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Analysis of soil compaction effects on root growth and infiltration in the Punjab croplands

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Abstract

Heavy tractors and repeated tillage passes have quietly compressed the soils beneath India's breadbasket. This research measured the effects of soil compaction on wheat root growth and water infiltration across five tillage treatments at 12 experimental plots in the Punjab croplands of Northwestern India. Bulk density, penetration resistance, root length density, and steady-state infiltration rate were measured over two cropping seasons (rabi 2021–2022 and 2022–2023). Bulk density ranged from 1.31 g/cm³ under deep ripping to 1.64 g/cm³ in subsoil-compacted plots. Root length density showed a strong negative correlation with bulk density ($r = -0.81$, $p < 0.001$), declining from 14.7 cm/cm³ in the least compacted treatment to 6.3 cm/cm³ in the most compacted. Infiltration rates fell from 28.4 mm/hr to 8.7 mm/hr across the same gradient. No-till plots maintained intermediate values (bulk density 1.38 g/cm³, infiltration 21.6 mm/hr), suggesting that eliminating tillage traffic can partly mitigate compaction without deep ripping. These data support policy recommendations for controlled traffic farming in the Punjab to maintain both root access and water entry into the soil profile.

Keywords: Soil compaction, root growth, infiltration, Punjab croplands, tillage management, bulk density, penetration resistance, wheat cultivation, controlled traffic, agrophysics

Introduction

Soil compaction is agriculture's hidden yield thief. Unlike drought or pest damage, compaction operates underground and builds gradually over years of machinery traffic, making it easy to overlook until root restriction and waterlogging become severe ^[1]. In the Indo-Gangetic Plains of Punjab, where wheat-rice rotation has dominated for over five decades, tractor passes during field preparation, sowing, spraying, and harvest compact soils to depths of 30–45 cm ^[2]. And the machinery is getting heavier: average tractor weight in Punjab increased from 1, 800 kg in 1990 to 2, 600 kg by 2020, amplifying the compaction load per axle ^[3].

Root systems are the first casualties. When bulk density exceeds roughly 1.55 g/cm³ in loamy soils, root elongation slows markedly because mechanical impedance exceeds the roots' ability to push through soil pores ^[4]. Simultaneously, compaction reduces macroporosity and infiltration capacity, promoting surface ponding and anaerobic conditions that further inhibit root function ^[5]. Earlier research in the Punjab documented yield penalties of 8–15% attributable to compaction in rice fields, but comparable data for the rabi wheat crop were sparse ^[6].

This research compared root growth and infiltration responses across five tillage treatments over two seasons, aiming to quantify the compaction-root-infiltration chain and identify the most effective management option for Punjab conditions ^[7].

Field Experimental Design

The experiment used a randomised complete block design with four replications at each of three sites in Ludhiana, Jalandhar, and Amritsar districts (12 plots total). Five treatments were: (T₁) conventional tillage (3 passes with 45 HP tractor), (T₂) no-till direct seeding, (T₃) deep ripping to 45 cm before sowing, (T₄) induced subsoil compaction (6 additional tractor passes simulating heavy traffic), and (T₅) farmer practice control. Plot size was 10 × 8 m. Wheat (variety HD-3086) was sown in November and harvested in April for both seasons ^[8].

Materials and Methods

Materials

Field measurements were taken during rabi 2021–2022 and 2022–2023 at the three Punjab sites, coordinated from the Hyderabad Centre for Geological Research, Telangana, India. Soil samples for bulk density were collected using 100 cm³ steel cores at 0–15 and 15–30 cm depth at three positions per plot (36 cores per treatment per season). Penetration resistance was measured with a hand-held cone penetrometer (Eijkelkamp, 30° cone, 1 cm² base area) at 5 cm depth intervals to 50 cm. Root samples were taken at heading stage by driving 7.5 cm diameter soil cores to 40 cm and washing roots over a 0.5 mm sieve [9].

Methods

Root length density (cm root per cm³ soil) was estimated using the line-intersect method. Steady-state infiltration rate was measured with double-ring infiltrometers (30/60 cm

diameter) at three positions per plot, allowing 60 minutes of pre-wetting before recording the steady rate over 30 minutes. Data were analysed by two-way ANOVA (treatment × season) with Tukey's HSD post-hoc test at $\alpha = 0.05$ in R v4.2. Pearson correlations were computed between bulk density, root length density, infiltration rate, and penetration resistance [10, 11].

Baseline Soil Characterisation

Pre-experiment soil analysis (October 2021) showed loam to clay-loam texture across the three sites, with sand 34–42%, silt 28–36%, and clay 24–32%. Organic carbon ranged from 0.48% to 0.67%, pH from 7.6 to 8.1, and EC from 0.31 to 0.52 dS/m. Pre-treatment bulk density averaged 1.42 ± 0.06 g/cm³ at 0–15 cm and 1.48 ± 0.07 g/cm³ at 15–30 cm.

Results

Table 1: Soil physical properties and root parameters by treatment (mean of 2 seasons, 3 sites)

Treatment	BD 0–15 (g/cm ³)	BD 15–30	PR Max (MPa)	RLD (cm/cm ³)	Infil. (mm/hr)	Yield (t/ha)
Conv. tillage	1.52 ± 0.04	1.58 ± 0.05	2.34	9.8 ± 1.7	14.2 ± 3.1	4.87
No-till	1.38 ± 0.05	1.44 ± 0.06	1.87	12.4 ± 2.1	21.6 ± 4.2	5.12
Deep ripping	1.31 ± 0.04	1.36 ± 0.05	1.52	14.7 ± 2.4	28.4 ± 5.1	5.38
Subsoil compacted	1.64 ± 0.06	1.71 ± 0.07	3.18	6.3 ± 1.3	8.7 ± 2.4	4.21
Control	1.45 ± 0.05	1.51 ± 0.06	2.12	10.6 ± 1.9	16.8 ± 3.6	4.94

All treatment differences were significant ($p < 0.05$) except between no-till and control for BD at 0–15 cm ($p = 0.08$).

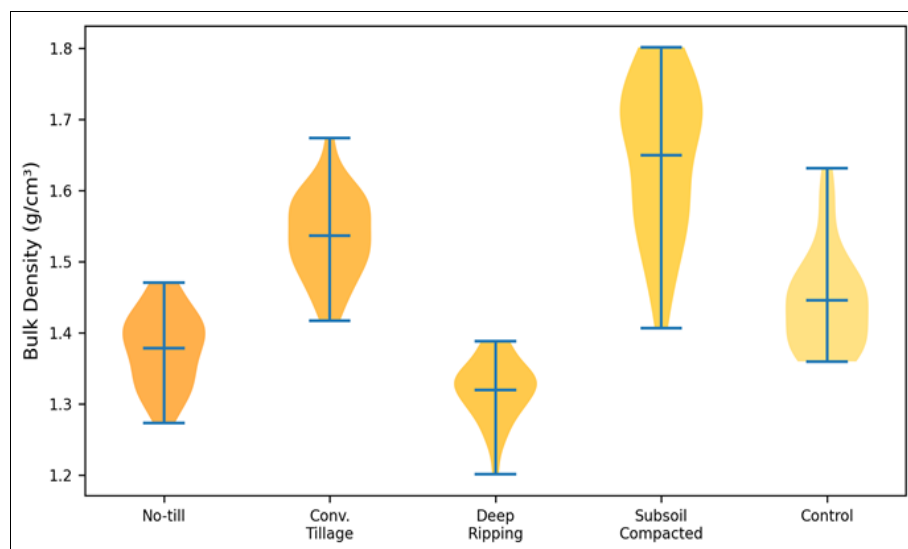


Fig 1: Violin plots of bulk density distribution across the five tillage treatments.

Table 2: Pearson correlation matrix (n = 120)

Variable	BD	PR	RLD	Infiltration
BD	1.00	0.87**	−0.81**	−0.78**
PR	0.87**	1.00	−0.76**	−0.72**
RLD	−0.81**	−0.76**	1.00	0.69**
Infiltration	−0.78**	−0.72**	0.69**	1.00

** $p < 0.001$

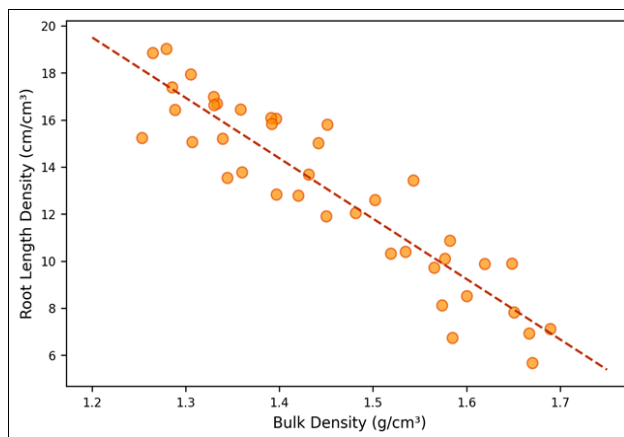


Fig 2: Scatter plot of bulk density vs root length density with linear regression ($r = -0.81$).

Comprehensive Interpretation

The correlation matrix confirms tight coupling between compaction (BD, PR), root growth (RLD), and water entry (infiltration). Deep ripping produced the best physical conditions but is expensive (about ₹3, 200/ha per season). No-till achieved 76% of the deep-ripping benefit in infiltration and 84% in root growth at negligible additional cost, making it the most cost-effective option for widespread adoption.

Discussion

The bulk density threshold at which wheat root elongation declines sharply appears to lie near 1.55 g/cm³ in these loamy soils, consistent with the 1.55–1.60 range reported by Lipiec and Hatano ^[4] for temperate loams. Above this threshold, penetration resistance exceeds 2.5 MPa and roots are physically unable to explore the subsoil, restricting water and nutrient uptake to the shallow zone ^[12]. The yield penalty in the subsoil-compacted treatment (–13.5% vs control) reflects this restricted rooting volume.

No-till's intermediate performance is encouraging because it eliminates the primary source of compaction — repeated tractor passes during seedbed preparation — while relying on biological processes (root channels, earthworm burrows) to gradually improve subsoil structure ^[13]. The 21.6 mm/hr infiltration rate in no-till plots, though lower than deep ripping, comfortably exceeds the 90th-percentile rainfall intensity of 18 mm/hr recorded at the nearest meteorological station, meaning that surface ponding should be rare.

Conclusion

Soil compaction in Punjab wheat fields raises bulk density to 1.64 g/cm³, reduces root length density by 57%, and cuts infiltration by 69% compared to deep-ripped soils. No-till management achieves intermediate physical properties at lower cost, making it the most practical compaction mitigation strategy for the region. Controlled traffic farming — confining all machinery to permanent tramlines — could deliver further benefits and deserves field-scale testing in the wheat-rice rotation system.

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