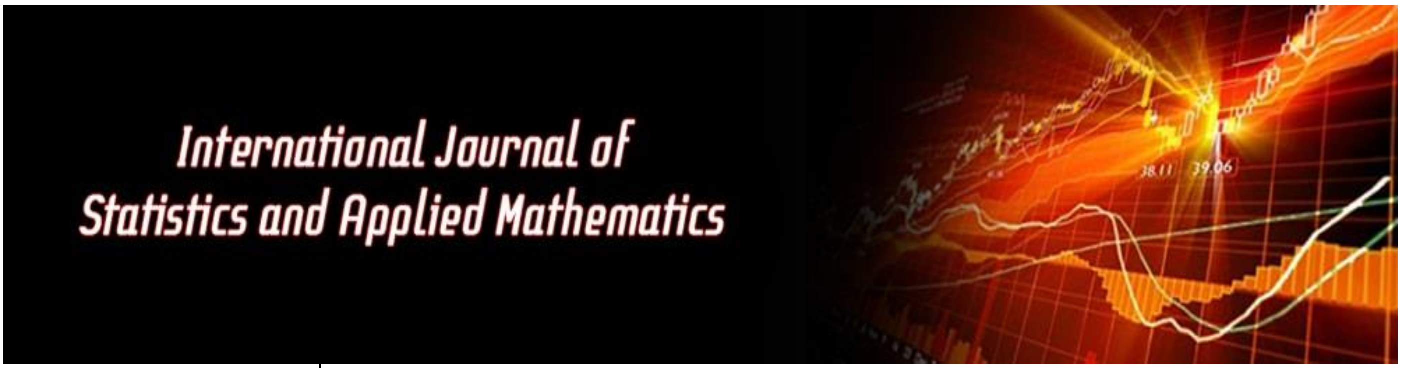

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Soil physical property transitions under conservation agriculture in the Kandi Region of Jammu district

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Abstract
Conservation agriculture (CA) has emerged as a promising approach for improving soil health and enhancing the sustainability of rainfed farming systems, particularly in ecologically fragile and water-stressed regions like the Kandi belt of Jammu. Assessing soil physical properties is essential for evaluating the effectiveness of conservation agriculture (CA) in enhancing water retention, infiltration, and overall soil health, particularly in dryland ecosystems. These parameters directly influence resource use efficiency and agricultural sustainability. This study examines the effects of CA practices on soil moisture dynamics, infiltration rates, and bulk density in the Akhnoor tehsil of Jammu district. The field experiments were conducted during the wheat-growing season of 2019 on sandy clay soils to assess the influence of conservation structures specifically contour bund cum trench, contour trench, and contour bund on soil physical properties. Measurements were taken at distances of 1 m and 5 m from these structures. The results indicated notable improvements in infiltration rates, with increases of 114.28%, 100%, and 85.71% at 1 m from the respective structures, and 39.53%, 25.58%, and 11.63% at 5 m. Additionally, soil bulk density (0-10 cm depth) measured 0.5 m from the structures was reduced by 5.063%, 3.797%, and 3.165%, respectively, compared to control plots. The CA-treated areas also exhibited consistently higher soil moisture throughout the season, indicating enhanced water-use efficiency. Although no severe drought occurred during the study period, the findings highlight the potential of conservation agriculture to improve rainwater utilization and increase the resilience of dryland farming systems under variable climatic conditions. These results affirm CA as a key strategy for promoting sustainable agriculture and mitigating the risks associated with climate change in vulnerable agro ecological zones.

Keywords: Conservation agriculture, soil moisture dynamics, infiltration rates, bulk density, water use efficiency, dry land regions

1. Introduction
The sustainable agriculture has emerged as a vital approach to address the challenges of soil degradation, water scarcity, and climate variability in ecologically fragile regions. The Kandi belt of Jammu, located in the sub-tropical Shivalik foothills of northern India, represents one such vulnerable agro-ecological zone and characterized by undulating terrain, erratic rainfall, low soil fertility, and recurring droughts, the region faces significant limitations in conventional farming productivity. The surface soil faces significant threats from pervasive soil degradation caused by several factors such as mining, fire, overgrazing, and unsustainable agricultural practices [1]. This soil degradation compromises the soil's capacity to provide essential ecosystem services for future generations. The pressures of a growing global population, coupled with climate change, further strain soil and other natural resources [2]. Conservation agriculture (CA) a holistic approach combining soil and water conservation measures, residue retention, and crop rotation has demonstrated positive impacts on soil fertility, including enhanced water infiltration and moisture retention [3]. Due to these benefits, CA is often regarded as "climate-smart" [4], with much of its success attributed to the role of soil cover [5].
The higher crop yields under CA are primarily linked to improved water infiltration and increased soil organic matter [6].

However, adoption surveys often focus solely on tillage practices, as tillage is considered a cornerstone of CA and the most easily measurable indicator in large-scale studies [7]. In hilly terrains, the conversion of forests to croplands exacerbates soil erosion, reduces productivity, and threatens food security [8]. The Himalayan Region of India (HRI), home to over 60 million people, is particularly vulnerable due to its fragile geology, steep slopes, and heavy rainfall [9]. Soil erosion in the HRI leads to an estimated annual loss of 13.4 million tonnes of food grains, valued at USD 1.85 billion [10], posing a critical challenge for agriculture in these areas [11].

The technologies such as trenching, terracing, contour bunds, and check dams have proven effective in reducing runoff and soil erosion while enhancing crop yields [12]. However, the high costs of implementing these technologies make them inaccessible to many subsistence farmers in the HRI, who rely on intensive tillage practices that exacerbate runoff, erosion, and soil degradation [13, 14]. This underscores the urgent need for cost-effective strategies to manage surface runoff, improve land productivity, and prevent further resource degradation.

The conservation agriculture offers a sustainable solution by integrating minimum soil disturbance, crop residue management, and crop diversification to enhance soil biological, chemical, and physical properties. While studies have explored the role of vegetation cover, trenching, afforestation, and biological geotextiles in controlling runoff and erosion [15], limited information exists on the impacts of different tillage practices conventional tillage (CT), minimum tillage (MT), and zero tillage (ZT) on runoff and erosion in sloping fields under maize wheat crop rotation in the sub-tropical Himalayan ecosystem.

Despite the growing adoption of sustainable agriculture in parts of Jammu, systematic evaluations of its impact on soil physical parameters remain limited. Understanding these transitions is essential for validating conservation agriculture as a sustainable model for land management in fragile ecosystems. Therefore, this study aims to assess the changes in soil physical properties under sustainable farming practices in the Kandi region of Akhnoor, Jammu district. The findings will help in identifying soil improvement trends and provide empirical evidence to guide policy, farmer adoption, and future research in semi-arid agriculture. This study hypothesized that conservation tillage reduces runoff and soil loss, even during severe rainfall events. Over three years, the research aimed to assess the effects of conservation tillage compared to intensive tillage, while also examining the transition from conventional to conservation agriculture. The findings address critical knowledge gaps regarding the long-term impacts of adopting conservation tillage on runoff and soil erosion in the agro fragile Himalayan ecosystem.

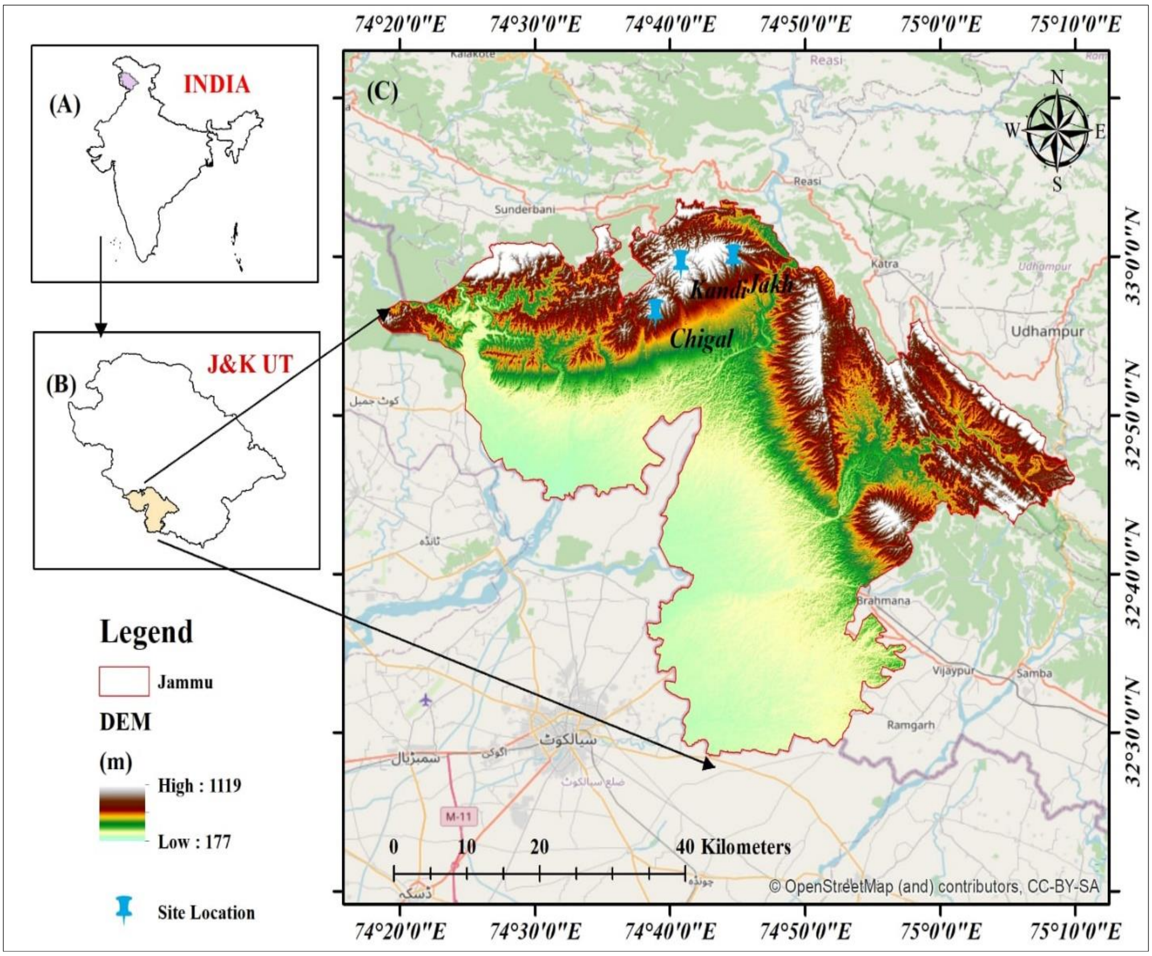


Fig 1: Geographic location of study area

2. Materials and Methods

2.1 Description of the Experimental Site

The conservation agriculture field experiment was initiated in 2019 on an 8% slope in Akhnoor tehsil, Jammu district, Jammu and Kashmir, situated in the Himalayan Region of India (Figure 1). The study was conducted in Kandi village, located at 32°59'34"N latitude and 74°40'55"E longitude, at an elevation of 773 meters above sea level. The region has a subtropical climate, with an average annual rainfall of 1154.52 mm (2003-2017), approximately 74% of which occurs during the peak monsoon season from June to September. The experiment reached full establishment within

5-6 months, and this study focused on winter wheat cultivation in 2019, continuing the crop rotation initiated at the start of the experiment. The area's mean daily temperatures range from a low of 4°C to a high of 36°C, occasionally fluctuating between 4°C and 40°C. Rainfall distribution is uneven, with nearly 80% of the annual precipitation occurring between July and September due to the southwest monsoon. The remaining rainfall is received during the winter months (December to February) through western disturbances.

Meteorological data, including evaporation rates measured using an open pan evaporimeter, were obtained from the SKUAST Jammu meteorological station. The soil at the experimental site is classified as sandy clay, offering a distinct substrate for assessing the impact of conservation agriculture practices.

2.2 Treatment details and agronomic practices

The field experiment was conducted for 5-6 months in 2019 with the same setup and the same agronomical practices under three different systems like Contour bund cum trench (T1), contour trench (T2) and Contour Bund (T3) and control plot (T4), in a wheat crop system. The treatments of Contour Bund cum trench and a contour bund had an length of 10-20m, top width 0.5m, bottom width 0.1m and an height of 0.6m and a contour trench of width 0.8m and depth 0.5m and a length of 10-20m was constructed for three plots to separate each treatment and wheat seeds were manually sown in rows.

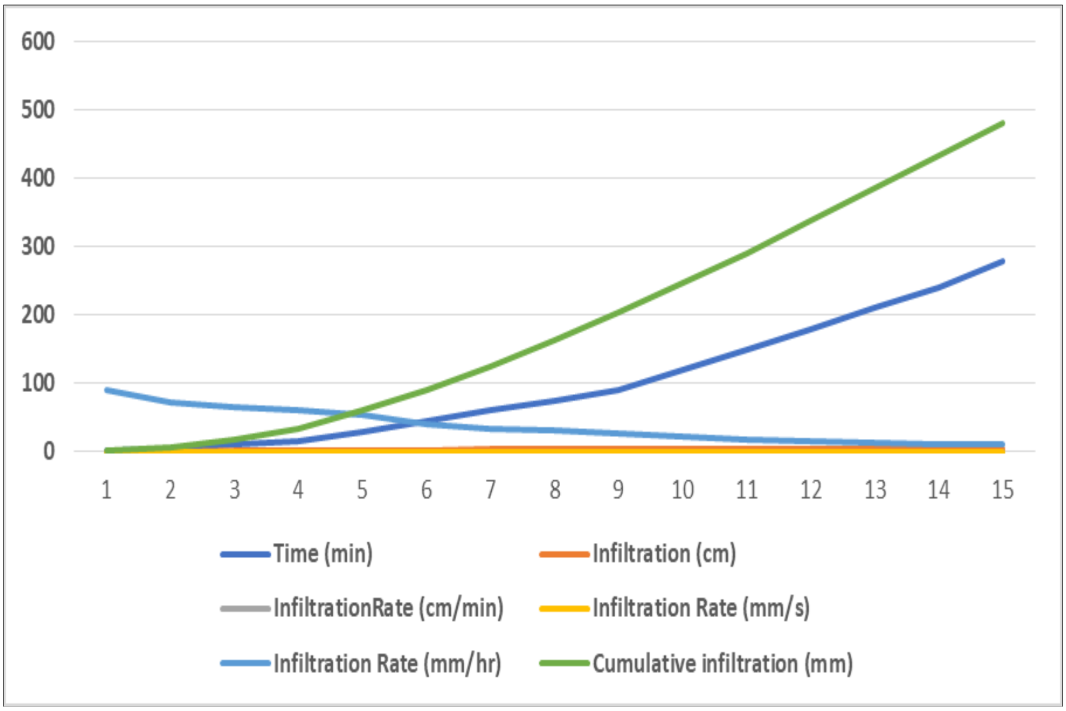
2.3 Collection and Analysis of Soil Properties

During the study period, data on infiltration rate and bulk density were systematically collected across all treatments. The soil textural class was determined based on the USDA soil classification system. Infiltration rate measurements were carried out using a mini disk infiltrometer, while saturated hydraulic conductivity was estimated following the standard methodology outlined in relevant literature. The soil bulk density (BD) was determined using the core sampling method. Undisturbed soil samples were extracted using stainless-steel cylindrical cores with an internal diameter and height of 5 cm. The samples were subsequently oven-dried at 105 °C for 24 hours to determine their dry mass. The bulk density was then calculated by dividing the oven-dry weight of the soil by the volume of the sampling core.

3. Results

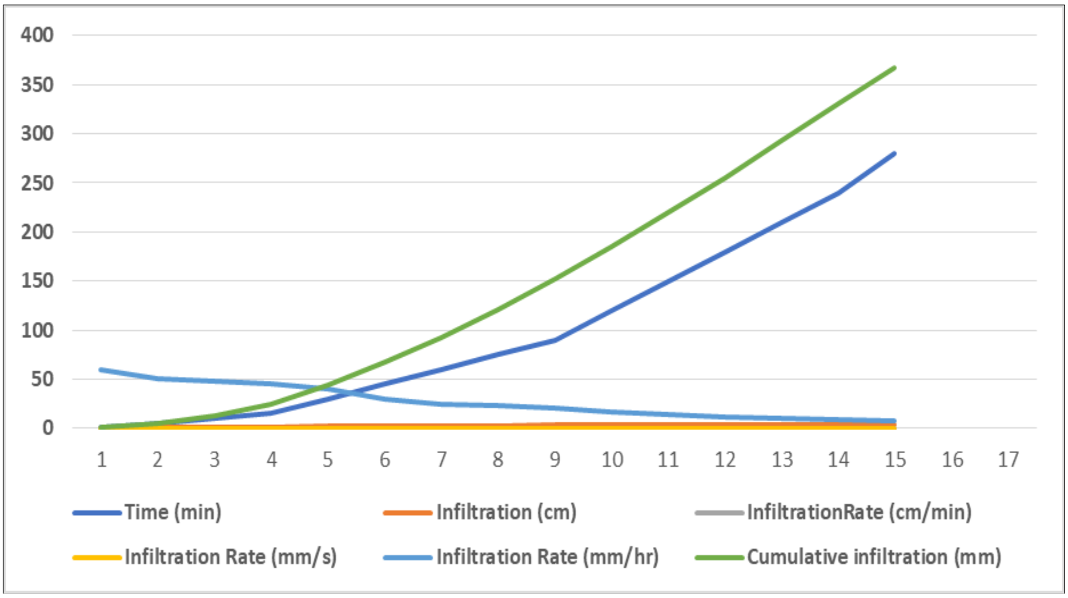
The study conducted in the Kandi belt of Jammu revealed notable insights into infiltration behavior and its implications for soil moisture dynamics under conservation agriculture. Infiltration rates were consistently higher in proximity to conservation structures, indicating the positive influence of these interventions in enhancing soil water intake capacity. This improvement is primarily attributed to enhanced soil structure and reduced surface runoff resulting from conservation measures. As depicted in Graphs 1 to 8, infiltration rates exhibited a declining trend with increasing distance from the conservation structures. This spatial variability suggests that the effectiveness of conservation practices diminishes with distance, highlighting the localized nature of their impact on soil physical properties. The data presented in Table 1 further confirm that higher infiltration rates were associated with increased soil moisture content. This correlation underscores the vital role of infiltration in maintaining soil water availability an essential factor for vegetation growth and long-term soil health, particularly in semi-arid environments like the Kandi region.

The cumulative infiltration values showed a steady increase over time, reflecting the soil's ability to absorb water under sustained application. However, as expected, infiltration rates decreased with time due to gradual soil saturation, which is a typical infiltration pattern. These findings collectively highlight the significance of conservation structures in improving soil hydrological functions, promoting moisture retention, and ultimately supporting sustainable agricultural practices in water-deficient regions. The Graph 1 illustrates the infiltration rate and cumulative infiltration over time at a 1 m distance from the contour bund cum trench, demonstrating the localized enhancement in water absorption due to conservation measures.



Graph 1: Infiltration rate and cumulative infiltration over time, at a distance of 1 m from the contour bund cum trench

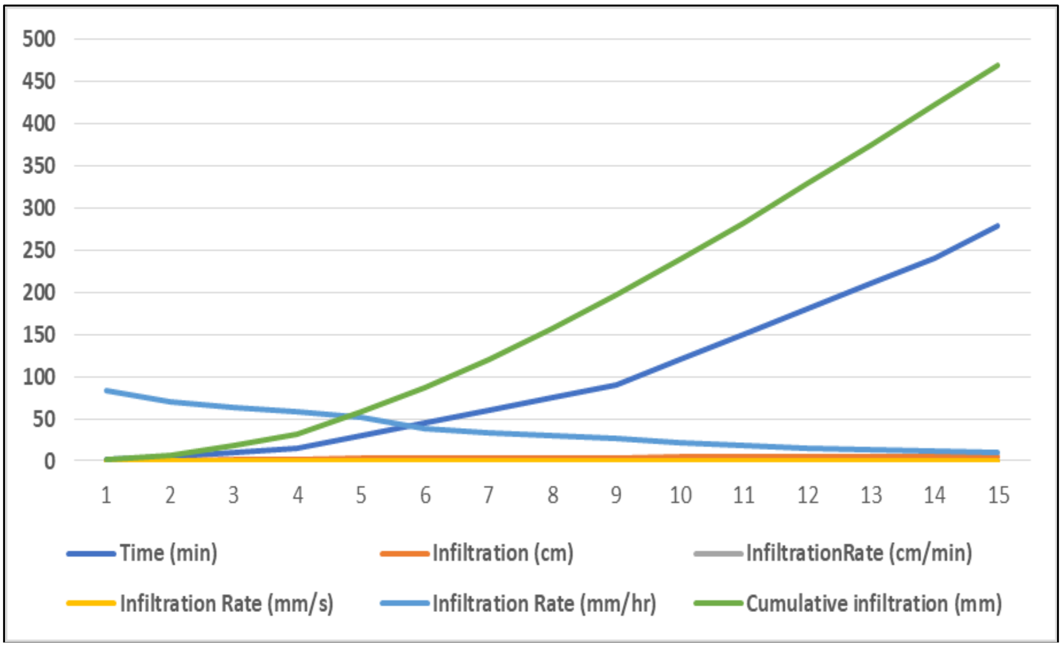
The Graph 2 illustrates the infiltration rate and cumulative infiltration over time at a distance of 5 m from the contour bund cum trench conservation structure, capturing the dynamic response of the soil to water application in a relatively distal zone from the intervention.



Graph 2: Infiltration rate and cumulative infiltration over time, at a distance of 5 m from the contour bund cum trench

At the outset, the infiltration rate is notably high, beginning at 0.100 cm/min (equivalent to 0.017 mm/s or 60 mm/hr) during the first minute. As the infiltration process continues, the rate progressively declines, reaching 0.013 cm/min (0.002 mm/s or 8.036 mm/hr) by 280 minutes. This gradual reduction reflects the natural behaviour of soil under wetting conditions, wherein the pore spaces become saturated, leading to a decrease in the infiltration rate over time. Meanwhile, cumulative infiltration exhibits a steady upward trend, rising from 1 mm at the start to 367.7 mm at 280 minutes. This consistent increase underscores the soil's capacity to absorb and store water during extended exposure, a vital factor for improving soil moisture retention and facilitating groundwater recharge in semi-arid regions. The initially high infiltration rates at 5 m, albeit lower than those observed at 1 m, still indicate residual benefits of conservation measures in enhancing soil structure and reducing compaction. However, the attenuation of impact with distance suggests that the effectiveness of such interventions is spatially limited. The observed temporal decline in infiltration rate also implies that during prolonged rainfall or irrigation events, the risk of surface runoff increases as the soil nears saturation. These observations highlight the need to align irrigation scheduling with the soil's infiltration capacity to minimize water loss and maximize efficiency. Integrating such insights into water management strategies can improve resource use, enhance crop productivity, and support sustainable agriculture in water-limited environments like the Kandi belt.

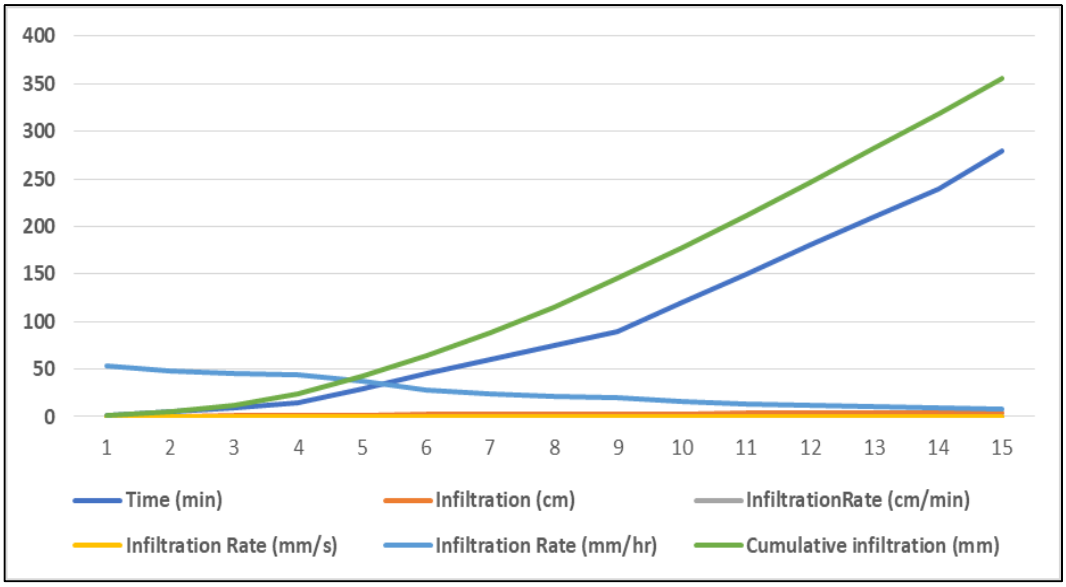
The Graph 3 illustrates the infiltration rate and cumulative infiltration over time at a distance of 1 m from the contour bund, capturing the direct influence of the conservation measure on soil water absorption dynamics.



Graph 3: Infiltration rate and cumulative infiltration over time, at a distance of 1 m from the contour bund

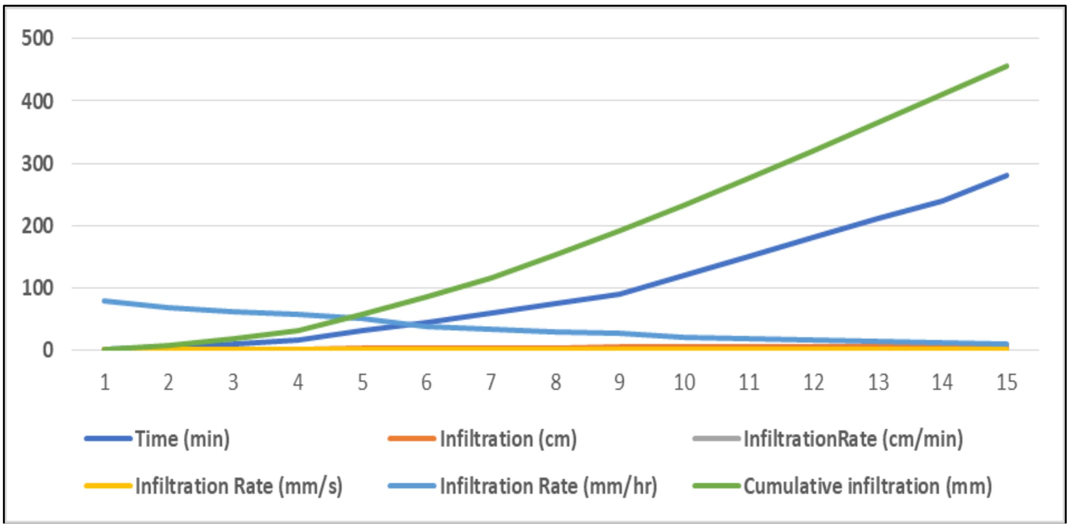
The infiltration rate begins at a high value of 0.140 cm/min (0.023 mm/s or 84 mm/hr.) during the initial minute, indicating rapid initial water intake due to unsaturated pore spaces and favourable soil structure. As expected, the infiltration rate gradually declines over time, reaching 0.017 cm/min (0.003 mm/s or 10.071 mm/hr) by 280 minutes. This declining trend is characteristic of soil infiltration behaviour as the pores become progressively saturated. The cumulative infiltration values show a consistent upward trend throughout the observation period, increasing from 1.4 mm in the first minute to 469.2 mm at 280 minutes. This continuous accumulation demonstrates the soil's capacity to absorb and store water over extended periods, which is essential for maintaining soil moisture levels and supporting crop growth in water-limited environments. These results indicate that areas closer to conservation structures like contour bunds benefit from improved infiltration rates and greater water retention capacity. Such outcomes underscore the effectiveness of conservation agriculture in enhancing soil physical conditions and promoting sustainable water management in the semi-arid Kandi region of Jammu.

The Graph 4 presents the infiltration rate and cumulative infiltration at a distance of 5 m from the contour bund. The initial infiltration rate is 0.090 cm/min (0.015 mm/s or 54 mm/hr), which steadily declines to 0.013 cm/min (0.002 mm/s or 7.821 mm/hr) by 280 minutes due to progressive soil saturation. Cumulative infiltration increases from 0.9 mm in the first minute to 355.4 mm at 280 minutes, indicating consistent water absorption over time. The results reflect reduced infiltration efficiency with increasing saturation and distance from the conservation structure, though water retention remains significant for soil moisture improvement and vegetation support.



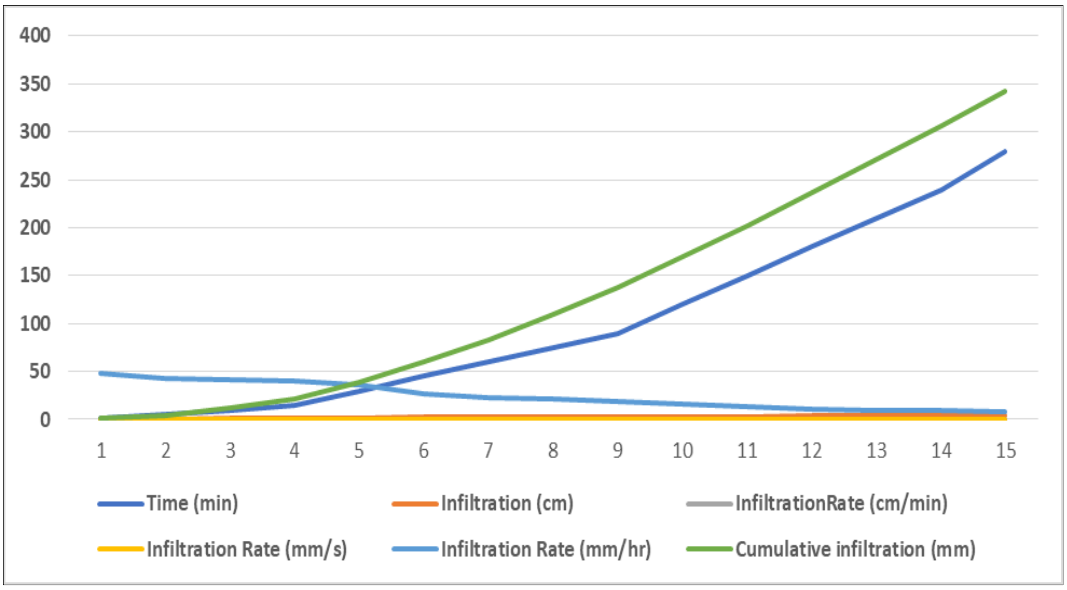
Graph 4: Infiltration rate and cumulative infiltration over time, at a distance of 5 m from the contour bund

The Graph 5 below illustrates the infiltration rate and cumulative infiltration over time, at a distance of 1 m from the contour bund conservation measures reflecting the effects as shown.



Graph 5: Infiltration rate and cumulative infiltration over time, at a distance of 1 m from the contour bund

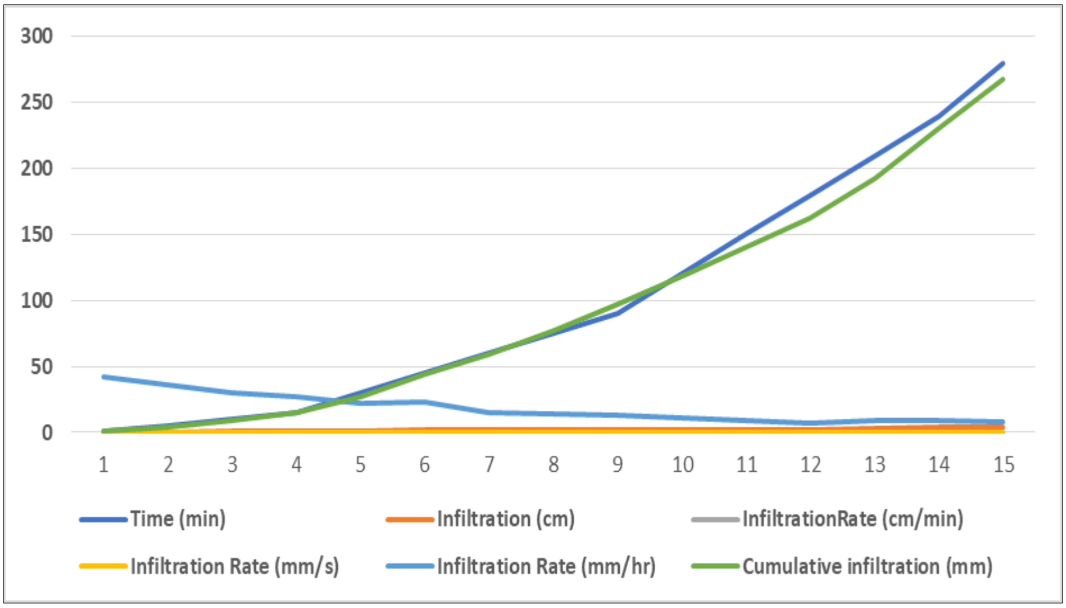
The Graph 5 showcases infiltration data over time, detailing the infiltration depth, rate, and cumulative infiltration. Initially, the infiltration rate is high at 0.130 cm/min (0.022 mm/s or 78 mm/hr) during the first minute, reflecting rapid water absorption. As time progresses, the rate declines steadily, reaching 0.016 cm/min (0.003 mm/s or 9.857 mm/hr) by 280 minutes. This decline is typical as soil pores become saturated over time. The cumulative infiltration increases consistently, starting at 1.3 mm in the first minute and reaching 457.4 mm by 280 minutes. This trend indicates the soil's capacity to absorb and retain water over extended periods. The decreasing infiltration rate and increasing cumulative infiltration highlight the dynamic process of water movement into the soil. The Graph 6 below illustrates the infiltration rate and cumulative infiltration over time, at a distance of 1 m from the contour bund conservation measures reflecting the effects as shown.



Graph 6: Infiltration rate and cumulative infiltration over time, at a distance of 1 m from the contour bund

The Graph 6 provides infiltration data over time, showing the infiltration depth, rate, and cumulative infiltration. Initially, the infiltration rate is 0.08 cm/min (0.01 mm/s or 48 mm/hr) at the 1-minute mark, reflecting rapid water absorption by the soil. Over time, the infiltration rate decreases steadily, reaching 0.01 cm/min (0.00 mm/s or 7.61 mm/hr) by 280 minutes. This reduction is due to the gradual saturation of soil pores, which slows down the infiltration process. Cumulative infiltration increases consistently throughout the observation period, starting at 0.80 mm in the first minute and reaching 342.40 mm by 280 minutes. This trend indicates the soil's capacity to absorb and retain water over time. The data demonstrates that while the infiltration rate diminishes, the total amount of water infiltrated continues to rise.

The Graph 7 below illustrates the infiltration rate and cumulative infiltration over time, at a distance of 1 m from the control plot reflecting the effects as shown.



Graph 7: Infiltration rate and cumulative infiltration over time, at a distance of 1 m from the control plot

The Graph 7 tracks soil water infiltration over time, showing how quickly water is absorbed and accumulates in the soil. Initially, infiltration rates are high (e.g., 42 mm/hr at 1 minute) but decline over time as the soil saturates (e.g., 7.3 mm/hr at 180 minutes). Cumulative infiltration steadily increases, reaching 268.2 mm by 280 minutes. This trend highlights the soil's decreasing ability to absorb water as saturation progresses, which is typical in infiltration studies.

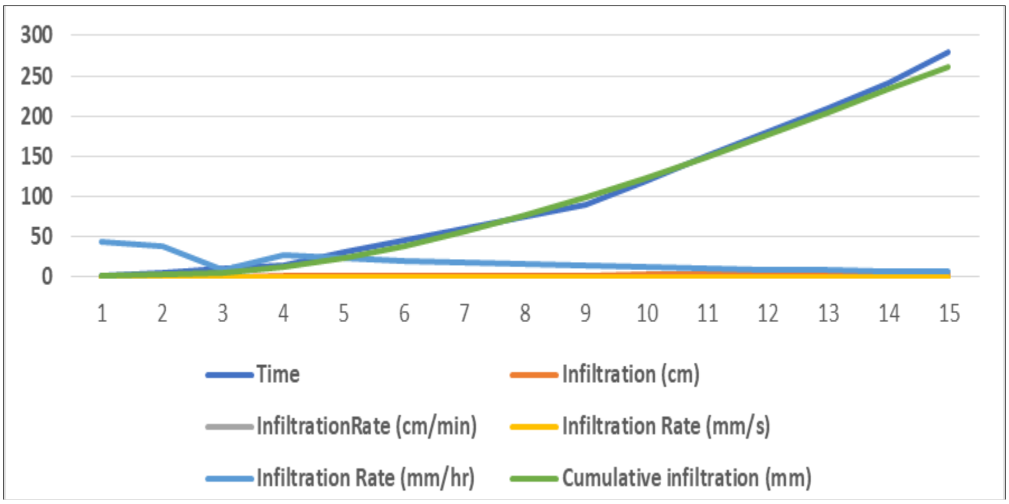
The Graph 8 below illustrates the infiltration rate and cumulative infiltration over time, at a distance of 5 m from the control plot reflecting the effects as shown.

Table 1: Soil moisture content and bulk density table (after rainfall event)

Plot Type	Distance from Conservation Measure (m)	Soil Depth (cm)	Moisture Content (%)	Bulk Density (g/cm³)
Contour Bund Cum Trench	0.5	0–10	26–30%	1.50
	1	10–20	24–28%	1.53
	1.5	20–30	22–26%	1.56
	5	0–10	24–29%	1.52
	5.5	10–20	22–26%	1.54
	6	20–30	20–24%	1.57
Contour Trench	0.5	0–10	24–28%	1.52
	1	10–20	22–26%	1.54
	1.5	20–30	20–24%	1.56
	5	0–10	22–26%	1.55
	5.5	10–20	20–24%	1.57
	6	20–30	18–22%	1.59
Contour Bund	0.5	0–10	22–26%	1.53
	1	10–20	20–24%	1.55
	1.5	20–30	18–22%	1.57
	5	0–10	20–24%	1.56
	5.5	10–20	18–22%	1.58
	6	20–30	16–20%	1.60
Control Plot	0.5	0–10	15–20%	1.58
	1	10–20	13–18%	1.57
	1.5	20–30	12–16%	1.56
	5	0–10	17–22%	1.59
	5.5	10–20	15–19%	1.58
	6	20–30	14–18%	1.57

Table 2: soil moisture content and bulk density table (before rainfall event)

Plot Type	Distance from Conservation Measure (m)	Soil Depth (cm)	Moisture Content (%)	Bulk Density (g/cm³)
Contour Bund Cum Trench	0.5	0–10	12–16%	1.58
	1	10–20	16–20%	1.56
	1.5	20–30	18–22%	1.54
	5	0–10	12–16%	1.57
	5.5	10–20	16–20%	1.55
	6	20–30	18–22%	1.53
Contour Trench	0.5	0–10	12–16%	1.58
	1	10–20	16–20%	1.56
	1.5	20–30	18–22%	1.54
	5	0–10	12–16%	1.57
	5.5	10–20	16–20%	1.55
	6	20–30	18–22%	1.53
Contour Bund	0.5	0–10	12–16%	1.58
	1	10–20	16–20%	1.56
	1.5	20–30	18–22%	1.54
	5	0–10	12–16%	1.57
	5.5	10–20	16–20%	1.55
	6	20–30	18–22%	1.53
Control Plot	0.5	0–10	12–16%	1.58
	1	10–20	16–20%	1.56
	1.5	20–30	18–22%	1.54
	5	0–10	12–16%	1.57
	5.5	10–20	16–20%	1.55
	6	20–30	18–22%	1.53



Graph 8: Infiltration rate and cumulative infiltration over time, at a distance of 5 m from the control plot

The Graph 8 tracks soil infiltration over time, showing an initially high rate (43.2 mm/hr at 1 minute) that decreases as the soil saturates (6.257 mm/hr at 280 minutes). Cumulative infiltration steadily rises, reaching 261.82 mm by 280 minutes, reflecting the soil's water absorption capacity over time. This trend highlights typical soil behavior, with infiltration slowing as saturation increases. The Contour Bund Cum Trench retained the highest soil moisture (26-30% at 0-10 cm, decreasing to 20-24% at 20-30 cm) and had the lowest bulk density (1.50-1.57 g/cm³), indicating superior water retention and soil structure (Table 2). The Contour Trench followed, with slightly lower moisture (24-28% to 18-22%) and bulk density (1.52-1.59 g/cm³). The Contour Bund showed moderate performance, with moisture content ranging from 22-26% to 16-20% and bulk density of 1.53-1.60 g/cm³. The Control Plot had the lowest moisture content (15-20% to 12-16%) and the highest bulk density (1.56-1.59 g/cm³), reflecting poor water retention and compacted soil.

4. Discussion

The present study demonstrates that conservation agriculture (CA) interventions-particularly the Contour Bund Cum Trench (CBCT)-significantly enhanced soil physical properties in the fragile Kandi region of Jammu. Improved infiltration rates and reduced bulk density near conservation structures clearly indicate better soil porosity and aggregation, likely due to reduced surface runoff and minimal mechanical disturbance. At 1 m distance, CBCT achieved the highest infiltration rate increase (114.28%) compared to control, followed by contour trench (100%) and contour bund (85.71%). Even at 5 m, improvements persisted, although diminished, underscoring the localized but consistent effectiveness of structural interventions. This aligns with findings of [6] and [12], which reported improved infiltration and water retention with structural conservation measures in sloping terrains.

Bulk density reductions were most pronounced near CBCT, where a 5.06% decrease (from 1.58 to 1.50 g/cm³) was observed at the surface (0-10 cm), suggesting loosening of compacted layers and enhanced root-zone aeration. The corresponding soil moisture improvements (26-30%) after rainfall further confirm that CA improves water-holding capacity, likely due to both improved infiltration and reduced evaporation losses. Pre-rainfall values also indicated the superior moisture-retaining ability of treated plots, showing clear benefits even before new water inputs. This improvement in soil moisture dynamics under CA can significantly enhance crop resilience in rainfed systems, a critical factor in regions facing erratic rainfall and drought episodes.

The spatial variation in infiltration and moisture, decreasing with distance from the structures, reflects the gradient influence of CA and suggests potential benefits from denser structural deployment in future designs. Control plots exhibited both highest bulk density (up to 1.59 g/cm³) and lowest moisture (as low as 12%), indicating soil compaction and poor water availability-hallmarks of degraded, unprotected soils. These findings provide compelling evidence that conservation tillage practices and structural measures like CBCT are vital for reversing soil degradation, improving hydrological functioning, and enhancing sustainable land productivity in ecologically vulnerable zones like the Kandi belt. Overall, the study supports the hypothesis that CA not only reduces runoff and erosion but also transforms physical soil health, improving infiltration, water retention, and structural integrity. These outcomes are particularly significant in semi-arid, sloping ecosystems where water-use efficiency directly governs agricultural viability. The positive soil transitions observed here reinforce the growing consensus that conservation agriculture is essential for climate-resilient and resource-efficient farming, especially in fragile agro-ecological zones.

Conclusion

This study demonstrates that conservation agriculture (CA) interventions-particularly Contour Bund Cum Trench (CBCT)-significantly enhance key soil physical properties in the fragile, rainfed Kandi belt of Jammu. Among the treatments, CBCT exhibited the highest initial infiltration rate (0.150 cm/min) and maximum cumulative infiltration (481.2 mm), outperforming Contour Trench (469.2 mm) and Contour Bund (457.4 mm), while the Control Plot lagged behind with the lowest infiltration values. These results confirm the superior performance of CBCT in improving water infiltration and retention, crucial for optimizing water use in semi-arid agriculture.

The study also revealed that the effectiveness of conservation measures decreases with distance, particularly beyond 5 m from the structures, indicating the need for strategic spatial planning in CA deployment. Notably, CBCT also led to the lowest soil bulk density (1.50-1.57 g/cm³) and the highest moisture retention (26-30%), indicating improved soil structure and enhanced porosity. The Contour Trench also showed positive effects, though slightly less effective, while the Contour Bund and Control Plot displayed relatively modest improvements.

Overall, the findings confirm that CA practices substantially improve soil hydrological behavior, particularly in degraded and water-limited regions. By reducing bulk density, enhancing infiltration, and increasing soil moisture content, CA strengthens the resilience of cropping systems against climate variability. Therefore, Contour Bund Cum Trench emerges as the most effective and practical intervention among the tested measures, offering a viable, cost-effective strategy for sustainable land and water management in dryland farming systems. Promotion of such practices through research-backed extension services and policy support can play a pivotal role in revitalizing fragile agro-ecological landscapes like those in the Kandi region.

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Author Contributions

All authors contributed to the study conception and design. Supervision, writing review and editing of the manuscript is the responsibility of [Zubair Ahmad Khan]. The first draft of the manuscript was written by [Zubair Ahmad Khan]. Data curation and Investigation were performed by [RK Srivastava, Sheikh Aadil Mushtaq and Zubair Ahmad Khan]. Methodology, Software, Validation and Visualization was written by [Malik Arif Bashir, Maliqa Majid, Aadil Majeed and Ussama Magray]. All authors read and approved the final manuscript.

Data Availability

Datasets and other materials are available with the authors, and may be accessible at any time upon request.

Declarations

- **Consent to Participate:** Consent.
- **Consent to Publish:** Consent.
- **Competing Interests:** The authors have no relevant financial or non-financial interests to disclose.
- **Conflict of Interest:** The authors declare no conflict of Interest.
- **Funding:** No

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