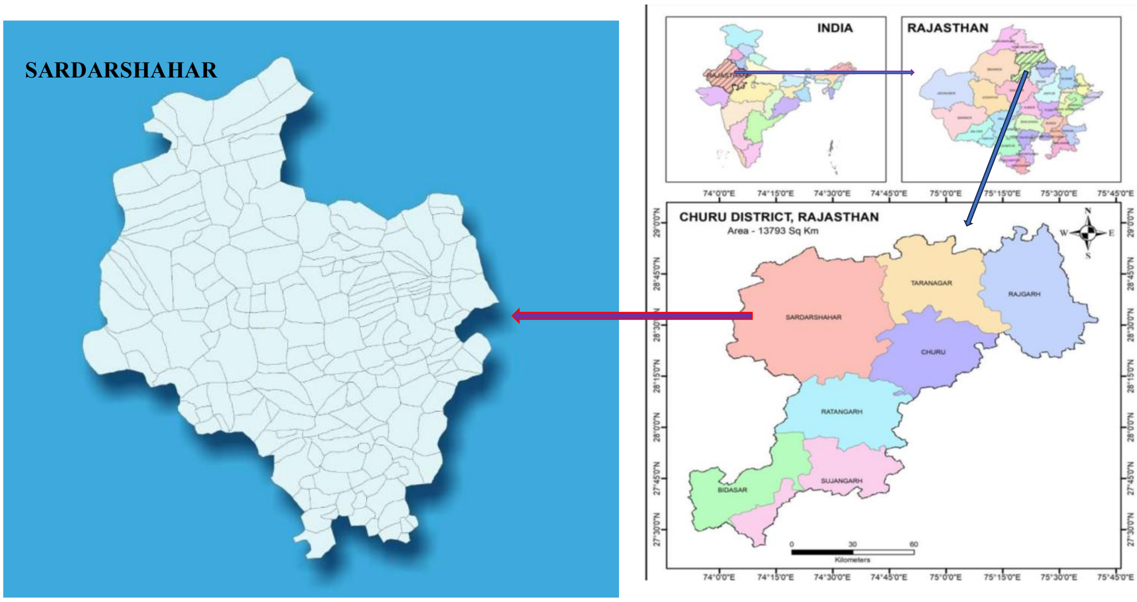

Fig. 1: Map of SARDARSHAHAR (Not to scale)

2.2 Sampling design and dataset

The supplied dataset represents *Acacia nilotica* and two soil depths: 0–15 cm and 15–30 cm. Four seasons were considered: winter, spring, summer and rainy. The field notes indicate four replicates per season × depth combination (n = 4).

2.3 Soil properties

The evaluated properties were soil reaction (pH), electrical conductivity (EC), soil organic carbon (SOC) and bulk density (BD). Soil pH and EC are standard indicators of soil chemical status and soluble-salt conditions, whereas SOC is a major indicator of soil quality and carbon storage. Bulk density provides an estimate of soil compaction/porosity and is also required for converting carbon concentration into an areal stock.

The analytical framework is consistent with standard soil laboratory approaches. Jackson (1973) provides standard procedures for soil chemical analysis, while Walkley and Black (1934) established the classical dichromate oxidation approach for soil organic matter/organic carbon. USDA-NRCS soil survey manuals also describe standardized procedures for pH, organic carbon and bulk-density measurements.

2.4 Statistical analysis

For each variable, overall mean, sample standard deviation (SD), minimum, maximum and coefficient of variation (CV = SD/mean × 100) were calculated across the four supplied season × depth means. Seasonal means were calculated by averaging the two soil depths within each season, and depth means were calculated by averaging the four seasonal values within each depth. Percentage difference between surface and subsurface SOC was calculated as (surface − subsurface)/subsurface × 100.

III. RESULTS

3.1 Overall variation in soil physicochemical properties

The soil physicochemical properties measured beneath *Acacia nilotica* showed distinct differences in their magnitude and variability across seasons and soil depths (Table 1). Soil pH remained slightly to moderately alkaline throughout the observation period, ranging from 7.50 to 8.10, with an overall mean of 7.78 ± 0.19. The relatively low coefficient of variation (CV = 2.45%) indicates that pH was the least variable of the measured soil properties.

Electrical conductivity (EC) varied from 0.45 to 0.63 dS m^{-1}, with an overall mean of 0.53 ± 0.06 dS m^{-1} and a CV of 10.90%. Soil organic carbon (SOC) exhibited comparatively greater variability, ranging from 0.32 to 0.58%, with a mean of 0.44 ± 0.08% and a CV of 18.78%. Bulk density (BD) showed relatively limited variation, with values ranging from 1.48 to 1.54 g cm^{-3} and an overall mean of 1.51 ± 0.04 g cm^{-3}.

Table 1. Descriptive statistics of soil physicochemical properties under Acacia nilotica in the arid region of Rajasthan.

Soil Property	Mean	SD	CV (%)	Minimum	Maximum	Unit
pH	7.775	0.191	2.45	7.50	8.10	pH units
EC	0.531	0.058	10.90	0.45	0.63	dS m^{-1}
SOC	0.441	0.083	18.78	0.32	0.58	%
Bulk density	1.510	0.042	2.81	1.48	1.54	g cm^{-3}

Overall, the magnitude of variation followed the order SOC > EC > BD > pH, based on the coefficient of variation. This indicates that SOC was more responsive to seasonal and depth-related changes than the other measured soil properties.

3.2 Seasonal and depth-wise variation in soil pH

Soil pH remained within a relatively narrow alkaline range (7.50–8.10), although a clear seasonal pattern was evident. Seasonal mean pH increased progressively from winter (7.70) to spring (7.80) and reached the highest value during summer (8.00), followed by a marked decline during the rainy season to 7.60 (Table 2; Fig. 2).

Depth-wise differences were comparatively small but consistent across the study period. The mean pH of the 0–15 cm layer was 7.68, whereas the 15–30 cm layer recorded a higher mean of 7.88. Thus, the subsurface soil was approximately 0.20 pH units more alkaline than the surface layer.

The relatively narrow range and low CV of pH suggest that soil reaction remained comparatively stable beneath *A. nilotica*, despite seasonal fluctuations. The lowest pH during the rainy season coincided with the period of maximum SOC accumulation, whereas the highest pH occurred during summer.

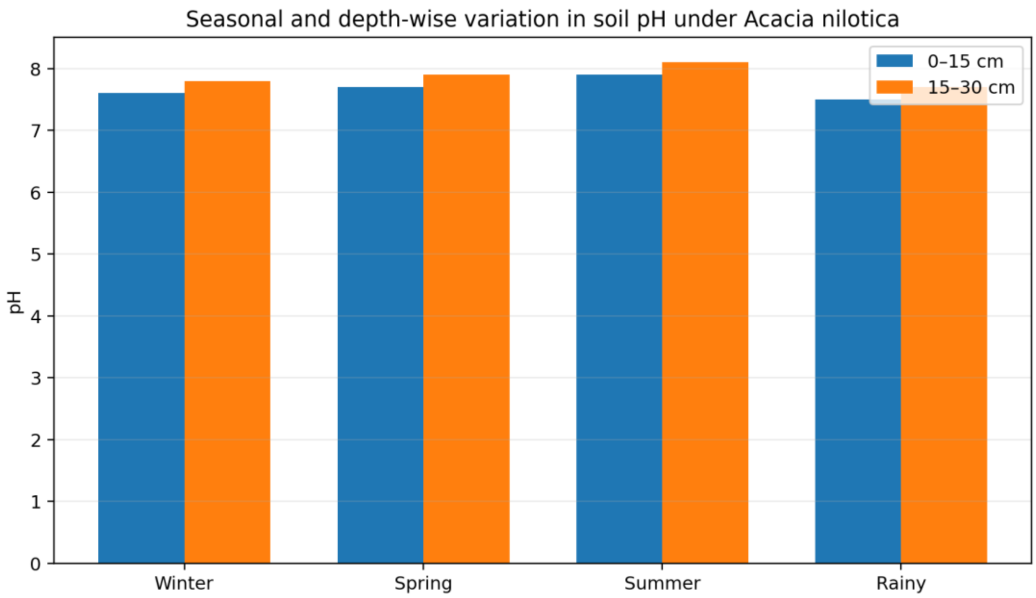

Fig.2. Seasonal and depth-wise variation in soil pH under Acacia nilotica.

3.3 Seasonal and depth-wise variation in electrical conductivity

Soil EC exhibited greater temporal variability than pH, with values ranging from 0.45 to 0.63 dS m^{-1} (Table 1). Seasonal mean EC increased from winter (0.515 dS m^{-1}) to spring (0.540 dS m^{-1}) and reached a maximum during summer (0.590 dS m^{-1}). This was followed by a decline during the rainy season, when EC decreased to 0.480 dS m^{-1} (Table 2; Fig. 3). A clear depth-related pattern was also observed. The 0–15 cm layer had a mean EC of 0.567 dS m^{-1}, compared with 0.495 dS m^{-1} in the 15–30 cm layer. Thus, surface-soil EC was approximately 14.5% higher than that of the subsurface layer.

The higher EC observed during summer and in the surface layer indicates greater concentration of soluble salts near the soil surface during the relatively dry period. In contrast, the lower EC recorded during the rainy season suggests dilution and/or downward movement of soluble ions associated with rainfall and increased soil-water availability.

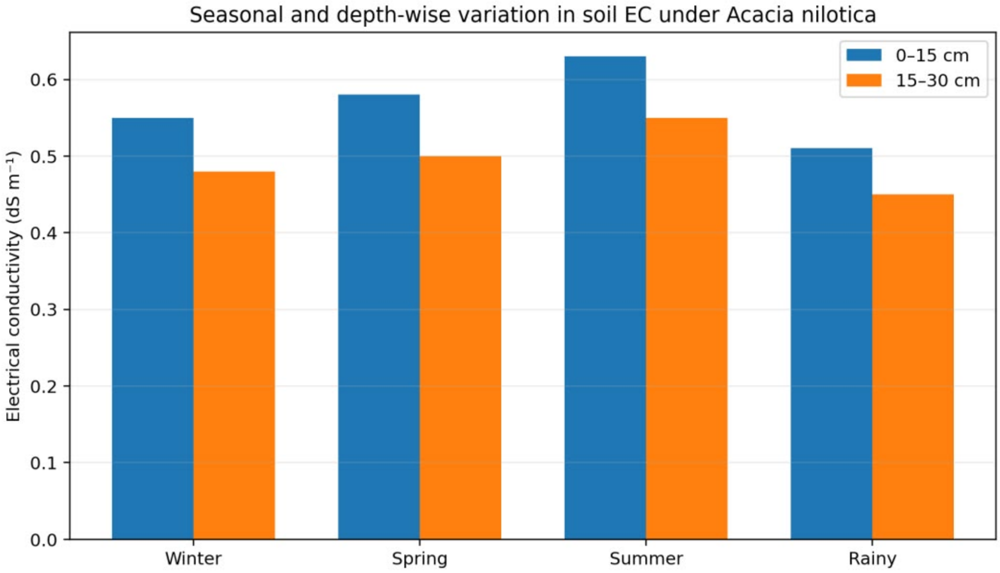

Fig.3. Seasonal and depth-wise variation in soil electrical conductivity under Acacia nilotica.

3.4 Seasonal and depth-wise soil organic carbon

SOC showed the greatest variability among the measured soil properties, with concentrations ranging from 0.32 to 0.58% and an overall mean of 0.441% (Table 1). Unlike pH and EC, SOC exhibited a pronounced seasonal pattern, with the highest seasonal mean during the rainy season (0.515%) and the lowest during summer (0.375%) (Table 2; Fig. 4). SOC increased from 0.425% in winter to 0.450% in spring, declined to 0.375% during summer, and subsequently increased sharply to 0.515% during the rainy season. The rainy-season value was approximately 37.3% higher than the summer value.

A pronounced vertical gradient in SOC was also evident. The 0–15 cm soil layer contained an average SOC concentration of 0.500%, compared with 0.383% in the 15–30 cm layer. Thus, surface SOC was approximately 30.7% higher than that of the subsurface layer.

The concentration of SOC in the surface layer, together with its seasonal increase during the rainy period, indicates stronger accumulation of organic matter in the upper soil beneath *A. nilotica*. The seasonal pattern was opposite to that observed for EC, with SOC increasing during the rainy season while EC declined.

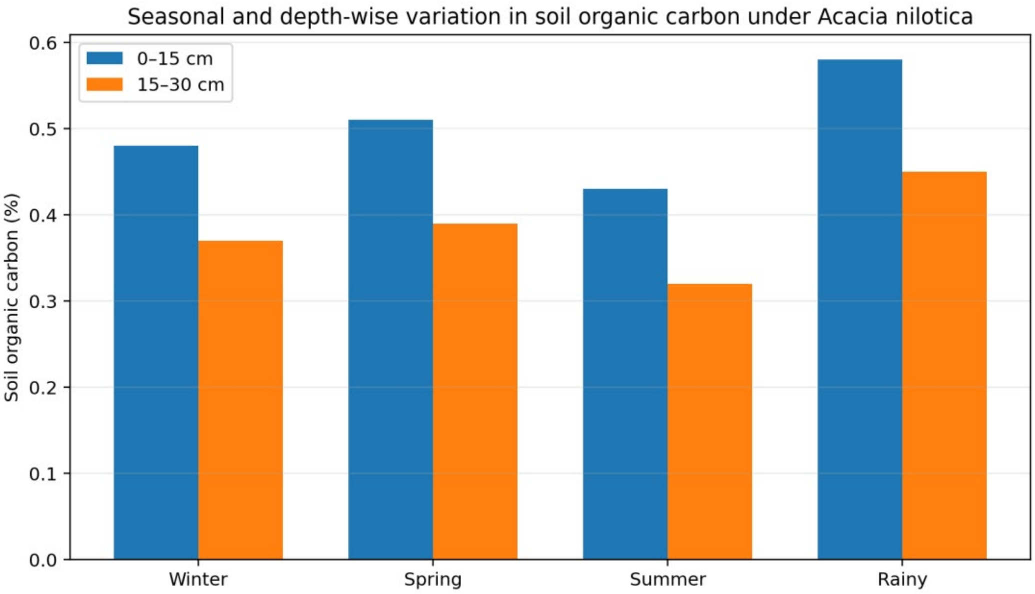

Fig.4. Seasonal and depth-wise variation in soil organic carbon under Acacia nilotica.

3.5 Bulk density

Bulk density showed a relatively narrow range (1.48–1.54 g cm^{-3}) and a low coefficient of variation (2.81%), indicating limited variability compared with SOC and EC (Table 1). The mean BD was 1.48 g cm^{-3} in the 0–15 cm layer and increased to 1.54 g cm^{-3} at 15–30 cm depth (Fig. 5). The subsurface layer was therefore 0.06 g cm^{-3}, or approximately 4.1%, denser than the surface layer. The lower BD in the upper soil layer corresponded with its substantially higher SOC concentration. This pattern indicates comparatively greater organic matter accumulation and potentially greater pore-space development in the surface soil beneath *A. nilotica*.

Because the available BD observations were depth-wise means rather than season-specific measurements, seasonal comparisons of BD were not undertaken.

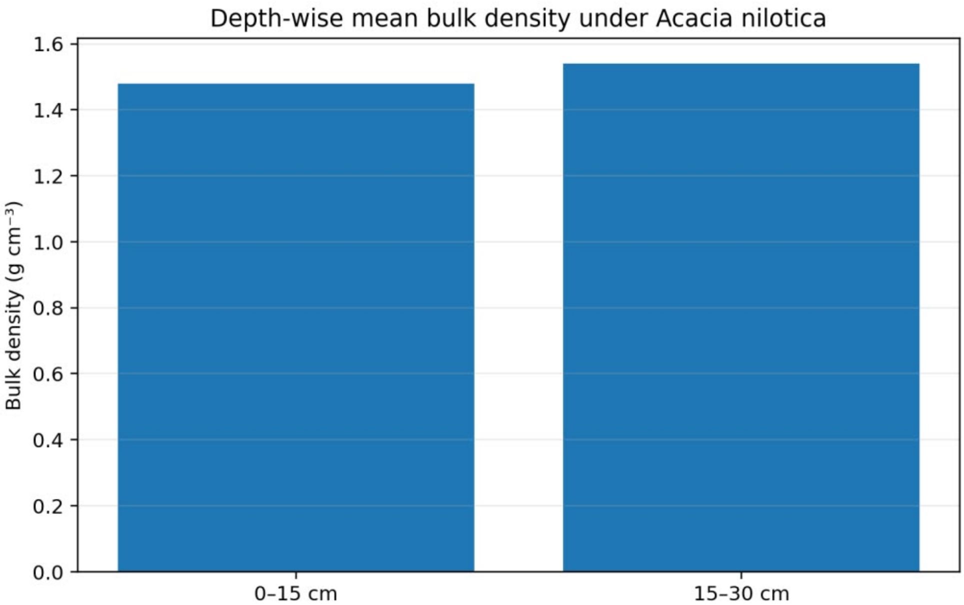

Fig.5. Depth-wise mean bulk density under Acacia nilotica.

3.6 Seasonal synthesis of soil properties

The seasonal means revealed contrasting responses among the measured soil properties (Table 2). Summer was characterized by the highest mean pH (8.00) and EC (0.590 dS m^{-1}), but the lowest SOC (0.375%). In contrast, the rainy season exhibited the lowest pH (7.60) and EC

(0.480 dS m⁻¹), while SOC reached its maximum value (0.515%). The simultaneous increase in SOC and decline in EC during the rainy season represents the most notable seasonal shift in the measured soil properties. Winter and spring showed intermediate values for most parameters. Collectively, these patterns indicate that soil conditions beneath *A. nilotica* were characterized by relatively stable soil reaction and bulk density but stronger seasonal dynamics in soluble salts and soil organic carbon.

Table 2. Seasonal mean values of soil physicochemical properties under Acacia nilotica.

Season	Mean pH	Mean EC (dS m^{-1})	Mean SOC (%)
Winter	7.70	0.515	0.425
Spring	7.80	0.540	0.450
Summer	8.00	0.590	0.375
Rainy	7.60	0.480	0.515

IV. DISCUSSION

The present study shows that soil pH was relatively stable compared with EC and SOC. The maximum pH was observed in summer, while the rainy season showed a decline. In arid soils, seasonal moisture status and salt redistribution can alter soil solution chemistry and measured pH. The observed values (7.5–8.1) indicate neutral to moderately alkaline soil reaction, which is consistent with the generally alkaline character reported for many soils of arid Rajasthan. Raina (2003) reported pH values of approximately 7.4–8.45 beneath tree canopies in arid Rajasthan, demonstrating that the range observed here is environmentally plausible.

EC displayed a stronger seasonal signal than pH, with the highest seasonal mean in summer and the lowest in the rainy season. A plausible mechanism is concentration of soluble salts during the hot and dry period because of high evaporative demand, followed by dilution and redistribution after monsoon rainfall. The reduction from summer to rainy-season EC was evident at both soil depths. The absolute EC values were relatively low compared with strongly saline soils, indicating that the measured soil under A. nilotica was not characterized by high salinity in the supplied dataset. Raina (2003) likewise documented substantial EC variability among arid Rajasthan soils beneath tree canopies.

SOC showed the clearest vertical pattern: the surface layer consistently exceeded the 15–30 cm layer in all four seasons. Surface SOC was 0.11–0.13 percentage points higher than subsurface SOC across seasons. This pattern is consistent with greater accumulation of leaf litter, fine roots, root exudates and decomposed organic residues near the soil surface. Studies across Rajasthan have also reported greater SOC concentration or stock in upper soil layers and declining SOC with increasing depth (Singh et al., 2007; Singh et al., 2022). The rainy-season maximum in SOC may reflect greater moisture availability, litter incorporation and biological activity, although the present summary data cannot isolate the relative contribution of each process.

The summer minimum SOC is ecologically important. High temperature, rapid mineralization, low soil moisture and greater susceptibility of exposed organic residues to decomposition or wind redistribution can reduce the persistence of organic carbon in arid soils. Singh et al. (2007) emphasized that rainfall, canopy cover, soil texture, available water capacity and land use can strongly influence SOC dynamics in arid Rajasthan. The seasonal pattern observed here is therefore consistent with the broader understanding that water availability is a major control on carbon cycling in drylands.

Bulk density was higher at 15–30 cm than at 0–15 cm. This agrees with the common vertical relationship in which surface soils contain more organic matter and biological pores, while deeper soil can be relatively compacted. Sharma (2022) reported a minimum BD of 1.32 Mg m^{-3} in surface forest soil and higher values in deeper cultivated soil, together with a strong negative relationship between SOC and BD. In the present data, the higher SOC and lower BD of the surface layer occur together, supporting the expected inverse relationship, although a formal correlation cannot be established from only two depth means.

Taken together, the results indicate that the *Acacia nilotica* soil environment exhibits a distinct seasonal pulse: summer is associated with comparatively high pH and EC and low SOC, whereas the rainy season is associated with lower pH and EC and higher SOC. This suggests that rainfall-driven moisture dynamics are important in regulating both soluble salts and soil carbon in the arid environment of Sardarshahar.

V. CONCLUSION

The present analysis demonstrates pronounced seasonal and depth-related patterns in soil physicochemical properties under *Acacia nilotica* in the arid region of Sardarshahar, Rajasthan. Soil pH was comparatively stable but increased towards summer and declined during the rainy season. EC showed the strongest summer enrichment and the lowest values during the rainy season. SOC was consistently greater in the 0–15 cm layer and reached its highest seasonal mean during the rainy season, while summer had the lowest SOC. Bulk density was greater in the 15–30 cm layer than in the surface layer. The combination of higher surface SOC and lower surface BD indicates a relatively more organic-rich and biologically influenced upper soil layer. These findings support the ecological importance of tree-associated soils for maintaining soil quality and carbon in arid landscapes.

VI. PRACTICAL IMPLICATIONS

The results have implications for dryland restoration and tree-based land management. Maintaining tree cover can promote litter inputs, root-derived carbon and localized soil improvement. Monitoring SOC alongside pH, EC and BD across seasons can provide a useful indicator set for evaluating soil-condition changes under arid agroforestry. Future sampling should retain replicate-level observations, soil moisture, rainfall, temperature, texture and litter inputs so that the mechanisms responsible for seasonal changes can be evaluated quantitatively.

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