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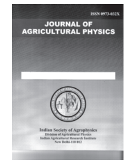

Research Article

Variations in Root Growth Parameters of Wheat under Long-term Conservation Agriculture-based Rice-Wheat Cropping System

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ABSTRACT

The use of intensive tillage and other management practices in crop production systems can cause soil erosion, degrade soil quality and water quality, and reduce crop yield, thereby hindering the attainment of sustainable agricultural production systems. In the present study, root growth parameters were assessed under long-term conservation agriculture (CA)-based rice-wheat cropping system with seven treatments, i.e., T1, Zero-till direct seeded rice (ZTDSR) - zero till wheat (ZTW); T2, ZTDSR + BM (Sesbania brown manuring)-ZTW; T3, Zero-till direct seeded rice (ZTDSR) + wheat residue (WR) -zero till wheat (ZTW) + rice residue (RR); T4, (ZTDSR)+wheat residue (WR) +sesbania brown manuring (SBM) -zero till wheat (ZTW) +rice residue (RR); T5, (ZTDSR) -zero till wheat (ZTW) -zero till mungbean (ZTMB); T6, (ZTDSR) + mungbean residue (MR) - (ZTW) + rice residue (RR) -zero till mungbean (ZTMB) + wheat residue (WR); T7, Transplanted rice (TPR)-conventional till wheat (CTW) -conventionally tilled mungbean (CTMB). Root system responses to conservation agriculture (CA) practices were quantified using plant root scanning and image analysis with the WINRHIZO system in a rice-wheat cropping system. Root length density (RLD), root mass density (RMD), root diameter (RD), root surface area density (RSAD), and root volume density (RVD) were assessed at 0-15 and 15-30 cm soil depths under seven crop establishment and residue management treatments. At the surface layer (0-15 cm), only T6 (zero tillage + residue retention + mungbean inclusion) recorded a significantly higher RLD (23.5%) compared with conventional tillage (CT), whereas other CA treatments showed no improvement or significantly lower RLD (30-46%) relative to CT. Root mass density at 0-15 cm increased significantly under CA treatments integrating residues or brown manuring, by 12-25% over CT, whereas zero tillage without residues remained comparable to CT. In the subsurface layer (15-30 cm), CA treatments markedly enhanced root proliferation; RLD, RMD, RSAD, and RVD were significantly higher than CT, with maximum values consistently observed under T6, followed by T4 and T5. Residue retention increased RVD by 154-181% in both double and triple cropping systems compared to residue-free treatments. Surface layer root diameter was 34-47% higher under integrated CA treatments than under CT, whereas no significant differences were observed at depth. Overall, the results demonstrate that system-level integration of zero tillage, residue retention, and legume inclusion is critical for improving root distribution and density, particularly in subsurface soils, thereby enhancing the functional rooting environment in intensive rice–wheat-based cropping systems.

Key words: Conservation Agriculture, Root length density, Root mass density, Root volume density, Root surface area density, Root diameter

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Introduction

The rice-wheat cropping system (RWCS) is one of the most widely practised agricultural production systems worldwide, covering about 12.3 million ha in India, 0.5 million ha in Nepal, 2.2 million ha in Pakistan, and 0.8 million ha in Bangladesh (Bhatt *et al*., 2019). However, the conventional RWCS in the Indo-Gangetic Plains (IGP) is increasingly constrained by yield stagnation (Verma *et al.,* 2025), groundwater depletion (Humphreys *et al.,* 2010) and progressive soil degradation (Nawaz *et al.,* 2019). Intensive tillage operations, particularly rice puddling, delay wheat sowing and reduce wheat yields by 8-9% (Kumar & Ladha, 2011), while also consuming large volumes of water, with puddling alone accounting for 25-30% of total irrigation demand (Kakraliya *et al.,* 2018). Such practices deteriorate soil structure, accelerate organic matter depletion (Lal, 2015; Bhattacharyya *et al*., 2015), and substantially increase labour requirements, energy use, and production costs (Das *et al.,* 2020). In addition, widespread crop residue burning exacerbates air and soil pollution (Kumar *et al.,* 2019) and poses serious risks to human health. Subsurface soil compaction has been widely documented in conventional tillage (CT) based rice-wheat cropping systems (RWCS) across India (Aggarwal *et al.,* 2006; Kumar *et al.,* 2014). In this context, the adoption of conservation agriculture (CA), as a resource-efficient and climate-resilient management strategy, is increasingly recognized as essential for sustaining crop productivity and improving soil health in the RWCS of the IGP (Singh *et al*., 2021). According to Jat *et al*. (2023), in the rice-wheat systems of South Asia, conservation agriculture (CA) practices are predominantly adopted in wheat (often termed partial CA), whereas rice is generally cultivated using conventional methods due to challenges such as severe weed infestation and iron deficiency, which limit the productivity of zero-till dry-seeded rice. Under CA-based rice–wheat systems, more than 75% of wheat straw is removed after combine harvesting for use as livestock fodder, with only the remaining wheat stubbles (~ 2 Mg ha^{-1}) retained as surface mulch. In contrast, nearly 75% of rice straw is typically removed through on-farm burning to facilitate timely wheat sowing, leading to severe air pollution problems in northwestern India.

Conservation agriculture (CA), founded on the principles of zero tillage, retention of organic residues, and diversified crop rotations, plays a key role in improving soil health and strengthening climate resilience (Kar *et al*., 2023). As practiced worldwide on more than 205 million ha (Kassam *et al.,* 2020), CA enhances input-use efficiency, minimizes soil erosion, promotes carbon sequestration, and reduces greenhouse gas emissions (Gathala *et al.,* 2020). In South Asia, CA has been extensively adopted in wheat within the rice-wheat cropping system, although its implementation in rice remains constrained by several challenges (Parihar *et al.,* 2016). Adoption of CA improves soil chemical properties by increasing nutrient availability, soil organic carbon, and microbial activity, while reduced tillage and residue retention contribute to higher soil N, P, and K availability (Choudhary *et al.,* 2020).

Roots act as a bridge between the soil's physical changes and the shoot response (Klepper, 1990). The root system is crucial for plant adaptation to changes in soil conditions. However, root sampling is highly labour-intensive and time-consuming. Assessing root growth and development in field conditions is particularly challenging due to the extensive spatial variability and complex branching patterns of roots, as well as the opaque nature of the soil environment (Bengough *et al.,* 2000). Consequently, a large number of replicates is required to obtain reliable estimates of root parameters. Considerable variation in root morphology has been reported across different sampling times and soil depths. Previous studies indicate that root parameter values are influenced by factors such as crop variety, climatic conditions, and soil management practices. Sattelmacher *et al.* (1993) emphasized that root morphological traits are critical determinants of a plant's capacity to absorb mineral nutrients from the soil. Singh *et al.* (2014) found that the greatest root density was observed in soils with lighter textures, measuring 1663 mg per 100 cubic centimetres. Root density decreased as the soil texture became finer, with values of 1575 mg/100 cm^3 in loam soils and 1200 mg/100 cm^3 in clay loam soils. Sur *et al.* (1980) observed that root growth reduction in wheat was more pronounced in rice-based cropping systems (such as rice-wheat) compared to maize-based systems (such as maize-wheat) when grown in sandy loam soil.

Mosaddeghi *et al.* (2009) reported that tillage could influence root function and development due to modifications in the root growth environment. It is well accepted that root proliferates maximum in the surface soil layer due to greater availability of water and nutrients (Hodge, 2009; Lynch, 2022). Reduced yield potential and restricted root growth under compacted subsoil layer have been reported (Bengough *et al.,* 2011). CT creates a fine seedbed and promotes root growth in the surface soil layer, but the formation of a compacted subsurface layer from long-term conventional tillage can negate its beneficial effects. However, a higher bulk density of the surface layer in NT can inhibit the downward development of the root system (Mosaddeghi *et al.,* 2009). Research by Kaur *et al*. (2019) focused on the impact of CA on root architecture in wheat. They found that under CA practices, wheat roots exhibited a more extensive, fibrous architecture than under conventional tillage. The improved root architecture included increased root length density and finer root hairs, which are crucial for enhancing nutrient uptake and water absorption efficiency. Chen and Weil (2011) also observed higher root growth under the NT system due to better soil physical conditions. Zero-tillage under CA led to deeper root penetration and greater root spread in both rice and wheat crops, attributed to reduced soil compaction and improved soil structure. The presence of crop residue on the surface in ZT and the improved balance between macro- and micro-porosity likely led to a greater root density in the upper soil layer. This also supported the growth of a longer root system in wheat, which was better able to access water from deeper soil layers (Bonfil *et al.,* 1999). Rahman *et al.* (2005) reported that straw mulching or residue retention under no-tillage significantly influenced wheat root weight and the root-to-shoot ratio (R/S), with the highest R/S, RLD, and RWD observed under NT combined with rice straw mulch applied at 4.0 Mg ha{ ¹. Straw mulch reduced soil mechanical resistance by conserving soil moisture, thereby promoting root development. Similarly, Sharma and Acharya (2000) documented enhanced wheat root growth under mulched conditions. Consistent findings under no-till systems were also reported by Gill *et al.* (1996) for maize and by Rathore *et al*. (1998) for chickpea, in which mulching resulted in superior root growth compared with unmulched treatments. Very limited studies are reported in which root parameters of wheat crop under different CA-based rice wheat cropping systems were analysed. The study's hypothesis was H1: There is a significant difference in wheat root parameters between CA and CT-based practices in RWCS. Objectives of our studies were (i) to evaluate the effects of long-term conservation agriculture practices on root architectural traits of wheat in the rice wheat cropping system.

Materials and Methods

Study area and experimental details

A long-term field experiment entitled "Enhancing Resource Efficiency and Productivity of Rice (Oryza sativa)-based Cropping Systems through Conservation Agriculture Practices" was initiated in 2010 at the ICAR-Indian Agricultural Research Institute (ICAR-IARI), New Delhi, India, at the experimental farm (Field No. MB 14B; 28°38′38″ N, 77°09′08″ E; 228 m above mean sea level). The study was designed to evaluate the effects of contrasting tillage, residue management, and crop establishment methods. The experimental soil is classified as an Inceptisol (Typic Haplustept), non-saline, with a clay loam texture to a depth of 30 cm and a loamy texture below. The initial soil properties in the 0-15 cm layer included a pH of 8.3, Walkley-Black carbon of 6.0 g kg^{-1}, soil organic carbon (SOC) of 7.5 g kg^{-1}, and an electrical conductivity (EC) of 0.69 dS m^{-1}. The experimental site experiences a wide temperature range, from a minimum of 3.5°C in February to a maximum of 38°C in April. The region receives an average annual rainfall of approximately 800 mm, of which about 80% occurs during the southwest monsoon (July-September), while the remaining rainfall is contributed by western disturbances during December-February. This study was conducted during the 13th year (2023) of a long-term conservation agriculture (CA) based rice-wheat system (RWS). Seven tillage and crop residue management treatments were evaluated using a randomized complete block design (RCBD) with three replications. Each experimental plot measured 15.0 m × 8.0 m. The treatments included two triple-cropping systems incorporating mungbean (*Vigna radiata* (L.) R. Wilczek), with and without crop residue retention, which were compared with CA-based double-cropping systems and the conventional puddled transplanted rice conventional till wheat (PTR-CTW) system. Brown manuring was implemented by sowing Sesbania simultaneously with rice and chemically suppressing it approximately 25 days after sowing using 2,4-D (2,4-dichlorophenoxyacetic acid) at 0.50 kg active ingredient ha^{-1}. The rice cultivar PRH-10 and wheat cultivar HD-2894 were used throughout the study. Detailed treatment descriptions are provided in Table 1.

Under the zero-tillage direct-seeded rice (ZTDSR) system, approximately 40% of wheat residue (≈3.1 t ha^{-1} yr^{-1}) was retained, while 40% of rice residue (≈2.7 t ha^{-1} yr^{-1}) was retained in the zero-till wheat (ZTW) plots. In the triple zero-tillage system, 100% of mungbean residue (≈3.0 t ha^{-1} yr^{-1}) was retained under ZTDSR, along with 40% rice residue in ZTW and 40% wheat residue in zero-till mungbean, reflecting an integrated and efficient residue management strategy.

Plant root scanning and image analysis

Root sampling

Total root mass density across all tillage systems reached its maximum at the flowering stage and declined thereafter (Gao-bao *et al.,* 2012). Therefore, three to four root samples from each treatment were collected at the flowering stage. After removing the above-ground plant parts, the soil surface was cleaned. The core of the auger was placed to keep the base of the stem at the centre, and the soil core was excavated from each 15 cm depth layer down to a 30 cm depth. After the excavation, the soil cores were sealed in polythene bags and stored in a refrigerator (maintained at 4°C) for washing and scanning later.

Separation of roots from soil and organic debris

The root samples were soaked overnight in water containing sodium hexametaphosphate in a small amount in a pail (Aggarwal and Sharma, 2002). The water on the top with the floating water was decanted into another container. Roots were then separated by carefully passing the decanted water over a fine sieve (35 mesh). The procedure was repeated 3-4 times to ensure complete separation of the roots from the soil. The washed roots were then placed in butter paper bags and stored in the refrigerator to prevent degeneration until they were scanned.

Root scanning and image analysis

The scanner of the RHIZO system (WINRHIZO System, Regent Instrument Inc.) had two light sources, one below the scanner glass called the flat bed or reflective and one above it (in the scanner cover) called the transparency unit or TPU. For root morphological measurements TPU lighting system was used for scanning. The light rays from TPU passed through the sample and then to the camera sensor below the scanner glass. The resulting image was sharp and clear with a well-contrasted silhouette. The image analysis system RHIZO acquires a digital (grayscale) image from the scanner and then creates two other types of images for its analysis. One type of image created was termed as 'Pixels classification image' in which all parts of the original image that fell below a user-defined threshold of grayscale values were removed. The image had only two intensities: black for pixels belonging to roots and white for pixels belonging to the background. Another created image was termed a skeleton image, which consisted of a line, one pixel in diameter, superimposed over the earlier root image. RHIZO system measured the root length by scanning the length of the root skeleton. The colour of the skeleton indicated the diameter classification. The advantage of Regent's non-statistical method over Tennant's statistical method was that, in addition to root length density, root surface area and volume measurements, it further gave information on their distribution in various size classes based on their diameter. The washed roots were spread with a thin layer of water on a transparent plate for scanning. After image acquisition, the root portion was selected for analysis to obtain different root parameters. Root morphology and architecture parameter measurement (viz., total root length, root surface area, root volume, average root diameter, etc.) were done by the Win-RHIZO programme (Reagent Instruments Inc., Canada). The cleaned root samples were dried in an oven at 65°C for 48 h and weighed. The measured root length,

Table 1. Treatment details of the long-term experiment

Treatments	Operations performed	Short form
Zero-till direct seeded rice (ZTDSR) –zero till wheat (ZTW)	Direct-seeded rice (DSR) was sown with a turbo seeder at 20 kg/ha, maintaining 20 cm row spacing and 5–6 cm between seeds. Zero-till wheat (ZTW) was sown at 100 kg/ha using the same seeder after pre-sowing irrigation, with calibration done for both rice and wheat seed rates prior to sowing.	ZTDSR-ZTW (T1)
ZTDSR + BM (Sesbania brown manuring)-ZTW	In the ZTDSR–ZTW system, Sesbania was sown for brown manuring by broadcasting 20 kg/ha of seed immediately after DSR sowing. It grew alongside rice for 25 days, producing 1.5–2.0 t/ha of dry biomass and contributing 30–35 kg N/ha. At 25 DAS, 2,4-D (0.5 kg a.i./ha) was applied to terminate Sesbania, which then served as mulch for about 40 days.	ZTDSR+BM -ZTW (T2)
Zero-till direct seeded rice (ZTDSR)+wheat residue (WR) - zero till wheat (ZTW) + rice residue (RR)	In addition to implementing Zero-Till Direct-Seeded Rice (ZTDSR) followed by Zero-Till Wheat (ZTW), 40% of wheat residue was left on the rice crop, and 40% of rice residue was left on the wheat crop.	ZTDSR +WR– ZTW+ RR (T3)
(ZTDSR)+wheat residue (WR) + sesbania brown manuring (SBM) –zero till wheat (ZTW) +rice residue (RR)	In addition to ZTDSR + WR –ZTW + RR, Sesbania was grown as a co-culture with DSR for brown manuring.	ZTDSR + WR + SBM –ZTW + RR (T4)
(ZTDSR) –zero till wheat (ZTW) –zero till mung-bean (ZTMB)	Following the ZTDSR–ZTW sequence, short-duration mungbean variety SML 832 (60–65 days) was sown in mid-April under zero-till conditions using a turbo seeder. It produced 1.6–2.0 t/ha of shoot dry biomass and contributed about 50–55 kg N/ha to the soil.	ZTDSR-ZTW - ZTMB (T5)
(ZTDSR)+mung-bean residue (MR)– (ZTW) + rice residue (RR)-zero till mung-bean (ZTMB) + wheat residue (WR)	After harvesting mungbean pods, the remaining biomass was incorporated using a disk plough and harrow, followed by sowing of ZTDSR. This was succeeded by wheat with rice residues (RR), and then ZTW with wheat residues (WR).	ZTDSR+ MR – ZTW + RR – ZTMB + WR(T6)
Transplanted rice (TPR)-conventional till wheat (CTW)–conventionally tilled mungbean (CTMB)	For Transplanted Rice (TPR), the soil was tilled twice with disks, harrowed twice, and puddled before transplanting rice seedlings. After TPR, Conventional Tillage Wheat (CTW) involved two disking, two harrowing, and leveling, followed by sowing with a seed drill at a 20 cm row spacing and a seeding rate of 100 kg per hectare.	TPR-CTW-CTMB (T7)

surface area, and root dry weight were divided by the core volume (577.5 cm^3) to obtain the respective densities at each depth.

Result and Discussion

Figure 1, 2 and Table 2 shows root mass density (RMD mg/cm$^{3)}$, root length density (RLD cm/cm^3), root volume density (RVD cm^3/cm^3), root surface area density (RSAD cm^2/cm^3) and root diameter (RD mm) for 7 treatments for 0-15 cm and 15-30 cm of soil depth.

Root Length Density (RLD)

Root length density (RLD) is a key indicator for assessing the effects of different tillage systems on crop growth and yield (Ibrahim *et al.,* 2010; Ishaq *et al.,* 2001; Sarwar *et al.,* 2008). At the 0-15 cm soil depth, root length density (RLD) responded differentially to crop establishment and residue management practices (Fig. 1). Among all treatments, only T6, representing a triple cropping system with mungbean inclusion, residue retention and zero tillage, recorded a significantly higher RLD (23.5%) compared to the conventional puddled transplanted rice-conventional till wheat system without residue retention (T7). This indicates that the combined effects of legume integration, continuous residue retention, and zero tillage were necessary to achieve a measurable improvement in surface-layer root proliferation compared with conventional tillage (CT). This study was supported by Mondal *et al.* (2020), who used meta-analysis and found a 34.7% higher RLD under zero tillage (ZT) in the 0-5 cm layer. This increase was attributed to significantly improved soil structural stability (39% increase in MWD and a substantial rise in SOC content (~38%). Whereas in the other soil layers, the differences

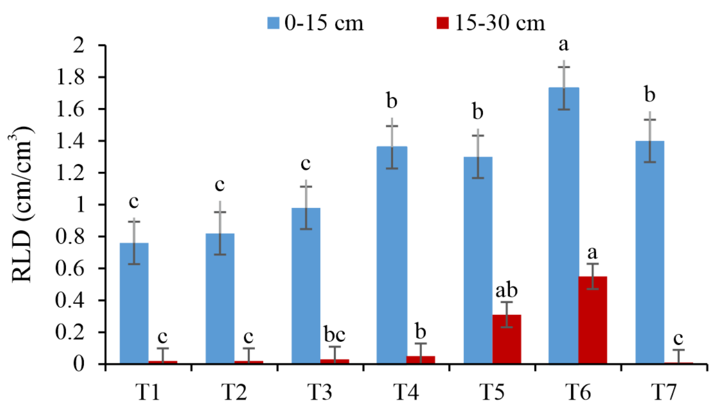
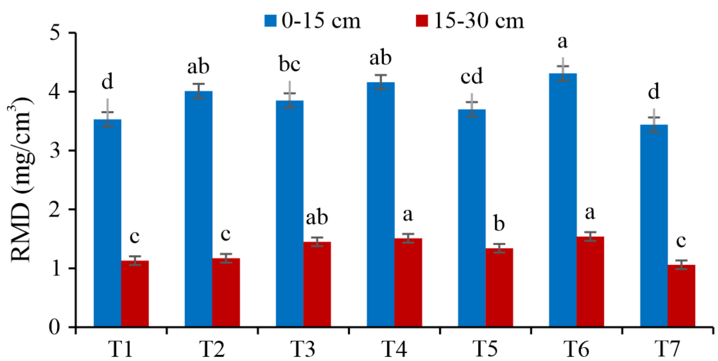


Fig. 1. Root length density (RLD) of wheat under different CA and CT treatments



T1, ZTDSR-ZTW; T2, ZTDSR + BM-ZTW; T3, ZTDSR+ Wheat residues (WR)-(R) +ZTW; T4, ZTDSR+(WR) +BM-RR+ZTW; T5, ZTDSR-ZTW-ZTMB; T6, ZTDSR+MBR-ZTW+RR-ZTMB+WR; T7, TPR –CTW

Fig. 2. Root mass density (RMD) of wheat under different CA and CT treatments

Table 2. Root diameter (RD), Root surface area density (RSAD) and Root volume density (RVD) of wheat roots

Treatments	Root DIA (mm)		RSAD (cm^2/cm^3)		RVD ($cm^3/100cm^3$)	
	0-15cm	15-30cm	0-15cm	15-30cm	0-15cm	15-30cm
T1	0.32d	0.28ab	0.08b	0.01d	0.122b	0.011e
T2	0.54ab	0.23b	0.13a	0.01d	0.113c	0.008f
T3	0.42bcd	0.29ab	0.1ab	0.04bc	0.112c	0.027d
T4	0.51ab	0.3ab	0.14a	0.05b	0.159a	0.033c
T5	0.46abc	0.34a	0.11ab	0.11a	0.121b	0.043b
T6	0.56a	0.37a	0.14a	0.03c	0.160a	0.121a
T7	0.38cd	0.29ab	0.08b	0.007d	0.125b	0.005f

between ZT and CT were not significant. RLD was slightly lower under ZT by 2.2, 12.5 and 13.9% in the 5-10 cm, 10-20 cm, and 20-30 cm layers, respectively, but showed a slight increase of 5.3% in the 30-60 cm layer and a minor decrease beyond 60 cm. The meta-analysis by Ruis *et al.* (2024) also showed that no-tillage (NT) significantly increased RLD in the 0-10 cm soil layer, whereas RLD was reduced in the 10-20 cm layer compared with tilled systems. He also reported that below 30 cm depth, NT exhibited mixed effects on RLD, and when evaluated across the entire soil profile (≥50 cm depth), NT had no overall effect on RLD. Stratification of RLD under NT was evident mainly relative to high-intensity tillage systems, but not in dry regions, mild or hot climates, medium-textured soils, or when compared with intermediate-intensity tillage. Conservation tillage, along with the incorporation of organic matter/crop residue into the soil, enhanced root proliferation, as evidenced by an increase in RLD (Ishaq *et al.,* 2003). Our study also showed that other CA treatments like T5 (triple cropping system without residue retention) and T4 (Double cropping system having brown manuring and rice wheat residue retention) did not show any significant changes from CT, suggesting that either residue retention and brown manuring or crop intensification alone was insufficient to enhance RLD at this depth. These results highlight the importance of system-level integration of multiple CA components rather than isolated adoption of individual practices. Our results contradicted those of Gao-Bao *et al.* (2012), who reported that at all crop growth stages, root length density in the upper 10 cm soil layer was significantly higher under no-tillage systems than under tilled systems, mainly due to improved soil water availability under no-tillage management. At the same time, T1, T2 and T3 showed significantly lower RLD (46, 41, 30%) compared to CT, respectively, which showed that only brown manuring in rice wheat cropping system or only rice wheat residue retention without brown manuring in ZT practices was inadequate in improving RLD compared to CT. This finding was consistent with Ibrahim *et al*. (2011), who reported that, when averaged across tillage practices, root length density in both wheat and rice followed the order deep tillage > conventional tillage > minimum tillage in the rice-wheat cropping system. It may be due to the monotonous rice-wheat systems' lack of the diverse root architectures and rhizosphere effects provided by legumes. Without diversified rooting patterns, soil pore networks may remain underdeveloped, limiting root penetration and reducing RLD. Present results also showed that in ZT treatments, only brown manuring or rice wheat residue retention did not improve RLD whereas brown manuring and rice wheat residue retention combinedly (T4) showed a significant 79% increase in RLD compared to T1 may be due to both worked synergistically by balancing carbon and nitrogen dynamics, accelerating residue decomposition and promoting the formation of stable soil aggregates and higher RLD. For subsurface layer (15-30 cm), all the CA treatment except T1, T2 and T3 showed significantly higher RLD compared to CT with highest in T6 followed by T5 and T4 may be due to improved bio pore continuity or reduced subsurface compaction or enhanced soil aggregation from residue and legume inputs or greater microbial activity or improved soil moisture regimes, unlike CT where plough-pan formation restricted root growth.

Root Mass Density (RMD)

At the surface soil layer (0-15 cm), all CA treatments except T1 and T5 recorded significantly higher RMD than T7 (CT), indicating that zero tillage alone without residue retention did not improve RMD over CT whereas zero tillage combined with residue retention or brown manuring (T2, T3, T4, and T6) significantly increased RMD by 16.5, 12, 21, and 25%, respectively, compared to T7 may result from improved soil aggregation, reduced surface compaction, greater organic carbon inputs and enhanced microbial activity whereas zero tillage without residues failed to offset surface soil strength constraints, resulting in RMD comparable to conventional tillage. Similar results were also reported by Sharma *et al.* (2019), who documented higher RMD under CA systems, highlighting improved soil fertility and nutrient availability as contributing factors. Mishra *et al.* (2022) emphasized that increased RMD under CA is linked to enhanced soil organic matter, which supports greater root biomass and root health. Son and Lee (2011) attributed the improvement in RMD to enhanced soil porosity resulting from minimal tillage combined with residue retention. Similarly, Oliveira and Merwin (2001) emphasized that increased soil porosity plays a crucial role in crop development by facilitating improved root growth. In contrast, Gangwar *et al.* (2004) found that tillage practices significantly affected root dry weight, with CT resulting in a higher average root dry weight than RT and ZT. Alam *et al*. (2014) found that the total root biomass density (RMD) across three sampling depths was similar for both rice and wheat, ranging from 13.11 to 11.71 mg/cm³ for wheat and 7.54 to 6.87 mg/cm³ for rice. In the 0-15 cm depth, root growth was greater under zero tillage (ZT) and minimum tillage (MT) compared to CT and deep tillage (DT). However, the opposite trend was observed in the subsurface (15-30 cm) and deeper soils (30-45 cm), where CT and DT showed higher root growth. Only brown manuring in ZT (T2) caused a significant 13.6% increase in RMD compared to T1, further supporting the importance of organic matter in improving RMD. A similar result was also found in a 15-30 cm soil layer. T6 showed the highest RMD (45%), followed by T4 (42%), compared to T7 in the sub-surface layer. Conversely, the CT control likely suffered from repeated soil disturbance and subsurface compaction, while zero tillage without residue inputs was insufficient to alleviate subsurface soil strength constraints. Gao Bao *et al.* (2012) reported that, relative to the conventional tillage (CT) system, no-tillage without wheat stubble mulching (NT), no-tillage with standing wheat stubble (NTSS), and no-tillage with wheat stubble mulching (NTS) significantly increased mean DRWD within the 0-70 cm soil profile at flowering by 12.2-19.5%, 18.0-23.7%, and 28.0-34.3%, respectively. In contrast, the present study also showed that among ZT treatments, brown manuring alone(T2) was unable to improve RMD, whereas rice wheat residue retention (T3) or brown manuring with residue retention (T4) showed a significant increase of 28% and 34% respectively, compared to T1. Gao Bao *et al.* (2012) also reported a significant difference was observed only between NT and NTS systems, which supports our result. The higher dry root weight density observed in no-tillage systems with residue mulching (NTS and NTSS) enhanced crop water and nutrient uptake, ultimately leading to improved yields. Including legumes in cropping systems without residue retention also did not improve RMD, which may be due to the rapid decomposition of legume biomass under bare-soil conditions, limiting sustained carbon inputs, microbial activity, and moisture conservation, resulting in root growth conditions comparable to those in residue retention systems. Gangwar *et al*. (2004) also found that the seeding method used in the preceding rice crop did not significantly affect the root dry weight of wheat. However, the highest average root dry weight was observed with direct seeding, followed by manual and mechanical transplanting. The meta-analysis by Ruis *et al.* (2024) showed that No-tillage significantly increased root biomass yield (RBY) in the 0-20 cm soil layer, while RBY was reduced in the 20-30 cm layer relative to tilled systems. Below a depth of 30 cm, NT effects on RBY were inconsistent. Across the full soil profile (≥50 cm), NT showed no significant effect on total RBY. Like RLD, NT-induced stratification of RBY was primarily observed relative to high-intensity tillage, whereas no stratification occurred under dry conditions, in warmer climates, or on medium-textured soils. In contrast, Singh *et al.* (2014) reported that wheat root biomass density not only at the surface but also up to a depth of 40 cm was significantly higher under zero tillage (ZT) than under conventional tillage (CT) across all sites. Maximum root density occurred in lighter-textured soils and declined with increasing soil fineness, a trend also observed under CT. Most roots were confined to a depth of 0.15 m under CT, whereas ZT promoted deeper rooting up to 0.25 m, enabling greater water and nutrient extraction. Surface residue retention and improved soil pore balance under ZT likely enhanced root proliferation and deeper root development (Bonfil *et al*., 1999). In the present study, T1 consistently recorded the lowest RMD among the CA treatments across both soil layers, with values comparable to the CT treatment. A similar trend was reported by Alam *et al.* (2017), who observed that zero tillage under wheat-fallow-rice conditions resulted in the lowest wheat RMD across all soil depths and study years. In the present study, T5 (the triple-cropping system including mungbean) recorded a significantly higher RMD (19%) than T1 (double-cropping system) at the 15-30 cm soil depth, whereas differences between the two treatments were non-significant in the 0-15 cm layer. A similar study by Alam *et al*. (2017) found that the highest RMD under WDT (wheat–dhaincha (Sesbania rostrata)–T. aman) and WMT (wheat–mungbean (Vigna radiata L. Wilczek)-T. aman) across soil depths of 0-150, 150-300, and 300-450 mm, attributed to the incorporation of dhaincha and mungbean biomass that enhanced surface soil organic matter and root growth. Consistent results have also been documented by Parker and Lear (1996), Varsa *et al.* (1998), and Hassan *et al.* (2005).

Root Diameter (RD)

At soil depths of 0-15 cm, CA treatments such as T6 showed the highest average root diameter, followed by T2 and T4, with significant increases of 47, 42, and 34% over CT (T7). It may be due to greater surface soil strength and mechanical impedance under zero tillage, which encourages roots to thicken as an adaptive response to penetrate compacted surface layers. Additionally, higher organic matter concentration and greater moisture availability near the soil surface, due to residue retention and legume inputs, may reduce the need for extensive fine-root proliferation, favouring thicker roots. In support, several studies have noted that roots tend to be thicker and have reduced surface area under no-tillage methods compared to conventional plough tillage (Barber, 1996; Karunatilake *et al.,* 2000). In contrast, Jat *et al*. (2017) examined the relationships among CA, root diameter, and water use efficiency in rice-wheat systems and found that under CA, roots tend to exhibit finer diameters, which are associated with increased surface area for nutrient absorption and water uptake. This finer root diameter contributes to enhanced drought tolerance and improved crop resilience in variable climatic conditions. Mondal *et al.* (2023) also reported that the average root diameter was slightly greater under conventional tillage than under conservation agriculture up to a soil depth of 30 cm. The double-cropping system with residue retention (T3) did not differ significantly from CT in terms of average root diameter. This finding is consistent with Mondal *et al.* (2019), who reported that root diameter remained unaffected by conservation agriculture compared with conventional tillage across different growth stages and soil depths, whereas in the following year (7^{th} and 8^{th} year), root diameter was 17% smaller in the 0-15 cm layer under CA. The higher soil strength below the plough layer led to the development of coarser roots (increased diameter) in spring maize (You *et al.,* 2017). Under CA treatments, brown manuring alone (T2) or with residue retention (T4) showed significant 74% and 64% increases in RD compared to T1, underscoring the importance of organic matter for root diameter. At soil depths of 15-30 cm, there was no significant difference between CA and CT, with roots prioritising elongation over thickening under physical constraints, resulting in comparable root diameters. The meta-analysis by Ruis *et al.* (2024) showed that No-tillage resulted in a significant increase in average root diameter within the 0-20 cm soil layer, but reduced root diameter at 20-30 cm depth compared with tilled systems. Below 30 cm, NT effects on root diameter were variable and inconsistent. These changes in root diameter under NT are likely associated with increased soil compaction at the tillage interface, influencing root thickening responses.

Root Surface Area Density (RSAD)

At soil depths of 0-15 cm, CA treatments like

T6 and T4 showed the highest RSAD values, followed by T2, with significant increases of 75, 75, and 62.5% over CT (T7). In ZT without residue retention, brown manuring (T2) showed a 62.5% higher RSAD, whereas brown manuring with residue retention (T4) had a significant 75% higher RSAD compared to T1. In the sub-surface soil layer, except for T1 and T2, the other CA treatments showed significantly higher values than CT, with the highest value of 0.11 cm^2/cm^3 in ZT, which had a triple-cropping system without residue retention (T5). In a similar study, Mondal *et al.* (2019) found that during initial period of CA at later growth stages, there is no significant difference in RSAD between CA and CT but in the following year, CA significantly increased RSAD (0.23 vs. 0.10 cm cm^{-3}) in the 15-30 cm layer compared with CT while a higher root surface area density (SAD) in the 0-15 cm soil layer was observed under CT-CT compared with the no-tillage treatment and difference was non-significant in 30-45 cm layer.

Root Volume Density (RVD)

In 0-15 cm of soil depth, CA treatments like T6 and T4 showed significantly higher values of RVD (28, 27%) compared to CT(T7), respectively. CA treatments like T1, T2, T3, and T5 showed significantly lower RVD values (i.e., 2.5, 10, 10.5, and 3%) compared to CT. At the sub-surface soil layer (15-30 cm), all CA treatments recorded significantly higher RVD than T7 (CT), with the highest RVD in T6, followed by T5, T4, T3 and T1. In contrast, Mondal *et al*. (2019) observed no significant differences in root volume density (RVD) among treatments in the surface layer, although CT-CT exhibited relatively higher RVD values in the plough layer (62-193%; P = 0.08). He also reported that, overall, the effects of tillage and residue management on RVD were not clearly distinguishable, indicating that root volume distribution was relatively insensitive to tillage practices compared with root length and surface area responses. In the triple cropping system, residue retention (T6) showed a significant 181% higher RVD value than T5 (triple cropping without residue retention). Similarly, in the double-cropping system, residue retention (T3) showed a significant 154% higher RVD than T1.

Brown manuring alone in ZT (T2) showed a significant increase in root parameters such as RMD, RSAD, and RD by 13.5, 62.5, and 69%, respectively, over T1 at the 0-15 cm soil depth, whereas T2 showed an 8% lower RVD compared to T2. At the same time, at a soil depth of 15-30 cm, only RVD showed a significant 27% higher T2 value than T1. In double cropping residue retention treatment(T3), only RMD had shown a significant increase in 0-15 cm and 15-30 cm soil depth over T1 by 9% and 28% respectively, whereas RSAD and RVD showed a significant increase (300, 145%) in 15-30 cm soil depth. In a similar study, Mondal *et al*. (2019) found that initially (at 45 DAS), CA showed higher RLD, RSAD, and RVD in the 15-30 cm and 30-45 cm soil layers compared to CT. However, as the stages progressed, these parameters became similar between CA and CT, except for the 30-45 cm layer, where all parameters were significantly higher in CA (with increases of 77, 73, and 83% in RLD, RSAD, and RVD, respectively, $p < 0.05$) due to a reduction in sub-surface compaction. It was further supported by Singh *et al.* (2014), who observed that under CT, most roots (approximately 96%) were concentrated within a soil depth of 0.15 meters. In contrast, ZT treatments were found to extend roots deeper, reaching depths of up to 0.25 meters. Some studies also showed that in the surface soil layer, CT slightly increased root length, surface area, and volume densities in wheat due to reduced soil strength. In contrast, in the sub-surface layer (>15 cm), where mechanical impedance is higher, CA significantly enhanced root length and surface area densities, with a marginal increase in root volume density. These improvements were attributed to surface residue retention and legume inclusion in the rice-wheat cropping system, which improved soil physical and hydrothermal conditions and promoted better root growth (Mondal *et al.,* 2019; Kumar *et al.,* 2018). Brown manuring, along with residue (T4), showed a significant increase in most root parameters compared with T1. The effect of the triple cropping system (T5) over the double cropping system (T1) was significant for RLD (71%) and RD (44%) at 0-15 cm, and for RVD, RMD, and RSAD at 15-30 cm, with the greatest influence on RVD (290%). The meta-analysis by Ruis *et al.* (2024) showed that, overall, NT tends to induce vertical stratification of

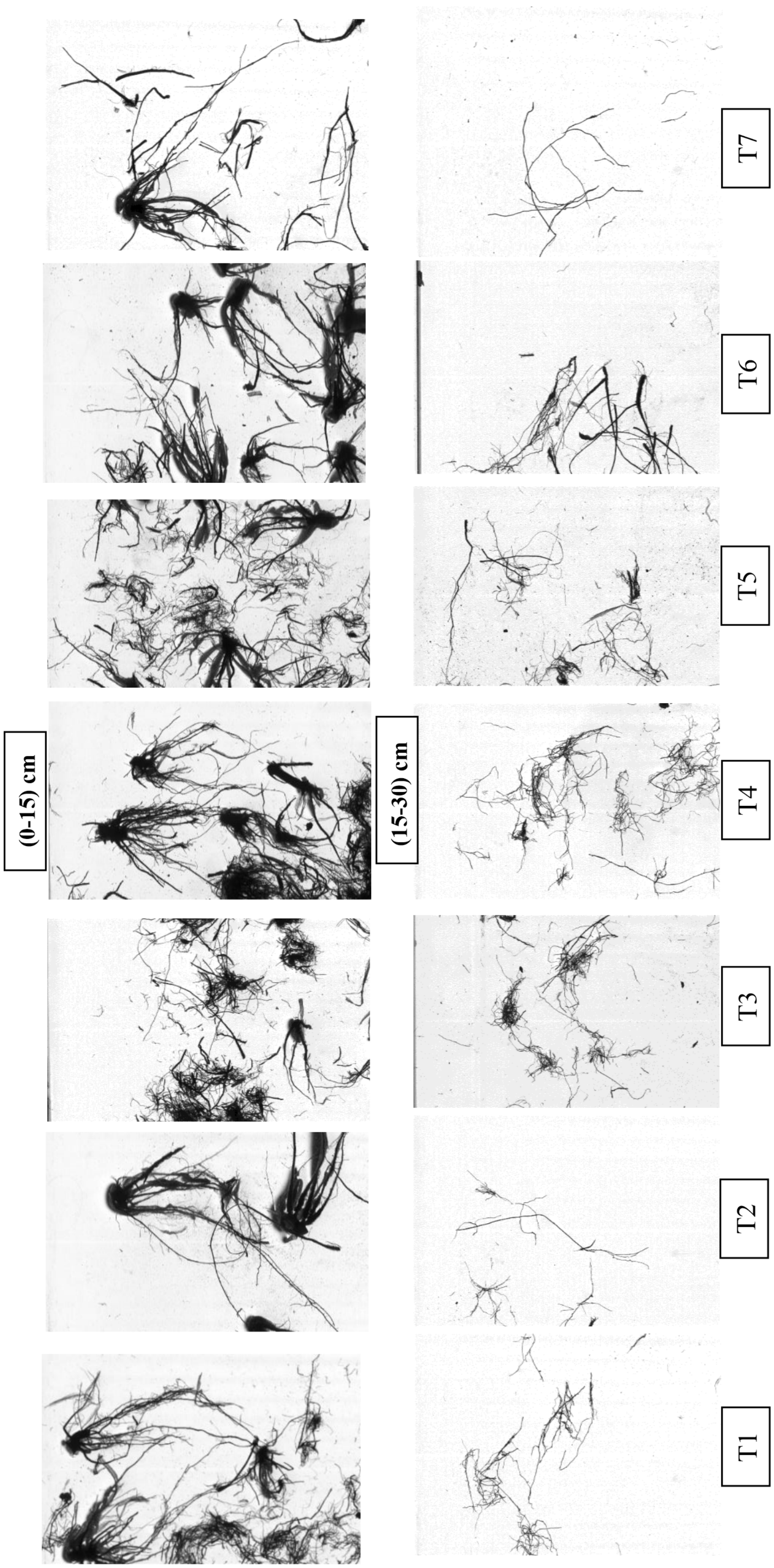


Fig. 3. Root morphology (from Win-RHIZO root scanner)

root traits, particularly RLD and RBY, relative to high-intensity tillage systems. However, across deeper soil profiles, NT does not significantly alter total root distribution, suggesting that NT mainly redistributes root traits within the soil profile rather than increasing total root growth.

Conclusion

The present study clearly indicated that long-term conservation agriculture (CA) practices substantially influence root system development in the rice-wheat-mungbean cropping system, with the magnitude of response depending on the degree of integration of CA components. Among all treatments, T6 (zero tillage + residue retention + legume inclusion) consistently exhibited superior root length density, root mass density, root surface area density, and root volume density, particularly in the 15-30 cm soil layer, demonstrating improved root penetration and proliferation. In contrast, zero tillage alone or legume inclusion without residue retention showed limited benefits, emphasizing that partial adoption of CA is insufficient to improve root traits.

The enhanced root growth under integrated CA systems can be attributed to improved soil aggregation, increased soil organic carbon, enhanced microbial activity, better soil moisture retention, and continuous biopore formation, which collectively reduced mechanical impedance and subsurface compaction (Singh *et al.,* 2014; Mondal *et al.,* 2019; Kumar *et al.,* 2018). Residue retention moderated soil temperature and moisture fluctuations, while legume inclusion contributed biologically fixed nitrogen and diversified root architectures, facilitating improved rhizosphere functioning (Alam *et al.,* 2017). The observed vertical stratification of root traits, with higher surface root concentration but improved subsurface rooting under CA, corroborates global meta-analyses reporting a redistribution rather than a net increase in roots under no-tillage systems (Mondal *et al.,* 2020; Ruis *et al.,* 2024). Variations in root diameter responses further suggest that root morphological adjustments under CA are context-specific, influenced by soil strength, residue cover, and nutrient availability (Barber, 1996; Jat *et al.,* 2017). Overall, the findings confirm that integrated CA practices, rather than individual components, are essential for improving root architecture, soil health, and long-term sustainability of intensive rice-wheat-based cropping systems, in agreement with earlier studies (Gathala *et al.,* 2020; Kassam *et al.,* 2020; Singh *et al.,* 2021).

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