

International Journal of Plant & Soil Science

Volume 38, Issue 11, Page 523-534, 2026; Article no.IJPSS.169984
ISSN: 2320-7035

Depth-Dependent Soil Moisture Response to Organic and Hydrogel Amendments during Restoration of a Degraded Rocky Hill in the Indian Thar Desert

Bhawana Sharma [a*], Karna Ram Choudhry [a], Sharat Kothari [a] and Ganga Ram Choudhry [a]

[a] ICFRE–Arid Forest Research Institute, Jodhpur, Rajasthan, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i116445

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/169984

Original Research Article

Received: 26/09/2026
Accepted: 17/11/2026
Published: 23/11/2026

Abstract

Aims: To assess depth-dependent gravimetric soil moisture under organic and hydrogel amendments during restoration of a degraded rocky hill. Study design: A randomised blocked factorial experiment included five replications, three amendments and six woody species across 90 plots. Place and duration of study: Lunawas Bhakhar, Jodhpur, western Rajasthan, India; the plantation was established in 2022, and soil moisture was assessed in January 2024. Methodology: Farmyard manure (5 kg pit^{-1}), sewage sludge (5 kg pit^{-1}) and hydrogel (20 g pit^{-1}) were compared. Soil was sampled at 0–30 and 30–60 cm, providing 180 determinations from 90 paired plot positions. Samples were oven-dried at 105 ± 2°C to constant mass. Paired comparisons, factorial analysis of variance, a mixed-effects model and descriptive spatial analyses were performed. Results: Mean moisture was 1.761 ± 0.106% at 0–30 cm and 2.695 ± 0.169% at 30–60 cm, an approximately 53% increase (paired $t = 4.61$, $df = 89$, $p < 0.001$). Farmyard manure had the highest numerical surface-layer mean (2.030%), whereas hydrogel had the highest deeper-layer mean (3.091%). Amendment, species and amendment × species effects were not statistically significant at either depth. Replication effects were significant (p =

**Corresponding Email(s): bhawana@icfre.org;*

Contact Email(s): bsharma1979sep@gmail.com;

Cite as: *Sharma, B., Choudhry, K. R., Kothari, S., & Choudhry, G. R. (2026). Depth-Dependent Soil Moisture Response to Organic and Hydrogel Amendments during Restoration of a Degraded Rocky Hill in the Indian Thar Desert. International Journal of Plant & Soil Science, 38(11), 523–534. https://doi.org/10.9734/ijpss/2026/v38i116445*

0.026 and 0.021), and coordinate–moisture correlations were weak ($|r| \leq 0.252$). Conclusion: Moisture was significantly greater in the deeper layer during the January 2024 campaign. Numerical amendment differences require seasonal confirmation and do not establish year-round treatment performance.

Keywords: Arid land restoration; gravimetric soil moisture; soil depth; farmyard manure; sewage sludge; hydrogel; woody species; rocky hill; Thar Desert; microsite heterogeneity.

1. Introduction

Drylands occupy a large proportion of the terrestrial surface and are highly vulnerable to degradation, climate variability and water limitation. Anthropogenic climate change and unsustainable land use have already contributed to desertification across extensive dryland areas, while restoration remains difficult because low and erratic rainfall interacts with high evaporative demand and poor soil water storage (Burrell *et al*., 2020; Stapleton *et al*., 2024). In such environments, the establishment and persistence of planted seedlings depend strongly on the timing, depth and duration of soil water availability. Restoration studies from arid regions consistently identify water supply and soil hydrology as major controls on seedling emergence, survival and early growth (James *et al*., 2011; Commander *et al*., 2013; Abella *et al*., 2015).

The Indian Thar Desert is characterised by high climatic aridity, strong evaporative demand and pronounced spatial variability in soil moisture. In long-term silvopastoral systems near Jodhpur, season and soil depth significantly controlled soil-moisture distribution, with rapid depletion in upper soil layers during dry periods (Sharma *et al*., 2003). Such depth-dependent behaviour is especially relevant on degraded rocky hills, where soil occurs in discontinuous pockets between exposed rock surfaces and where infiltration, runoff concentration, soil depth and fracture networks may vary over short distances. Comparable restoration studies in semi-arid post-mining and dryland environments have shown that rainfall, soil cover properties and microsite conditions can strongly influence plant-available water and establishment success (Golos *et al*., 2021; Li *et al*., 2021). Soil biological processes may also influence the physical pathways governing infiltration and moisture redistribution; a recent synthesis identifies termite tunnelling and mound formation as mechanisms that can alter soil porosity, nutrient cycling and water movement (Duta & Harit, 2026).

Soil amendments are frequently used to increase water retention or improve degraded-soil properties. Organic amendments can increase soil organic matter, aggregation and moisture retention, and field studies under arid and semi-arid Indian conditions have demonstrated improvements in soil-water status following FYM or related organic inputs (Rao & Sankar, 2007; Bhanwaria *et al*., 2022). A recent systematic review similarly found that organic amendments generally improve soil moisture and soil organic carbon in sandy soils, although the magnitude of response varies with soil type, application rate, crop and management (Musei *et al*., 2024). Sewage sludge may also supply organic matter and nutrients to infertile arid soils, but its agronomic use requires quality control because trace metals and organic contaminants can constrain safe application (Uddin *et al*., 2025). Recent research in degraded grasslands has also shown that soil amendments can modify soil hydraulic conductivity and structural properties, although the magnitude of response depends on the amendment combination and soil conditions (Xu *et al*., 2024).

Hydrogels represent a contrasting strategy because they function primarily as water-absorbing and water-releasing polymers. Experimental studies have shown that superabsorbent polymers can increase soil water retention and prolong seedling survival under drought, although field responses are not universally positive and depend on application rate, soil texture, salinity and species (Hüttermann *et al*., 1999; Clemente *et al*., 2004; Commander *et al*., 2013). Recent reviews confirm that hydrogels can improve water storage and reduce water stress, while also emphasising uncertainties related to field effectiveness, persistence, cost and environmental safety (Mandal *et al*., 2024; Qin *et al*., 2024; Muhammad *et al*., 2025). Recent research in an arid region has also evaluated biodegradable hydrogel formulations and reported improvements in soil moisture retention, while highlighting the need to account for local soil and climatic conditions (Azimov *et al*., 2026). In an Indian field experiment, hydrogel treatments were associated with slower soil-moisture depletion, although the response differed among hydrogel formulations and irrigation schedules (Cholavardan *et al*., 2026).

1.1 Research Gap

However, the available literature does not resolve how soil-moisture patterns vary by depth in degraded rocky-hill restoration settings in the Indian Thar Desert, particularly across organic and hydrogel amendments and planted woody species. The present study addresses this site-specific question using paired observations at 0–30 and 30–60 cm from the Lunawas Bhakhar restoration trial; because measurements were collected during one January 2024 campaign, the results are interpreted as a temporal snapshot rather than evidence of seasonal persistence.

The Lunawas Bhakhar restoration experiment near Jodhpur was established to evaluate native woody species and practical pit amendments for rehabilitation of a degraded rocky hill. The present study analyses the 2024 soil-moisture observations to determine whether gravimetric moisture differed between 0–30 and 30–60 cm soil depths, among FYM, sewage sludge and hydrogel treatments, and among six planted woody species. We hypothesised that (i) soil moisture would differ between surface and subsurface layers and (ii) amendment effects would vary with depth because organic amendments and hydrogels influence water retention through different mechanisms.

1.2 Objectives

The specific objectives were to (i) compare gravimetric soil moisture between the 0–30 and 30–60 cm layers; (ii) evaluate moisture differences among farmyard manure, sewage sludge and hydrogel treatments at each depth; and (iii) examine species-associated and spatial variation in soil moisture across the experimental plots.

2. Methodology

2.1 Study Site and Restoration Experiment

The study was conducted at Lunawas Bhakhar, Shiv village, Gram Panchayat Kalijal, Luni tehsil, approximately 33 km from Jodhpur, Rajasthan, India, within the arid zone of western Rajasthan. The site is a degraded rocky hill characterised by exposed rock, discontinuous soil pockets, shallow soil development and pronounced microsite variability. Approximately 12 ha was protected by fencing, of which about 10.8 ha was used for the experimental plantation established in 2022. Planting pits were prepared in the rocky substrate by drilling or blasting where required, followed by planting and field maintenance.

2.2 Experimental Design and Field Layout

The field experiment comprised 90 plots arranged in five replications (R1–R5). Each replication contained the complete 3 × 6 factorial set of three soil-amendment treatments and six woody species, giving 18 treatment × species combinations per replication and 90 experimental plots in total. Each plot contained 40 planted seedlings at a spacing of 5 m × 5 m; therefore, the experimental plantation comprised 3,600 seedlings. The treatment and species combinations were randomised within each replication according to the field layout used at establishment (Fig. 1). This blocked arrangement was retained during soil-moisture sampling so that replication could be included explicitly in the statistical analysis.

Experimental field layout (not to scale)

Five replications; each replication contains all 18 treatment × species combinations

R1	T1S2	T3S6	T1S3	T2S4	T2S5	T1S1
	T3S5	T1S4	T3S1	T3S2	T1S6	T3S3
	T2S6	T2S1	T2S3	T3S4	T1S5	T2S2

R2	T2S6	T1S4	T3S3	T2S2	T1S1	T2S5
	T1S3	T3S1	T3S5	T1S6	T2S4	T1S2
	T3S2	T1S5	T2S1	T3S4	T2S3	T3S6

R3	T3S4	T2S6	T1S3	T2S2	T1S1	T3S5
	T3S1	T1S2	T1S5	T2S4	T3S6	T2S3
	T2S5	T3S3	T1S4	T2S1	T3S2	T1S6

R4	T1S1	T2S4	T3S6	T2S2	T3S3	T2S5
	T3S2	T1S3	T3S5	T1S6	T1S4	T3S1
	T2S3	T1S2	T2S1	T3S4	T1S5	T2S6

R5	T3S5	T1S4	T3S3	T2S2	T3S1	T2S6
	T2S4	T1S3	T3S6	T1S5	T2S1	T1S2
	T1S1	T3S2	T2S5	T3S4	T1S6	T2S3

T1 = FYM (5 kg pit^{-1}); T2 = sewage sludge (5 kg pit^{-1}); T3 = hydrogel (20 g pit^{-1})

S1 = *Cordia gharaf*; S2 = *Azadirachta indica*; S3 = *Holoptelea integrifolia*; S4 = *Moringa concanensis*; S5 = *Ziziphus mauritiana*; S6 = *Commiphora wightii*

Fig. 1. Experimental field layout of the Lunawas Bhakhar restoration trial (not to scale). R1-R5 are field replications. T1 = FYM (5 kg pit^{-1}), T2 = sewage sludge (5 kg pit^{-1}), and T3 = hydrogel (20 g pit^{-1}). S1-S6 denote the six planted woody species listed below

2.3 Amendment Treatments and Planted Species

Three pit amendments were evaluated: T1, farmyard manure (FYM) at 5 kg pit^{-1}; T2, sewage sludge at 5 kg pit^{-1}; and T3, hydrogel at 20 g pit^{-1}. These treatments were tested in combination with six planted woody species. The treatment codes used in the field layout and in the statistical dataset were retained throughout the analysis.

S1 – *Cordia gharaf*
S2 – *Azadirachta indica*
S3 – *Holoptelea integrifolia*
S4 – *Moringa concanensis*
S5 – *Ziziphus mauritiana*
S6 – *Commiphora wightii*

2.4 Soil Sampling and Gravimetric Moisture Determination

Soil moisture was measured during the January 2024 monitoring campaign at two depth intervals, 0–30 cm and 30–60 cm. One soil-moisture observation was associated with each of the 90 experimental plots at each depth, yielding 90 observations per depth and 180 gravimetric moisture determinations in total. Thus, all five replications and all treatment × species combinations were represented at both depths. For each sample, the mass of the empty beaker was recorded, followed by the mass of the beaker plus fresh soil and the mass of the beaker plus dry soil. Gravimetric soil moisture was calculated from these recorded masses. The soil samples were oven-dried at 105 ± 2°C for approximately 24 hours, with drying continued until a constant mass was obtained. Gravimetric soil moisture (%) = $[(W_2 - W_3) / (W_3 - W_1)] \times 100$, where W_1 is the mass of the empty beaker, W_2 is the mass of the beaker plus fresh soil, and W_3 is the mass of the beaker plus oven-dried soil. This single campaign provides a temporal snapshot of gravimetric moisture rather than a measure of seasonal water retention or its rate of change. Although planting was established in 2022, one sampling date cannot determine the trajectory of amendment-induced changes in soil structure or distinguish gradual organic-matter effects from short-term moisture conditions.

2.5 Experimental Structure and Statistical Analysis

The randomised field layout provided five blocks (replications), each containing the complete 3 × 6 treatment-by-species factorial combination. The same 90 plot identities were represented at both soil depths, allowing depth to be treated as a paired within-plot factor. Means are reported with standard errors (SE). Overall moisture at 0–30 and 30–60 cm was compared using a paired t-test. For each depth separately, factorial analysis of variance included replication (block), treatment, species and the treatment × species interaction. A mixed-effects model was additionally fitted to the combined depth dataset, with plot/sampling position as a random intercept and depth, treatment, depth × treatment, species and replication as fixed effects. Statistical significance was assessed at $p < 0.05$; p-values between 0.05 and 0.10 are described only as tendencies and not as statistically significant effects. Figures present means ± SE unless otherwise stated.

2.6 Plot Georeferencing and Spatial Analysis

Plot-wise geographic coordinates for all 90 experimental plots were arranged in a 6 × 15 grid representing plot centroids. The field-design diagram was reconciled with the coordinate grid using verified field anchors (plot 1 = R1T1S1, plot 76 = R1T1S2 and plot 90 = R5T1S1), establishing the west-to-east replication sequence as R5, R4, R3, R2 and R1. Each replication comprised 18 plots representing all combinations of three soil amendments and six species, confirming consistency between the experimental design and spatial assignment. Decimal latitude and longitude were converted into relative east–west and north–south distances from the field centroid for visualisation. Gravimetric soil moisture values measured in January 2024 at depths of 0–30 and 30–60 cm were linked to the verified plot positions using replication–treatment–species codes. Spatial patterns were examined descriptively using maps of observed plot-wise values, replication means and Pearson correlations between spatial coordinates and soil moisture to assess broad directional trends and localised heterogeneity.

3. Results

3.1 Overall Depth Effect

Soil moisture increased markedly with depth. Mean gravimetric moisture was 1.761 ± 0.106% in the 0–30 cm layer and 2.695 ± 0.169% in the 30–60 cm layer (Table 1; Fig. 2). This corresponded to an approximately 53% increase in the deeper layer. The paired comparison of corresponding sampling positions showed a highly significant depth effect ($t = 4.61$, $df = 89$, $p < 0.001$). The mixed-effects model also retained a significant positive effect of the 30–60 cm layer ($p = 0.018$).

Table 1. Gravimetric soil moisture at two depths in January 2024. n = 90 plot observations per depth, paired by plot; SD = standard deviation; SE = standard error. Moisture is expressed as a percentage of oven-dry soil mass

Depth	n	Mean (%)	SD	SE
0–30 cm	90	1.761	1.006	0.106
30–60 cm	90	2.695	1.601	0.169

3.2 Amendment Effects

At 0–30 cm, FYM recorded the highest numerical moisture (2.030 ± 0.233%), followed by sewage sludge (1.701 ± 0.153%) and hydrogel (1.551 ± 0.148%). At 30–60 cm, the ranking changed: hydrogel recorded the highest numerical mean (3.091 ± 0.283%), followed by FYM (2.773 ± 0.330%) and sewage sludge (2.221 ± 0.244%) (Table 2; Fig. 3). Relative to the upper layer, mean moisture increased by 36.6% under FYM, 30.5% under sewage sludge and 99.3% under hydrogel. However, treatment effects were

not significant at either depth (0–30 cm: F = 1.83, p = 0.169; 30–60 cm: F = 2.62, p = 0.080). In the mixed model, the depth × hydrogel interaction was positive but remained non-significant (p = 0.072).

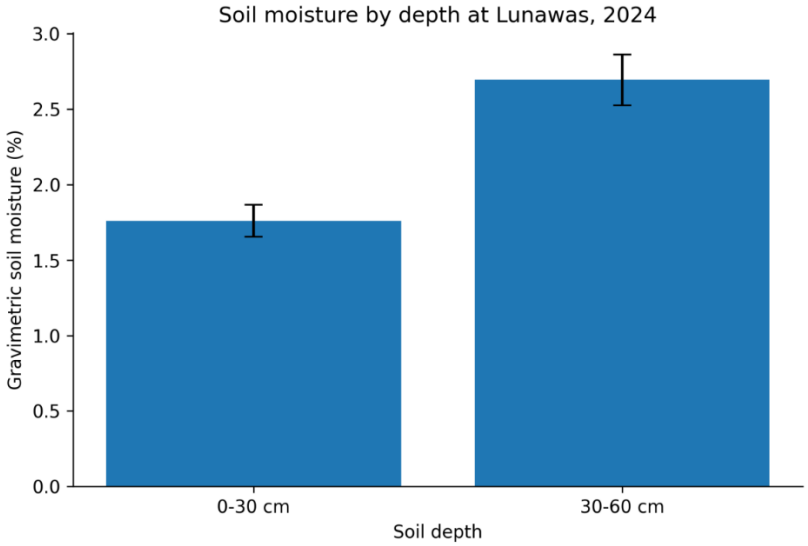


Fig. 2. Mean gravimetric soil moisture (± SE) at 0–30 and 30–60 cm depth in the Lunawas Bhakhar restoration trial (n = 90 paired positions per depth). The paired depth comparison was significant (t = 4.61, df = 89, p < 0.001). Observations represent the single January 2024 sampling campaign

Table 2. Amendment-wise gravimetric soil moisture (mean ± SE, %) in January 2024. n = 30 plots per amendment per depth. FYM = farmyard manure. Relative increase with depth = [(30–60 cm mean − 0–30 cm mean) / 0–30 cm mean] × 100. Amendment effects were non-significant at both depths (p = 0.169 and 0.080, respectively)

Amendment treatment	0–30 cm	30–60 cm	Increase with depth (%)
FYM (5 kg pit^{-1})	2.030 ± 0.233	2.773 ± 0.330	36.6
Sewage sludge (5 kg pit^{-1})	1.701 ± 0.153	2.221 ± 0.244	30.5
Hydrogel (20 g pit^{-1})	1.551 ± 0.148	3.091 ± 0.283	99.3

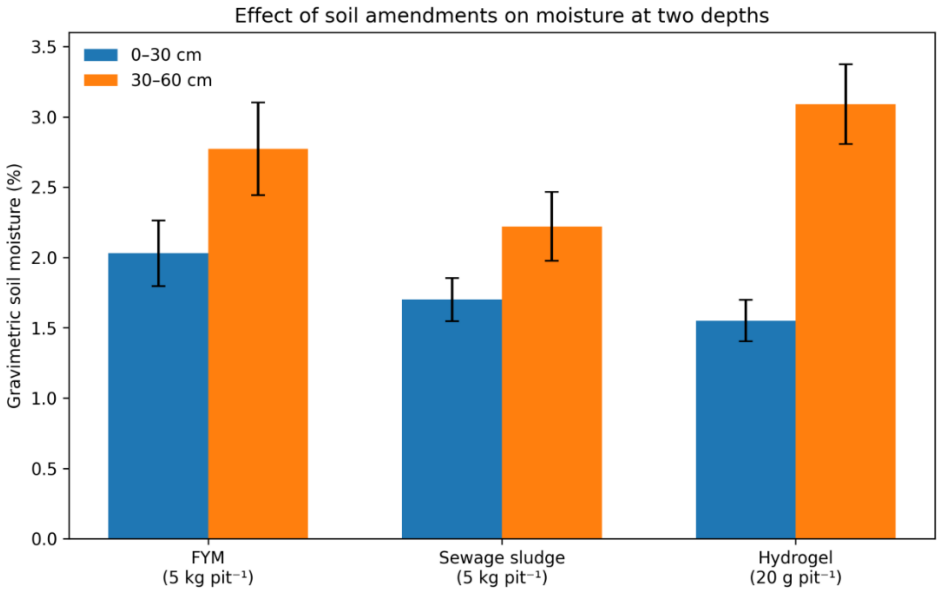


Fig. 3. Mean gravimetric soil moisture (± SE) under farmyard manure (FYM), sewage sludge and hydrogel at 0–30 and 30–60 cm depth. Treatment differences were non-significant within each depth (0–30 cm, p = 0.169; 30–60 cm, p = 0.080); therefore, differences among bars should be interpreted as numerical trends rather than significant treatment effects. Observations represent the single January 2024 sampling campaign

3.3 Species-associated Variation

Across planted species, soil moisture was generally higher at 30–60 cm than at 0–30 cm (Table 3; Fig. 4). The highest deeper-layer mean occurred in soil associated with *Ziziphus mauritiana* (3.380 ± 0.421%), followed by *Commiphora wightii* (2.816 ± 0.549%). The main species effect was not significant at either 0–30 cm (p = 0.418) or 30–60 cm (p = 0.460). Consequently, these differences are treated as species-associated field patterns rather than evidence that species identity caused differences in soil moisture.

Table 3. Species-associated gravimetric soil moisture (mean ± SE, %) in January 2024. n = 15 plots per species per depth. Species effects were non-significant at 0–30 cm (p = 0.418) and 30–60 cm (p = 0.460)

Species	0–30 cm	30–60 cm
Cordia gharaf	2.015 ± 0.366	2.359 ± 0.345
Azadirachta indica	1.426 ± 0.161	2.578 ± 0.537
Holoptelea integrifolia	1.651 ± 0.249	2.413 ± 0.249
Moringa concanensis	1.988 ± 0.302	2.623 ± 0.298
Ziziphus mauritiana	1.955 ± 0.254	3.380 ± 0.421
Commiphora wightii	1.530 ± 0.166	2.816 ± 0.549

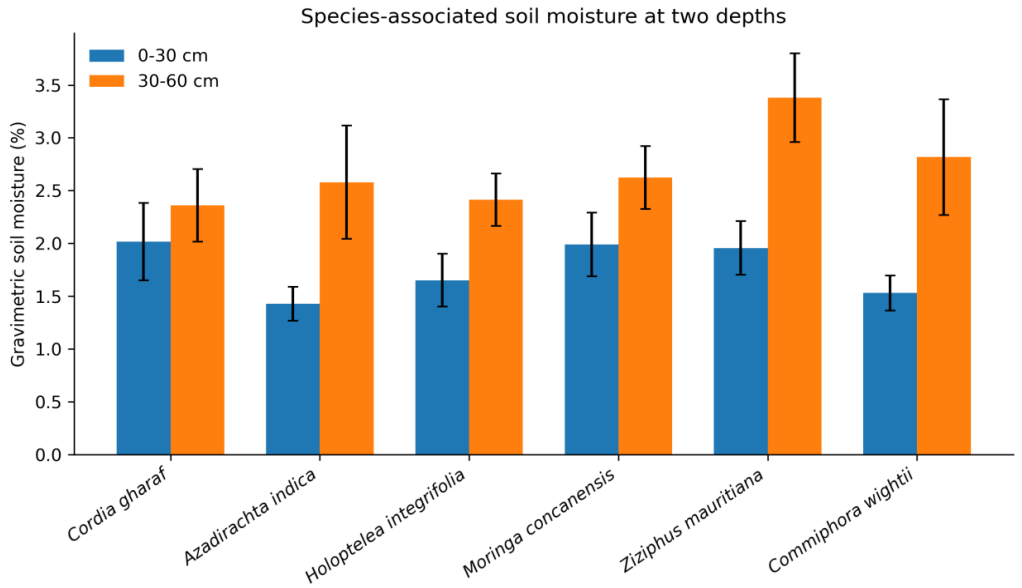


Fig. 4. Mean gravimetric soil moisture (± SE) associated with six planted woody species at 0–30 and 30–60 cm depth. Species effects were non-significant within both depth layers (p = 0.418 and p = 0.460, respectively). Observations represent the single January 2024 sampling campaign

3.4 Treatment × Species Patterns and Spatial Heterogeneity

The treatment × species interaction was not significant at either depth (0–30 cm: p = 0.979; 30–60 cm: p = 0.279). The corresponding analysis of variance results are presented in Table 4. Nevertheless, the 30–60 cm layer showed descriptive variation among treatment–species combinations (Fig. 5), with the largest numerical mean occurring under hydrogel in soil associated with *Ziziphus mauritiana*. Replication effects were significant at both depths (0–30 cm: p = 0.026; 30–60 cm: p = 0.021), demonstrating substantial microsite heterogeneity across the rocky hill.

3.5 Verified Spatial Pattern of Soil Moisture

The verified coordinate linkage confirmed five adjacent replication strips arranged from west to east as R5, R4, R3, R2 and R1 (Fig. 6). Replication-wise soil moisture differed numerically at both depths (Table 5). At 0–30 cm, mean moisture ranged from 1.411% in R1 to 2.264% in R5. At 30–60 cm, means ranged from 1.844% in R4 to 3.470% in R3. These spatially resolved block differences are consistent with the significant replication effects detected by ANOVA.

Observed plot-wise maps showed localised wetter and drier patches rather than a continuous field-wide gradient (Fig. 7). Correlation with east–west position was weak for surface moisture (r = −0.252) and negligible for deeper moisture (r = 0.044). Correlation with north–south position was also weak (r = −0.157 at 0–30 cm; r = 0.010 at 30–60 cm). Thus, the spatial pattern was better characterised as microsite heterogeneity than as a simple directional gradient. Several of the highest 30–60 cm moisture values occurred within R3, while isolated high-moisture plots also occurred in other replications.

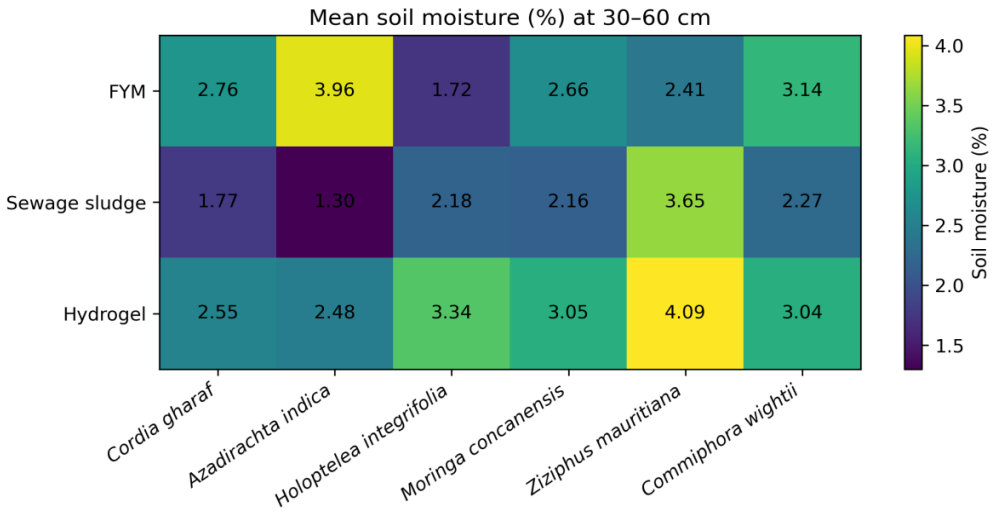


Fig. 5. Heat map of mean gravimetric soil moisture (%) for treatment × species combinations at 30–60 cm depth. Cell values are descriptive means across five replications. Because the treatment × species interaction was not significant (p = 0.279), the heat map is intended to show field patterning and should not be interpreted as evidence of significant pairwise differences. Observations represent the single January 2024 sampling campaign

Table 4. Factorial analysis of variance for gravimetric soil moisture at each depth in January 2024. df = degrees of freedom; SS = sum of squares; MS = mean square; F = variance ratio; p = probability value. Each depth was analysed separately with replication, amendment, species and amendment × species terms. Residual df = 68; significance threshold p < 0.05

Depth	Source	df	SS	MS	F	p
0–30 cm	Replication	4	11.649	2.912	2.960	0.026
0–30 cm	Treatment	2	3.594	1.797	1.826	0.169
0–30 cm	Species	5	4.975	0.995	1.011	0.418
0–30 cm	Treatment × Species	10	2.939	0.294	0.299	0.979
0–30 cm	Residual	68	66.912	0.984		
30–60 cm	Replication	4	27.499	6.875	3.100	0.021
30–60 cm	Treatment	2	11.631	5.816	2.622	0.080
30–60 cm	Species	5	10.433	2.087	0.941	0.460
30–60 cm	Treatment × Species	10	27.627	2.763	1.246	0.279
30–60 cm	Residual	68	150.801	2.218		

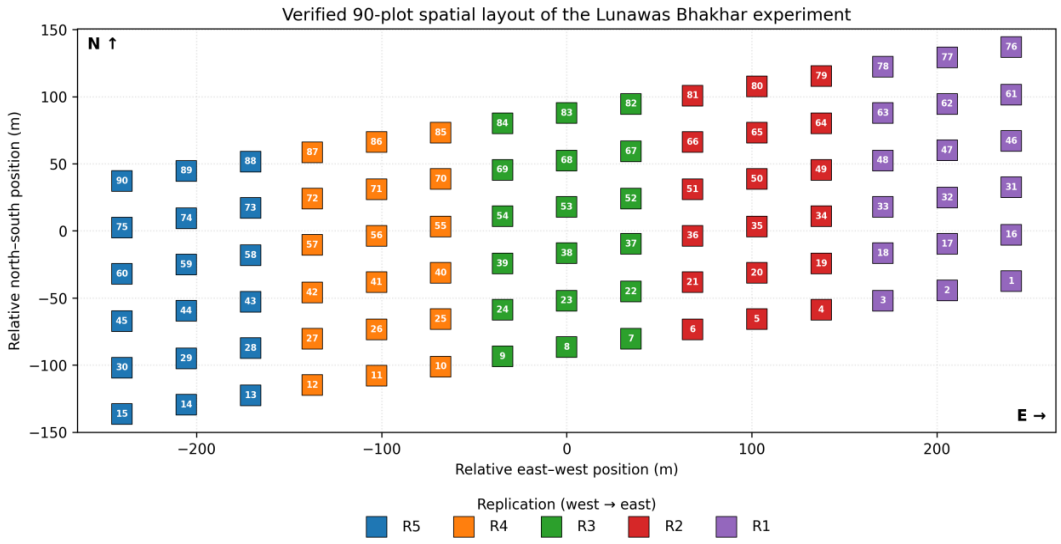


Fig. 6. Verified plot-coordinate layout of the Lunawas Bhakhar experiment. Plot numbers are shown at their geographic positions. Replications are arranged west to east as R5, R4, R3, R2 and R1. North is upward and east is to the right

Table 5. Replication-wise gravimetric soil moisture (mean ± SE, %) in January 2024 after verified plot-coordinate linkage. n = 18 plots per replication per depth. Each replication contained all 18 amendment × species combinations. Replication effects were significant at both depths (p = 0.026 and 0.021, respectively); no pairwise block comparisons are implied

Replication	0–30 cm	30–60 cm
R1	1.411 ± 0.187	2.399 ± 0.300
R2	1.475 ± 0.165	3.034 ± 0.338
R3	2.128 ± 0.297	3.470 ± 0.548
R4	1.525 ± 0.191	1.844 ± 0.181
R5	2.264 ± 0.263	2.728 ± 0.343

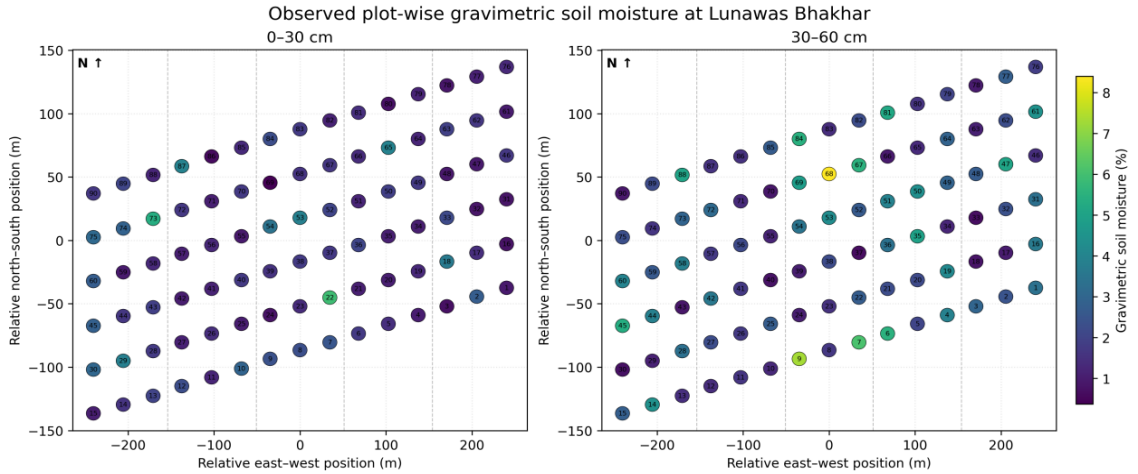


Fig. 7. Observed plot-wise gravimetric soil moisture at 0–30 and 30–60 cm depth after verified linkage of field design and geographic coordinates. Numbers inside points are plot numbers. The same color scale is used for both depth layers. Observations represent the single January 2024 sampling campaign

4. Discussion

The principal finding of the Lunawas experiment was a significant difference in gravimetric soil moisture between the two sampled depth intervals. Mean gravimetric moisture at 30–60 cm was approximately 53% greater than at 0–30 cm, showing greater subsurface moisture at the January 2024 sampling date; persistence of this difference through time was not measured. In hot drylands, surface horizons are exposed to rapid evaporative depletion, whereas deeper soil is partly buffered from direct atmospheric demand. Similar depth- and season-dependent soil-water behaviour has been reported from silvipastoral systems in the Thar Desert (Sharma *et al*., 2003). More importantly for the present site, rehabilitation studies on degraded hills in Rajasthan have shown that slope position, rainfall capture and soil-water conservation structures can substantially modify soil-water storage and thereby affect plantation growth and herbaceous biomass (Singh, 2012; Singh *et al*., 2013). The present depth effect therefore has direct ecological relevance: restoration success on rocky hills may depend less on short-lived surface wetting than on whether planting pits and surrounding microsites retain water within the effective rooting zone.

The higher subsurface moisture shows why surface-only sampling may incompletely describe the soil-moisture profile. Gravimetric water content alone, however, does not establish plant-available water without information on soil-water retention characteristics and rooting depth. Deep-profile water has been identified as an important constraint on sustainable vegetation restoration in other water-limited regions (Li *et al*., 2021), while global syntheses continue to identify soil-water availability as one of the dominant controls on dryland restoration outcomes (Stapleton *et al*., 2024). At Lunawas, the difference between the two sampled layers was much larger than the differences among amendments, emphasising that soil depth and microsite hydrology should be treated as primary design factors in degraded-hill restoration. This interpretation is consistent with the broader restoration response already documented at the same site, where protection and plantation were followed by development of a substantially richer plant community within the restored field (Sharma *et al*., 2026). The soil-moisture pattern reported here provides a plausible hydrological context for that vegetation recovery, although the present dataset cannot establish a direct causal link between moisture at individual plots and biodiversity response.

Farmyard manure produced the highest numerical moisture at 0–30 cm, although the treatment effect was not statistically significant. This tendency is physically plausible because organic amendments can influence aggregation, pore-size distribution, bulk density and the retention of capillary water. Studies under arid and semi-arid conditions have reported improved soil-water status after manure or compost additions (Rao & Sankar, 2007; Bhanwaria *et al*., 2022; Musei *et al*., 2024). Fieldwork in semi-arid soils further indicates that organic amendments can modify macroporosity, aggregate stability and hydraulic behaviour (Yazdanpanah *et al*., 2016), while long-term amendment experiments show that increases in soil organic carbon can enhance water retention in the wetter portion of the soil-water retention curve without necessarily increasing all fractions of plant-available water

(Zhou *et al*., 2020). This distinction is important for interpreting Lunawas: the numerical FYM advantage at the surface should be viewed as an ecologically credible tendency rather than evidence of a proven treatment effect from one sampling campaign.

Recent work also shows that organic amendments and synthetic water retainers can both improve soil-water status, but their relative performance depends strongly on amendment type, dose, soil texture, irrigation regime and the timing of observation. In a semi-arid field comparison, compost and a commercial water retainer both reduced soil-water deficit relative to unamended soil, with compost providing additional fertility benefits (Zgallai *et al*., 2024). Likewise, controlled dryland experiments have shown that compost can increase soil water content and that the magnitude of the response interacts with rainfall-pulse size and frequency (Amari *et al*., 2026). These findings support the conservative interpretation adopted here: amendment effects may emerge more clearly under particular moisture regimes or over longer periods, whereas a single January measurement can capture only one point in a highly dynamic soil-water cycle. Organic amendments act partly through decomposition and changes in aggregation and pore structure, processes whose expression depends on amendment properties, soil conditions and elapsed time (Yazdanpanah *et al*., 2016; Zhou *et al*., 2020). Repeated measurements of moisture together with soil organic carbon, bulk density and aggregation are therefore needed to test these mechanisms; the present campaign cannot determine whether such changes had occurred.

Hydrogel showed the strongest depth-dependent numerical response in the Lunawas dataset, increasing from 1.55% at 0–30 cm to 3.09% at 30–60 cm. Superabsorbent polymers can retain large quantities of water and release part of that water as the surrounding soil dries (Hüttermann *et al*., 1999; Mandal *et al*., 2024; Qin *et al*., 2024). Field evidence, however, is mixed. Commander *et al*. (2013) reported limited or negative responses to moisture-retaining gel under some arid-zone restoration conditions, whereas hydrogel use improved soil-moisture dynamics and water productivity in semi-arid Indian mustard, particularly under rainfed or deficit-irrigation conditions (Rathore *et al*., 2020). Recent reviews similarly conclude that polymer chemistry, soil texture, salinity, placement depth and application rate all influence hydrogel performance (Muhammad *et al*., 2025). Therefore, neither the 30–60 cm amendment effect ($p = 0.080$) nor the depth × hydrogel interaction ($p = 0.072$) met the stated significance threshold. These numerical patterns provide hypotheses for repeated seasonal testing and do not demonstrate hydrogel superiority over FYM or sewage sludge.

Sewage sludge showed intermediate or lower moisture values relative to FYM and hydrogel, but soil moisture alone is an incomplete criterion for judging its restoration value. Sewage sludge can improve organic matter and nutrient supply in low-fertility soils, but its suitability depends on feedstock composition, contaminant concentrations and application rate (Uddin *et al*., 2025). In restoration practice, any recommendation for sludge use at Lunawas should therefore integrate soil chemical quality, plant survival and growth, and longer-term monitoring of trace elements with soil-water response. The absence of a significant moisture advantage in January 2024 should not be interpreted as evidence that the amendment lacks value; rather, its potential benefits may operate through nutrient supply, aggregation or gradual changes in soil organic matter that are not fully expressed in a single gravimetric moisture measurement.

The significant replication effect at both depths is one of the most informative results of the study. Because every block contained the complete 3 × 6 amendment-by-species factorial set, block differences cannot readily be attributed to unequal treatment allocation. Instead, they point to genuine microsite heterogeneity in the rocky-hill environment. Degraded hill studies in Rajasthan have shown that soil-water content can vary substantially with slope and with local structures that alter runoff and infiltration (Singh, 2012; Singh *et al*., 2013). At Lunawas, analogous variation may arise from discontinuous soil pockets, exposed rock, fractures, local pit geometry, differences in refilled soil volume, runoff concentration and root occupancy. Similar microsite dependence has been documented in other restoration systems, where rainfall and soil-cover properties interact to produce strong small-scale variation in plant-available water and establishment success (Golos *et al*., 2021; Abella *et al*., 2015; Pérez *et al*., 2019).

The verified coordinate analysis reinforces this interpretation. Moisture did not follow a strong monotonic west–east or north–south gradient; instead, wetter and drier plots occurred as localised patches. This pattern argues against treating the site as spatially homogeneous and validates the decision to retain replication in the statistical model. It also suggests that future analyses should move beyond plot coordinates alone. Measurements of slope, aspect, elevation, exposed-rock fraction, effective soil depth, pit dimensions and runoff-contributing area would allow the observed moisture hotspots to be linked to physical mechanisms. If repeated seasonal data are collected, spatial autocorrelation and mixed spatio-temporal models could then distinguish persistent microsite effects from temporary responses to rainfall or irrigation.

From a management perspective, the results favour an integrated rather than amendment-only approach to rocky hill restoration. The clearest management signal is the importance of conserving water within the rooting profile. Earlier Rajasthan hill-rehabilitation studies demonstrated that rainwater-harvesting structures enhanced soil-water status and improved plantation and herbaceous growth (Singh, 2012; Singh *et al*., 2013), while the present experiment shows that substantial moisture can persist below the immediate surface even when amendment differences are modest. For Lunawas, amendment evaluation should therefore be combined with measures that improve infiltration and reduce rapid runoff, and treatment performance should be judged against survival, height, girth and seasonal moisture dynamics rather than one moisture observation alone. Repeated measurements before, during and after the monsoon would be especially valuable for determining whether the deeper hydrogel tendency persists, whether FYM progressively improves near-surface water retention, and whether these soil responses translate into superior woody plant establishment.

5. Limitations and Future Work

This study was based on one soil-moisture sampling campaign in January 2024 and therefore cannot resolve seasonal variation or the persistence of amendment responses. No unamended control was included, so amendment benefits relative to untreated soil

cannot be quantified. Slope, effective soil depth, rock exposure and runoff contributions were not included as explanatory covariates. Soil-water retention curves were not measured; consequently, gravimetric moisture does not directly quantify plant-available water. Repeated seasonal sampling and additional soil and seedling measurements are needed to address these limitations.

6. Conclusion

During the January 2024 sampling campaign, gravimetric soil moisture was significantly greater at 30–60 cm than at 0–30 cm, with an overall increase of approximately 53%. This result indicates that the deeper sampled layer contained more moisture at the time of observation; it does not establish that this pattern persisted throughout the year. No statistically significant amendment, species or amendment × species effects were detected at either depth. Farmyard manure had the highest numerical mean in the surface layer, whereas hydrogel had the highest numerical mean in the deeper layer, but these rankings do not demonstrate treatment superiority. Significant replication effects and localised wet and dry patches indicate that microsite variability should be considered when planning restoration and interpreting soil-moisture measurements. The absence of an unamended control also prevents the benefits of the three amendments from being quantified relative to untreated soil. Further evaluation should combine paired measurements at both depths across contrasting seasons and rainfall or irrigation conditions with soil physical properties and seedling survival and growth. Such monitoring would provide a stronger basis for assessing amendment performance and informing restoration decisions at the site.

Data Availability

The data supporting the findings of this study are available from the corresponding author on reasonable request, subject to institutional requirements.

Acknowledgements

The authors gratefully acknowledge the financial support provided by CAMPA, Ministry of Environment, Forest and Climate Change (MoEF&CC), Government of India. The authors sincerely thank the Director General, ICFRE, Dehradun, and the Director, ICFRE–Arid Forest Research Institute, Jodhpur, for their institutional support, guidance and encouragement. The authors also acknowledge the valuable cooperation and assistance extended by the local villagers of Lunawas Bhakhar, Shiv village, Luni Tehsil, Jodhpur District, Rajasthan, during restoration activities, site protection and field monitoring.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. ChatGPT, Claude and Perplexity were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abella, S. R., Chiquoine, L. P., Newton, A. C., & Vanier, C. H. (2015). Restoring a desert ecosystem using soil salvage, revegetation, and irrigation. *Journal of Arid Environments, 115*, 44–52. https://doi.org/10.1016/j.jaridenv.2015.01.003

Amari, K. N., Cueva, A., Blankinship, J. C., & Throop, H. L. (2026). Microbial and soil moisture responses to compost amendments and simulated rainfall pulses in degraded dryland soils. *Journal of Arid Environments, 235*, Article 105625. https://doi.org/10.1016/j.jaridenv.2026.105625

Azimov, A., Bolysbek, A., Iztleuov, G., Duissebayev, S., & Ashirbayev, Z. (2026). Development of biodegradable hydrogels with adjustable moisture retention capacity for agricultural applications. *Scientific Reports, 16*, Article 14098. https://doi.org/10.1038/s41598-026-44948-w

Bhanwaria, R., Singh, B., & Musarella, C. M. (2022). Effect of organic manure and moisture regimes on soil physiochemical properties, microbial biomass $C_{mi}c$:$N_{mi}c$:$P_{mi}c$ turnover and yield of mustard grains in arid climate. *Plants, 11*(6), Article 722. https://doi.org/10.3390/plants11060722

Burrell, A. L., Evans, J. P., & De Kauwe, M. G. (2020). Anthropogenic climate change has driven over 5 million km² of drylands towards desertification. *Nature Communications, 11*, Article 3853. https://doi.org/10.1038/s41467-020-17710-7

Cholavardan, D., Sushanth, & Tyagi, S. (2026). Soil moisture dynamics, bulk density, and economic water productivity of wheat as influenced by irrigation scheduling and hydrogel application. *Journal of Experimental Agriculture International, 48*(10), 387–399. https://doi.org/10.9734/jeai/2026/v48i104535

Clemente, A. S., Werner, C., Máguas, C., Cabral, M. S., Martins-Loução, M. A., & Correia, O. (2004). Restoration of a limestone quarry: Effect of soil amendments on the establishment of native Mediterranean sclerophyllous shrubs. *Restoration Ecology, 12*(1), 20–28. https://doi.org/10.1111/j.1061-2971.2004.00256.x

Commander, L. E., Rokich, D. P., Renton, M., Dixon, K. W., & Merritt, D. J. (2013). Optimising seed broadcasting and greenstock planting for restoration in the Australian arid zone. *Journal of Arid Environments, 88*, 226–235. https://doi.org/10.1016/j.jaridenv.2012.08.012

Duta, A., & Harit, A. K. (2026). Role of termites in soil conservation and sustainable agriculture practice. *Asian Journal of Plant and Soil Sciences, 11*(1), 77–87. https://doi.org/10.56557/ajopss/2026/v11i1129

Golos, P. J., Merino-Martín, L., Commander, L. E., Elliott, C. P., Williams, M. R., Miller, B. P., Dixon, K., & Stevens, J. (2021). Interactions between soil covers and rainfall affect post-mining plant restoration in a semi-arid Banded Iron Formation. *Ecological Engineering, 159*, Article 106101. https://doi.org/10.1016/j.ecoleng.2020.106101

Hüttermann, A., Zommorodi, M., & Reise, K. (1999). Addition of hydrogels to soil for prolonging the survival of *Pinus halepensis* seedlings subjected to drought. *Soil and Tillage Research, 50*(3–4), 295–304. https://doi.org/10.1016/S0167-1987(99)00023-9

James, J. J., Svejcar, T. J., & Rinella, M. J. (2011). Demographic processes limiting seedling recruitment in arid grassland restoration. *Journal of Applied Ecology, 48*(4), 961–969. https://doi.org/10.1111/j.1365-2664.2011.02009.x

Li, B.-B., Li, P.-P., Zhang, W.-T., Ji, J.-Y., Liu, G.-B., & Xu, M.-X. (2021). Deep soil moisture limits the sustainable vegetation restoration in arid and semi-arid Loess Plateau. *Geoderma, 399*, Article 115122. https://doi.org/10.1016/j.geoderma.2021.115122

Mandal, S., Chi, H., Moss, R. E., Dhital, P., Babatunde, E. O., Gurav, R., & Hwang, S. (2024). Seed gum-based polysaccharides hydrogels for sustainable agriculture: A review. *International Journal of Biological Macromolecules, 263*, Article 130339. https://doi.org/10.1016/j.ijbiomac.2024.130339

Muhammad, N., Kader, M. A., Al-Solaimani, S. G., Abd El-Wahed, M. H., Abohassan, R. A., & Charles, M. E. (2025). A review of impacts of hydrogels on soil water conservation in dryland agriculture. *Farming System, 3*(4), Article 100166. https://doi.org/10.1016/j.farsys.2025.100166

Musei, S. K., Kuyah, S., Nyawira, S., Ng'ang'a, S. K., Karugu, W. N., Smucker, A. S., & Nkurunziza, L. N. (2024). Sandy soil reclamation technologies to improve crop productivity and soil health: A review. *Frontiers in Soil Science, 4*, Article 1345895. https://doi.org/10.3389/fsoil.2024.1345895

Pérez, D. R., González, F., Ceballos, C., Oneto, M. E., & Aronson, J. (2019). Direct seeding and outplantings in drylands of Argentinean Patagonia: Estimated costs, and prospects for large-scale restoration and rehabilitation. *Restoration Ecology, 27*(5), 1105–1116. https://doi.org/10.1111/rec.12961

Qin, C., Wang, H., Zhao, Y., Qi, Y., Wu, N., Zhang, S., & Xu, W. (2024). Recent advances of hydrogel in agriculture: Synthesis, mechanism, properties and applications. *European Polymer Journal, 219*, Article 113376. https://doi.org/10.1016/j.eurpolymj.2024.113376

Rao, V. S., & Sankar, G. R. M. (2007). Effects of clay mineral application on soil moisture status, physiological traits and yield of rainfed tomato under semi-arid Alfisols. *Journal of Horticultural Sciences, 2*(1), 26–33. https://doi.org/10.24154/jhs.v2i1.633

Rathore, S. S., Shekhawat, K., Babu, S., & Singh, V. K. (2020). Mitigating moisture stress in *Brassica juncea* through deficit irrigation scheduling and hydrogel in ustocherpts soils of semi-arid India. *Heliyon, 6*(12), Article e05786. https://doi.org/10.1016/j.heliyon.2020.e05786

Sharma, B., Choudhry, K. R., & Kothari, S. (2026). Vegetation recovery and biodiversity enhancement following ecological restoration of a degraded rocky hill in the Indian Thar Desert. *Current Journal of Applied Science and Technology, 45*(11), 47–55. https://doi.org/10.9734/cjast/2026/v45i114792

Sharma, S. K., Rajora, M. P., & Mathur, B. K. (2003). Soil moisture dynamics in silvopastoral systems in the Thar Desert of India. *Annals of Arid Zone, 42*(1), 55–59. https://doi.org/10.56093/aaz.v42i1.65528

Singh, G. (2012). Enhancing growth and biomass production of plantation and associated vegetation through rainwater harvesting in degraded hills in southern Rajasthan, India. *New Forests, 43*(3), 349–364. https://doi.org/10.1007/s11056-011-9285-5

Singh, G., Mishra, D., Singh, K., & Parmar, R. (2013). Effects of rainwater harvesting on plant growth, soil water dynamics and herbaceous biomass during rehabilitation of degraded hills in Rajasthan, India. *Forest Ecology and Management, 310*, 612–622. https://doi.org/10.1016/j.foreco.2013.09.002

Stapleton, J., Bates, S., Lewis, M., Turner, S. R., Warne, D., & Florentine, S. (2024). A global review on arid zone restoration: Approaches and challenges. *Restoration Ecology, 32*(6), Article e14078. https://doi.org/10.1111/rec.14078

Uddin, S., Zaman, M., Martínez-Guijarro, K., Al-Murad, M., Behbehani, M., Habibi, N., & Al-Mutairi, A. (2025). Sewage sludge as soil amendment in arid soils—A trace metal, nutrient and trace organics perspective. *Emerging Contaminants, 11*(1), Article 100420. https://doi.org/10.1016/j.emcon.2024.100420

Xu, M., Liu, Y., Xi, J., Li, S., & Li, Z. (2024). Optimization of soil hydrological properties in degraded grasslands by soil amendments. *Journal of Hydrology, 643*, Article 131946. https://doi.org/10.1016/j.jhydrol.2024.131946

Yazdanpanah, N., Mahmoodabadi, M., & Cerdà, A. (2016). The impact of organic amendments on soil hydrology, structure and microbial respiration in semiarid lands. *Geoderma, 266*, 58–65. https://doi.org/10.1016/j.geoderma.2015.11.032

Zgallai, H., Zoghlami, R. I., Annabi, M., Zarrouk, O., Jellali, S., & Hamdi, H. (2024). Mitigating soil water deficit using organic waste compost and commercial water retainer: A comparative study under semiarid conditions. *Euro-Mediterranean Journal for Environmental Integration, 9*(1), 377–391. https://doi.org/10.1007/s41207-023-00437-4

Zhou, H., Chen, C., Wang, D., Arthur, E., Zhang, Z., Guo, Z., Peng, X., & Mooney, S. J. (2020). Effect of long-term organic amendments on the full-range soil water retention characteristics of a Vertisol. *Soil and Tillage Research, 202*, Article 104663. https://doi.org/10.1016/j.still.2020.104663

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of the publisher and/or the editor(s). This publisher and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

© Copyright (2026): Author(s). The licensee is the journal publisher. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:
The peer review history for this paper can be accessed here: https://pr.sdiarticle5.com/review-history/169984