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Effect of Tillage and Residue-based Conservation Agriculture Practices on Growth and Yield Attributes of Wheat-rice Cropping System in an Inceptisol

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Authors' contributions

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

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Abstract

The sustainability of the wheat–rice cropping system in the Indo-Gangetic Plains is constrained by intensive tillage, residue burning, and declining soil fertility. This study evaluated six tillage- and residue-based crop establishment practices, including mungbean integration, for their effects on the growth and yield attributes of rice and wheat in an Inceptisol. The field experiment used a randomised block design with six treatments and four replications. Plant height, greenness index, initial plant population, tiller density, spikes or panicles per square metre, spike or panicle length, grains per spike or panicle, and 1000-grain weight were assessed. Significant differences among crop establishment practices were observed for the measured growth and yield attributes. The conventional tillage treatment (CTPTR–CTW) generally recorded the lowest values, whereas ZTDSR–ZTW–ZTMB consistently produced the highest or among the highest values in both crops. At 90 DAS, CE6 recorded plant heights of 107.03 cm in wheat and 105.65 cm in rice. It also produced the highest wheat spike density (390.67 m^{-2}), rice panicle density (471.44

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m^{-2}), and 1000-grain weights of 40.90 g in wheat and 27.96 g in rice. The results indicate that combining zero tillage, residue retention, and mungbean integration can improve crop establishment, vegetative growth, and yield attributes within this wheat–rice system. These findings support the potential of the integrated conservation agriculture treatment for improving crop performance under the experimental conditions.

Keywords: Conservation agriculture; zero tillage; rice; wheat and mungbean; cropping system; tillage; Inceptisols.

1. Introduction

The wheat–rice cropping system is one of the most widely practised cereal production systems in South Asia, particularly across the Indo-Gangetic Plains, where it plays a vital role in ensuring food security and sustaining rural livelihoods (Ladha *et al*., 2009; Lal, 2015). Although this production system has contributed significantly to increasing food grain production, its long-term sustainability is under growing pressure. Continuous conventional tillage, burning of crop residues, excessive irrigation, and indiscriminate use of fertilisers have gradually degraded soil health. These practices have resulted in declining soil fertility, loss of soil organic carbon, reduced nutrient-use efficiency, and increasing production costs, raising concerns about the future sustainability of the system (Hobbs *et al*., 2008; Jat *et al*., 2020; Lal, 2015).

Conservation agriculture (CA) has emerged as a promising and sustainable alternative for improving crop production while protecting natural resources. The approach is built on three key principles: minimising soil disturbance, maintaining permanent soil cover through crop residue retention, and practising diversified crop rotations (Food and Agriculture Organization of the United Nations, 2022; Kassam *et al*., 2019). Together, these practices improve soil aggregation, enhance soil organic matter, conserve soil moisture, stimulate biological activity, and promote efficient nutrient cycling (Kassam *et al*., 2019). As a result, conservation agriculture contributes to higher productivity while strengthening the resilience of agricultural systems under changing environmental conditions (Lal, 2015).

Among the different management practices, tillage and residue management have a direct influence on crop establishment, soil health, and overall productivity. Conventional tillage often accelerates the breakdown of soil organic carbon, weakens soil aggregates, and increases moisture loss. In contrast, zero tillage helps maintain soil structure, improves water infiltration, encourages healthy root development, and creates favourable conditions for crop growth (Govaerts *et al*., 2009; Lal, 2015). Likewise, retaining crop residues on the soil surface protects the soil from temperature fluctuations, reduces evaporation, suppresses erosion, and provides an important source of organic matter for soil microorganisms. The inclusion of legumes such as mungbean further enhances system sustainability by fixing atmospheric nitrogen and improving nutrient recycling within the cropping system (Jat *et al*., 2020; Kassam *et al*., 2019).

Recent rice–wheat evidence further indicates that long-term combinations of zero or conventional tillage with residue management can influence soil properties and crop performance, supporting location-specific evaluation of these practices (Pabbu *et al*., 2025).

Growth parameters such as plant height, tiller number, crop greenness, and plant population are reliable indicators of crop health and the effectiveness of management practices. Under conservation agriculture, improved soil moisture availability, better nutrient supply, and enhanced root growth create favourable conditions for vigorous vegetative development and greater photosynthetic activity (Hobbs *et al*., 2008). This improved vegetative growth supports the formation of reproductive structures, leading to better yield attributes, including a higher number of productive spikes or panicles, greater spike or panicle length, more grains per spike or panicle, and increased thousand-grain weight. Since these characteristics are closely associated with final grain yield, they serve as valuable indicators for evaluating the performance of different tillage and residue management practices in the wheat–rice cropping system (Govaerts *et al*., 2009).

A recent field evaluation in eastern Uttar Pradesh also assessed wheat growth and yield attributes under zero-tillage establishment, providing contemporary regional context for interpreting crop performance under this management approach (Karada *et al*., 2025). Several studies conducted under wheat–rice production systems have demonstrated that zero tillage combined with crop residue retention significantly improves crop establishment, increases tiller density, enhances chlorophyll content, strengthens root growth, and ultimately increases grain yield compared with conventional tillage systems. Long-term adoption of conservation agriculture also improves soil organic carbon, aggregate stability, water-use efficiency, and nutrient-use efficiency, thereby sustaining crop productivity while reducing production costs and minimizing environmental impacts (Jat *et al*., 2020; Kassam *et al*., 2019).

Long-term studies from the Indo-Gangetic Plains further show that conservation-oriented crop establishment, reduced or zero tillage, and residue management can affect soil carbon, soil quality, system productivity, and environmental performance in rice–wheat-based systems (Fagodiya *et al*., 2024; Gora *et al*., 2024; Fagodiya *et al*., 2025).

Inceptisols occupy a substantial proportion of cultivated land in the Indo-Gangetic Plains and are characterised by moderate soil development, relatively low organic carbon content, and variable nutrient availability. Continuous intensive cultivation under conventional management often accelerates soil degradation. Therefore, evaluating the influence of tillage and residue-based conservation agriculture practices on crop growth and yield attributes in Inceptisols is essential for developing sustainable management strategies that improve soil health and enhance the productivity of wheat–rice cropping systems (Saurabh *et al*., 2021).

The specific comparative question addressed in this study is the extent to which contrasting combinations of conventional or zero tillage, residue management, and mungbean integration differ in their effects on crop establishment, vegetative growth, and yield attributes of both wheat and rice in an Inceptisol. This treatment-level comparison is required within the present experimental context because the six crop establishment practices combine these management components in distinct ways.

The present investigation was undertaken to assess the effects of different tillage and residue-based conservation agriculture practices, including the integration of mungbean, on the growth and yield attributes of wheat and rice grown in an Inceptisol. The findings are expected to provide scientific evidence for promoting sustainable crop management practices that improve productivity, resource-use efficiency, and long-term soil health in cereal-based production systems.

2. Materials and Methods

2.1 Experimental Site

During the Kharif seasons of 2023 and 2024, a field experiment was conducted at the Agricultural Research Farm of the Institute of Agricultural Sciences, Banaras Hindu University, located in Varanasi, India. The investigation used the same experimental plot throughout. The soil at this location was identified as sandy clay loam, featuring effective drainage and moderate fertility levels. Initial soil analysis revealed that the available nitrogen and phosphorus were low, whereas the potassium content was moderate.

2.2 Experimental Setup

The experiment was set up using a Randomised Block Design (RBD) that included six crop establishment methods (CEMs), each replicated four times. The treatments were as follows: CE1 involved conventional till puddled transplanted rice followed by conventional till wheat [CTPTR–CTW (without retaining or incorporating residues)]; CE2 included conventional till puddled transplanted rice, conventional till wheat, and conventional till mungbean [CTPTR–CTW–CTMB (with full incorporation of mungbean residues)]; CE3 consisted of conventional till direct-seeded rice and zero till wheat [CTDSR–ZTW (with retention of anchored rice residues)]; CE4 comprised conventional till direct-seeded rice, zero till wheat, and zero till mungbean [CTDSR–ZTW–ZTMB (retaining anchored rice residues and fully incorporating mungbean residues)]; CE5 involved zero till direct-seeded rice and zero till wheat [ZTDSR–ZTW (retaining anchored rice and wheat residues)]; and CE6 included zero till direct-seeded rice, zero till wheat, and zero till mungbean [ZTDSR–ZTW–ZTMB (retaining anchored rice and wheat residues with complete incorporation of mungbean residues)]. The field was prepared based on the tillage needs specific to each treatment. The rice variety 'Sarjoo 52' was cultivated across all treatments with a row spacing of 20 cm and a seeding rate of 30 kg ha^{-1}. For the puddled-transplanted treatments (CE1 and CE2), the field was subjected to both dry and wet tillage, followed by puddling, before transplanting seedlings that were 27 days old. To maintain a consistent physiological crop age among all crop establishment methods, the nursery sowing for transplanted rice was aligned with the direct seeding date used in the DSR treatments (CE3–CE6).

In the conventional direct-seeded rice treatments (CE3 and CE4), the seedbed was prepared by making two passes with a tractor-operated cultivator, followed by levelling with a plank. In contrast, the zero-till direct-seeded treatments (CE5 and CE6) were set up without any prior soil disturbance, using a tractor-mounted zero-till seed-cum-fertiliser drill. Weed control in these treatments involved applying glyphosate at a rate of 1 kg ha^{-1} before sowing, as needed. To ensure the soil had enough moisture, irrigation was applied before sowing, and further watering was scheduled based on crop water requirements throughout the growing season.

2.3 Statistical Analysis

The study data were examined using SPSS 16.0 for ANOVA (full randomised design). Duncan's multiple range test (DMRT) at a significance level of $p \leq 0.05$ was employed to assess whether mean values differed significantly.

3. Results And Discussion

3.1 Growth Parameters

The plant height of both wheat and rice was significantly influenced by tillage and residue-based conservation agriculture (CA) practices at all growth stages (Table 1). In wheat, plant height progressively increased from 30 to 90 DAS under all treatments, reflecting normal crop development. At 30 DAS, the tallest plants were recorded under CE6 (ZTDSR–ZTW–ZTMB) (44.29 cm), which was significantly superior to all other treatments, whereas the shortest plants were observed under the conventional tillage practice CE1 (CTPTR–CTW) (37.03 cm). At 60 DAS, CE6 again produced the maximum plant height (85.27 cm), followed by CE4 (82.73 cm), whereas CE1 recorded the lowest value (75.97 cm). At crop maturity (90 DAS), wheat grown under CE6 attained the greatest plant height (107.03 cm), followed by CE4 (102.57 cm) and CE5 (102.45 cm) treatments. Conventional tillage treatments (CE1, CE2, and CE3) produced significantly shorter plants than zero tillage-based conservation agriculture treatments.

Rice showed the same response pattern as wheat under different conservation agriculture practices. At 30 DAS, plant height varied from 26.75 cm in CE1 to 35.16 cm in CE6, indicating better early crop establishment under treatments involving zero tillage and residue retention. By 60 DAS, the maximum plant height was recorded in CE6 (79.42 cm), which was statistically comparable to CE4 (77.75 cm) and CE5 (78.48 cm), while CE1 produced the shortest plants (72.50 cm). This trend continued at 90 DAS, with CE6 recording the tallest plants (105.65 cm), followed by CE5 (104.19 cm), whereas CE1 consistently showed the lowest plant height (94.04 cm). These findings suggest that crop establishment practices combining zero tillage, direct-seeded rice, residue retention, and mungbean integration promoted better vegetative growth than the conventional tillage system.

The greater plant height observed under conservation agriculture is likely a result of the improved soil environment created by reduced tillage and crop residue retention. Leaving residues on the soil surface helps maintain soil moisture by limiting evaporation and buffering fluctuations in soil temperature, thereby creating favourable conditions for seedling establishment and crop growth. Reduced soil disturbance also preserves soil structure, allowing better root proliferation and more efficient uptake of water and nutrients. The combined effect of improved moisture conservation, enhanced nutrient availability, and healthier root development supports continuous vegetative growth and greater cell expansion, which ultimately contributes to taller plants. These findings suggest that conservation agriculture provides conditions that are more conducive to plant growth than conventional tillage, leading to improved crop performance (Kaduwal *et al*., 2023; Yuan *et al*., 2023).

The inclusion of mungbean in the cropping sequence further enhanced plant growth by contributing biologically fixed nitrogen and nutrient-rich organic residues to the soil. As the mungbean biomass decomposed, it released nitrogen and other essential nutrients, stimulated soil microbial activity, and improved nutrient cycling. The greater availability of nitrogen supported chlorophyll synthesis, protein formation, and photosynthetic activity, resulting in increased biomass production and improved vegetative growth. These positive effects were most evident under CE6, where the combined benefits of zero tillage, crop residue retention, and mungbean integration created favourable conditions for crop growth, leading to the maximum plant height in both wheat and rice (Banik & Sengupta, 2013).

The lower plant height observed under conventional tillage may be attributed to the repeated disturbance of the soil, which accelerates the breakdown of soil organic matter and weakens soil structural stability. Continuous tillage disrupts soil aggregates, increases moisture loss, and suppresses soil biological activity, leading to reduced nutrient availability and poor root development. These unfavourable soil conditions limit the efficient uptake of water and nutrients, resulting in reduced vegetative growth and shorter plants compared with those grown under conservation agriculture practices (Shweta *et al*., 2021).

The steady increase in plant height from 30 to 90 DAS in both wheat and rice indicates continuous vegetative development and efficient utilisation of soil resources under conservation agriculture. Greater plant height under zero tillage-based treatments suggests improved crop establishment and favourable growing conditions throughout the crop cycle, which can ultimately contribute to higher biomass production and grain yield. These results are consistent with previous long-term studies on wheat–rice cropping systems, which have shown that reduced tillage and crop residue retention improve crop growth by enhancing soil health, conserving moisture, and increasing resource-use efficiency (Kumar *et al*., 2022; Kumari *et al*., 2026).

The present findings are consistent with those of Hobbs *et al*. (2008), who reported that conservation agriculture improves soil moisture conservation, nutrient availability, and crop growth through reduced soil disturbance and permanent residue cover. Govaerts *et al*. (2009) also observed greater plant height and biomass production under zero tillage than under conventional tillage, owing to improved soil physical conditions and root development. Jat *et al*. (2020) demonstrated that conservation agriculture-based wheat–rice systems in the Indo-Gangetic Plains enhance crop growth by improving soil organic carbon, nutrient availability, and water-use efficiency. Similarly, Kassam *et al*. (2019) emphasised that minimum tillage and residue retention promote sustainable crop growth by maintaining favourable soil conditions throughout the cropping cycle. Lal (2015) further highlighted that improvements in soil quality and organic carbon under conservation agriculture enhance crop vigour and productivity by supporting efficient nutrient cycling and root activity.

3.2 Greenness Index

The greenness index of both wheat and rice was significantly influenced by tillage and residue-based conservation agriculture (CA) practices at different crop growth stages (Table 2). In wheat, the greenness index increased progressively from 30 to 90 DAS under all treatments, indicating enhanced canopy development and chlorophyll accumulation during crop growth. At 30 DAS, the highest greenness index was recorded under CE6 (ZTDSR–ZTW–ZTMB) (39.04), which was statistically at par with CE5 (ZTDSR–ZTW) (38.88), whereas CE2 (CTPTR–CTW–CTMB) (36.48) and CE3 (CTDSR–ZTW) (36.28) recorded comparatively lower values. At 60 DAS, CE5 produced the maximum greenness index (40.97), followed by CE4 (39.58) and CE6 (39.36), whereas CE3 recorded the lowest value (36.99). At 90 DAS, CE5 maintained the highest greenness index (44.39), although it remained statistically at par with CE2, CE3, CE4, and CE6. Conventional tillage treatment (CE1) consistently exhibited the lowest greenness index throughout the wheat-growing period.

Rice exhibited a response similar to wheat under different crop establishment practices. At 30 DAS, the highest greenness index was recorded in CE6 (39.60), followed by CE5 (38.14), while the lowest value was observed in CE2 (35.67). A similar trend was evident at 60 DAS, where CE6 registered the maximum greenness index (45.06), significantly outperforming the conventional tillage treatments. By 90 DAS, CE6 continued to record the highest greenness index (37.77), although its values were statistically comparable with those of CE1, CE3, and CE4. Overall, conservation agriculture practices based on zero tillage consistently maintained higher canopy greenness than conventional tillage, with the greatest improvement observed when zero tillage was combined with residue retention and mungbean integration (CE6). These findings indicate that conservation agriculture supports healthier crop canopies and sustained photosynthetic activity throughout the growing season. (Dudwal *et al*., 2023; Bhargaw *et al*., 2023).

The higher greenness index observed under zero tillage with residue retention is likely due to the improved soil environment created by conservation agriculture practices. Retained crop residues increase soil organic carbon, conserve moisture, regulate soil temperature, and promote microbial activity, all of which improve nutrient availability throughout the crop growth period. Better nitrogen availability supports chlorophyll synthesis, resulting in greener leaves and enhanced photosynthetic efficiency. Since the greenness index is closely related to leaf chlorophyll content and the nitrogen status of plants, the higher values observed under CE5 and CE6 reflect healthier crop canopies with greater photosynthetic capacity and improved overall crop vigour. (Hamdy *et al*., 2016; Kaduwal *et al*., 2023; Kumari *et al*., 2026).

Table 1. Effect of tillage and residue-based conservation agriculture practices on plant hight of wheat rice cropping system in an Inceptisol

Treatments	Plant height (cm) of wheat			Plant height (cm) of rice		
	30 DAS	**60 DAS**	**90 DAS**	**30 DAS**	**60 DAS**	**90 DAS**
CE1: CTPTR-CTW	37.03 ± 0.86d	75.97 ± 1.15c	96.2 ± 1.11c	26.75 ± 0.84d	72.5 ± 0.84c	94.04 ± 1.95c
CE2: CTPTR-CTW-CTMB	39.49 ± 0.55c	79.1 ± 0.82b	98.11 ± 0.93c	28 ± 0.18cd	74.57 ± 0.86bc	96.92 ± 0.48c
CE3: CTDSR-ZTW	41.54 ± 0.35bc	78.89 ± 1.23b	97.72 ± 1.7c	29.44 ± 0.06c	74.88 ± 1.08bc	102.14 ± 0.45b
CE4: CTDSR-ZTW-ZTMB	42.29 ± 1.46ab	82.73 ± 0.88a	102.57 ± 2.7b	33.48 ± 0.78b	77.75 ± 1.42a	102.27 ± 0.64b
CE5: ZTDSR-ZTW	43.11 ± 1.28ab	79.09 ± 1.1b	102.45 ± 1.23b	34.86 ± 0.97ab	78.48 ± 0.57a	104.19 ± 0.86ab
CE6: ZTDSR-ZTW-ZTMB	44.29 ± 0.77a	85.27 ± 1.53a	107.03 ± 1.02a	35.16 ± 0.52a	79.42 ± 0.48a	105.65 ± 2.38a

*Abbreviations: CTPTR, conventional till puddled transplanted rice; CT, conventional till; DSR, direct-seeded rice; ZT, zero till; R, rice; W, wheat; MB, mungbean; CA, conservation agriculture. **Values are expressed as mean ± standard deviation (SD) (n = 4). Means within the same column followed by different lowercase letters differ significantly according to Duncan's Multiple Range Test (DMRT) after one-way analysis of variance (ANOVA) at P ≤ 0.05*

Table 2. Effect of tillage and residue-based conservation agriculture practices on Greenness Index of wheat-rice cropping system in an Inceptisol

Treatments	Greenness Index of wheat			Greenness Index of rice		
	30 DAS	**60 DAS**	**90 DAS**	**30 DAS**	**60 DAS**	**90 DAS**
CE1: CTPTR-CTW	30 DAS	60 DAS	90 DAS	36.12 ± 0.16cd	43.08 ± 0.98b	37.73 ± 0.69a
CE2: CTPTR-CTW-CTMB	36.48 ± 1.25c	38.19 ± 0.53de	43.32 ± 1.35b	35.67 ± 0.37d	43.12 ± 0.47b	35.96 ± 0.62b
CE3: CTDSR-ZTW	36.28 ± 0.58c	36.99 ± 0.84e	43.54 ± 0.66b	36.47 ± 0.99bcd	43.39 ± 0.79b	37.45 ± 0.56a
CE4: CTDSR-ZTW-ZTMB	37.62 ± 0.34bc	39.58 ± 0.14c	42.7 ± 1b	37.71 ± 0.19bc	43.78 ± 0.35ab	37.39 ± 0.49a
CE5: ZTDSR-ZTW	38.88 ± 0.27ab	40.97 ± 0.4b	44.39 ± 0.85b	38.14 ± 1.14ab	44.01 ± 0.82ab	37.21 ± 0.46ab
CE6: ZTDSR-ZTW-ZTMB	39.04 ± 0.42ab	39.36 ± 0.94cd	43.52 ± 0.45b	39.6 ± 1.14a	45.06 ± 0.29a	37.77 ± 0.52a

*Abbreviations: CTPTR, conventional till puddled transplanted rice; CT, conventional till; DSR, direct-seeded rice; ZT, zero till; R, rice; W, wheat; MB, mungbean; CA, conservation agriculture. **Values are expressed as mean ± standard deviation (SD) (n = 4). Means within the same column followed by different lowercase letters differ significantly according to Duncan's Multiple Range Test (DMRT) after one-way analysis of variance (ANOVA) at P ≤ 0.05*

The inclusion of mungbean in the cropping sequence further contributed to improved greenness by supplying biologically fixed nitrogen and increasing the recycling of crop nutrients. Legume residues generally possess lower carbon-to-nitrogen ratios, which facilitates rapid decomposition and nutrient release. Consequently, wheat and rice grown after mungbean experienced improved nitrogen nutrition, resulting in increased chlorophyll accumulation and prolonged leaf greenness. Similar beneficial effects of legume integration in conservation agriculture have been reported for cereal-based cropping systems, where biological nitrogen fixation (BNF) improves crop productivity and nutrient-use efficiency. (Ahmad *et al*., 2001; Ilyas *et al*., 2018).

The gradual increase in the greenness index from 30 DAS to 60 DAS reflected the active vegetative growth phase, characterised by rapid leaf expansion and maximum chlorophyll synthesis. The slight decline at 90 DAS, particularly in rice, corresponded to the onset of reproductive growth and natural leaf senescence. However, conservation agriculture treatments maintained relatively higher greenness even during later growth stages, indicating delayed senescence and prolonged photosynthetic activity. Delayed leaf senescence contributes to sustained assimilate production during grain filling, ultimately supporting higher biomass accumulation and crop productivity.

The lower greenness index observed under conventional tillage is likely a consequence of repeated soil disturbance, which accelerates the loss of soil organic matter, weakens soil structure, and increases moisture loss through evaporation. These conditions reduce nutrient availability and limit root growth, ultimately restricting chlorophyll synthesis and canopy development. In contrast, zero tillage helps maintain soil structure, improves water infiltration, and supports better root growth, allowing crops to utilise water and nutrients more efficiently. As a result, plants grown under conservation agriculture maintained higher canopy greenness throughout the growing period (Prakash *et al*., 2019).

The results of the present study are consistent with earlier findings showing that conservation agriculture improves canopy greenness, chlorophyll content, and photosynthetic efficiency by creating a more favourable soil environment. Improved soil moisture conservation, enhanced nutrient availability, and better resource-use efficiency under conservation agriculture promote healthier crop canopies and sustained physiological activity throughout the growing season, ultimately supporting higher crop productivity. Hobbs *et al*. (2008) and Govaerts *et al*. (2009) reported greater chlorophyll content and improved crop growth under zero tillage with residue retention than under conventional tillage. Similarly, Jat *et al*. (2020) observed that conservation agriculture-based wheat–rice systems in the Indo-Gangetic Plains significantly improved crop vigour, nutrient uptake, and vegetation indices owing to improved soil quality. Kassam *et al*. (2019) reported that permanent residue cover and minimum soil disturbance enhance photosynthetic activity, delay leaf senescence, and increase productivity in cereal-based cropping systems. Lal (2015) also highlighted that improvements in soil organic carbon and biological activity under conservation agriculture enhance nutrient cycling, resulting in greater crop greenness and sustainable production.

3.3 Number of Tillers

The number of tillers per square metre in both wheat and rice was significantly affected by tillage and residue-based conservation agriculture (CA) practices throughout the crop growth period (Table 3). In wheat, tiller density increased from 30 to 90 DAS under all treatments, although the magnitude of the increase varied considerably among the tillage systems. At 30 DAS, the highest number of tillers was recorded under CE6 (ZTDSR–ZTW–ZTMB) (70.02 m^{-2}), which was significantly superior to all other treatments, followed by CE5 (ZTDSR–ZTW) (66.52 m ^{2}). The lowest tiller density was observed under the conventional tillage treatment CE1 (CTPTR–CTW) (52.58 m^{-2}), which remained statistically similar to that of CE2 and CE3. At 60 DAS, CE6 again produced the maximum number of tillers (100.18 m^{-2}), significantly exceeding all other treatments, whereas CE1 recorded the lowest value (92.62 m ^{2}). At 90 DAS, CE6 recorded the highest tiller population (103.30 m^{-2}), which was statistically comparable to CE4 (102.77 m^{-2}), whereas the lowest tiller population was observed under CE1 (92.76 m^{-2}). The greater tiller production under conservation agriculture treatments suggests that zero tillage, together with mungbean integration, provided more favourable conditions for crop establishment and vegetative growth. Overall, these findings indicate that conservation agriculture practices support sustained tillering in wheat throughout the growing season compared with conventional tillage.

Rice exhibited a response pattern similar to wheat under different crop establishment practices. At 30 DAS, CE6 recorded the highest tiller density (188.70 m^{-2}), followed by CE5 (185.92 m^{-2}), while the lowest tiller density was observed under the conventional tillage treatment, CE1 (160.85 m^{-2}). The advantage of conservation agriculture became more evident as the crop progressed. At 60 DAS, CE6 produced the maximum tiller density (445.62 m^{-2}), significantly exceeding all other treatments, whereas CE1 recorded the minimum value (336.67 m^{-2}). A similar trend continued at 90 DAS, with CE6 maintaining the highest tiller density (456.31 m^{-2}), followed by CE5 (441.62 m^{-2}) and CE4 (423.33 m^{-2}), while CE1 consistently recorded the lowest number of tillers (355.95 m^{-2}). These results indicate that conservation agriculture practices, particularly the combination of zero tillage, crop residue retention, and mungbean integration, created favourable conditions for tiller development, resulting in consistently greater tiller production in rice compared with the conventional tillage system. Wheat tiller density was significantly influenced by residue management, and the highest tiller density and grain yield were recorded under zero tillage with rice residue retention (Sraw *et al*., 2025).

The higher tiller production observed under conservation agriculture is likely due to the improved soil conditions created by reduced soil disturbance, residue retention, and enhanced nutrient cycling. Zero tillage helps maintain soil structure, improves aggregate stability, and promotes better root growth, enabling crops to utilise soil moisture and nutrients more efficiently. Crop residue retention conserves soil moisture, moderates soil temperature, and increases soil organic carbon, which supports microbial activity and ensures a steady release of nutrients during crop growth. Together, these factors provide a favourable environment for early crop establishment, stimulate tiller initiation, and improve tiller survival, ultimately resulting in greater tiller density under conservation agriculture than under conventional tillage (Saurabh *et al*., 2021; Sraw *et al*., 2025).

The inclusion of mungbean in the cropping sequence further promoted tiller production by enriching the soil with biologically fixed nitrogen and readily decomposable organic residues. As these residues decomposed, they released nitrogen and other essential nutrients that supported chlorophyll synthesis, leaf expansion, and photosynthetic activity. Improved nutrient availability and greater photosynthate production provided favourable conditions for the initiation and survival of productive tillers. In addition, enhanced microbial activity associated with legume residues improved nutrient cycling, particularly the availability of nitrogen and phosphorus, both of which are critical for tiller development. As a result, CE6 consistently recorded the highest tiller density in both wheat and rice, demonstrating the combined benefits of zero tillage, residue retention, and mungbean integration in promoting crop growth (Reddy *et al*., 2024).

The lower tiller population recorded under conventional tillage is likely a consequence of repeated soil disturbance, which accelerates the loss of soil organic matter and reduces the soil's ability to retain moisture. Continuous tillage disrupts soil structure, weakens soil biological activity, and limits the availability of essential nutrients during the vegetative stage. These unfavourable conditions restrict root development and reduce the initiation and survival of tillers, ultimately resulting in lower plant populations and reduced yield potential compared with conservation agriculture practices. The marked differences between conservation agriculture and conventional tillage treatments became increasingly evident during the later growth stages, suggesting that the long-term benefits of improved soil health under conservation agriculture are particularly important for sustaining the development of tillers (Laxman *et al*., 2024).

The present findings are consistent with earlier studies demonstrating that conservation agriculture significantly enhances tillering through improvements in soil moisture conservation, nutrient availability, and root development. Hobbs *et al*. (2008) reported that conservation agriculture promotes vigorous crop establishment and increases productive tillers by maintaining favourable soil physical conditions. Govaerts *et al*. (2009) observed significantly greater tiller density and biomass production under zero tillage with residue retention than under conventional tillage. Similarly, Jat *et al*. (2020) documented increased tiller production and improved crop performance in wheat–rice systems of the Indo-Gangetic Plains owing to enhanced soil organic carbon and resource-use efficiency under conservation agriculture. Kassam *et al*. (2019) also emphasised that residue retention and minimum soil disturbance improve crop establishment and sustain vegetative growth by conserving soil moisture and promoting efficient nutrient cycling, respectively. Lal (2015) further highlighted that improved soil health under conservation agriculture supports higher crop productivity through enhanced biological activity and efficient nutrient dynamics.

3.4 Initial Plant Population

The initial plant population of both wheat and rice was significantly affected by different tillage and residue management practices under conservation agriculture (Table 4). Clear differences in crop establishment among the treatments indicate that tillage practices and residue retention play a crucial role in seedling emergence and stand establishment. The highest initial plant population was recorded under CE6 (ZTDSR–ZTW–ZTMB), with 167.55 plants m^{-2}, followed by CE5 (ZTDSR–ZTW), which recorded 150.42 plants m^{-2}. Intermediate plant populations were observed under CE3 (CTDSR–ZTW) (140.66 plants m^{-2}) and CE4 (CTDSR–ZTW–ZTMB) (140.16 plants m^{-2}), with no significant difference between these treatments. In contrast, the conventional tillage treatments, CE1 (CTPTR–CTW) and CE2 (CTPTR–CTW–CTMB), recorded the lowest plant populations, with 124.08 and 127.27 plants m^{-2}, respectively. A similar trend was observed in both wheat and rice, indicating that conservation agriculture practices consistently improved crop establishment across the wheat–rice cropping system.

The higher initial plant population observed under zero tillage-based conservation agriculture is likely the result of improved soil conditions that promote rapid and uniform seed germination. Reduced soil disturbance helps maintain soil structure, preserve aggregate stability, and improve soil porosity, ensuring better seed-to-soil contact and facilitating the movement of water to germinating seeds. In addition, crop residue retention conserves soil moisture, moderates soil temperature, and minimises surface crust formation, creating favourable conditions for seedling emergence and early crop establishment. Together, these improvements provide a more suitable environment for crop establishment, which explains the superior plant stand recorded under the CE5 and CE6 treatments.

The inclusion of mungbean in the cropping sequence further improved crop establishment under CE6. Owing to their relatively low carbon-to-nitrogen ratio, mungbean residues decompose quickly and release nutrients in a readily available form, thereby stimulating soil microbial activity and enhancing soil fertility. Increased microbial activity also promotes the formation of stable soil aggregates, creating a more favourable environment for seed germination and early seedling growth. As a result, the combination of zero tillage and mungbean residue retention produced the highest initial plant population, demonstrating the complementary benefits of conservation agriculture and legume integration for improving crop establishment.

In contrast, the lower initial plant population recorded under conventional tillage may be attributed to repeated soil disturbance and the gradual deterioration of surface soil conditions. Frequent tillage disrupts soil aggregates, accelerates the decomposition of soil organic matter, and increases moisture loss from the seed zone, creating less favourable conditions for seed germination and seedling establishment. These changes can reduce germination efficiency and seedling survival, ultimately leading to poor crop establishment and lower yield potential. Moreover, puddling in transplanted rice systems can adversely affect the physical condition of the soil by increasing compaction and reducing porosity, which restricts root penetration and hampers the early growth of the succeeding wheat crop.

Table 3. Effect of tillage and residue-based conservation agriculture practices on No of tillers per meter square of wheat-rice cropping system in an Inceptisol

Treatments	No of tillers per meter square of wheat			No of tillers per meter square of rice		
	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS
CE1: CTPTR-CTW	52.58 ± 0.5d	92.62 ± 0.56b	92.76 ± 0.99c	160.85 ± 2.81d	336.67 ± 3.44e	355.95 ± 1.8f
CE2: CTPTR-CTW-CTMB	54.48 ± 1.07d	92.67 ± 1.42b	94.82 ± 0.76c	167.15 ± 3.61c	385.69 ± 9.68d	376.14 ± 3.43e
CE3: CTDSR-ZTW	55.08 ± 1.39d	94.52 ± 0.99b	98.46 ± 1.57b	174.3 ± 0.79b	393.73 ± 4.8cd	399.92 ± 2.16d
CE4: CTDSR-ZTW-ZTMB	62.53 ± 0.71c	95.36 ± 0.88b	102.77 ± 1.59a	176.41 ± 1.7b	399.09 ± 6.12cd	423.33 ± 2.73c
CE5: ZTDSR-ZTW	66.52 ± 1.32b	95.56 ± 2.26b	99.19 ± 1.7b	185.92 ± 2.12a	422.52 ± 3.06b	441.62 ± 2.91b
CE6: ZTDSR-ZTW-ZTMB	70.02 ± 1.38a	100.18 ± 2.78a	103.3 ± 0.95a	188.7 ± 2.83a	445.62 ± 1.84a	456.31 ± 2.4a

*Abbreviations: CTPTR, conventional till puddled transplanted rice; CT, conventional till; DSR, direct-seeded rice; ZT, zero till; R, rice; W, wheat; MB, mungbean; CA, conservation agriculture. **Values are expressed as mean ± standard deviation (SD) (n = 4). Means within the same column followed by different lowercase letters differ significantly according to Duncan's Multiple Range Test (DMRT) after one-way analysis of variance (ANOVA) at P ≤ 0.05*

Table 4. Effect of tillage and residue-based conservation agriculture practices on Initial plant population (no. per meter square) of wheat-rice cropping system in an Inceptisol

Treatments	Initial plant population (no. per meter square) of wheat	Initial plant population (no. per meter square) of rice
CE1: CTPTR-CTW	124.08 ± 2.09d	124.08 ± 2.09d
CE2: CTPTR-CTW-CTMB	127.27 ± 2.63d	127.27 ± 2.63d
CE3: CTDSR-ZTW	140.66 ± 1.29c	140.66 ± 1.29c
CE4: CTDSR-ZTW-ZTMB	140.16 ± 1.48c	140.16 ± 1.48c
CE5: ZTDSR-ZTW	150.42 ± 3.55b	150.42 ± 3.55b
CE6: ZTDSR-ZTW-ZTMB	167.55 ± 3.49a	167.55 ± 3.49a

*Abbreviations: CTPTR, conventional till puddled transplanted rice; CT, conventional till; DSR, direct-seeded rice; ZT, zero till; R, rice; W, wheat; MB, mungbean; CA, conservation agriculture. **Values are expressed as mean ± standard deviation (SD) (n = 4). Means within the same column followed by different lowercase letters differ significantly according to Duncan's Multiple Range Test (DMRT) after one-way analysis of variance (ANOVA) at P ≤ 0.05*

Uniform crop establishment is essential for achieving higher productivity in cereal-based cropping systems, as it ensures an optimum plant population and enables more efficient use of water, nutrients, and other available resources. A well-established crop stand also provides a strong foundation for improved tiller development and sustained crop growth throughout the season. Therefore, the higher initial plant population observed under conservation agriculture treatments is likely to contribute to greater biomass production and improved grain yield. These findings highlight that the combined use of zero tillage, crop residue retention, and mungbean integration not only enhances crop establishment but also supports long-term soil health and the sustainability of the wheat–rice cropping system.

The present results agree well with earlier reports demonstrating the beneficial effects of conservation agriculture on crop establishment. Hobbs *et al*. (2008) reported that minimum soil disturbance and residue retention improve seedling emergence by conserving soil moisture and maintaining favourable seedbed conditions. Govaerts *et al*. (2009) observed significantly better crop establishment under zero tillage than under conventional tillage because of improved soil structure and enhanced water availability. Jat *et al*. (2020) also reported that conservation agriculture practices in the Indo-Gangetic Plains significantly increased plant population and early crop vigour through improvements in soil physical quality and resource-use efficiency. Kassam *et al*. (2019) emphasised that residue retention and reduced tillage create favourable microclimatic conditions for seed germination and early plant growth in wheat. Similarly, Lal (2015) concluded that improvements in soil organic carbon and soil biological activity under conservation agriculture enhance seedling establishment and sustain crop productivity over the long term.

3.5 Yield Component

The yield attributes of both wheat and rice were significantly influenced by tillage and residue-based conservation agriculture (CA) practices (Table 5). The integration of zero tillage, residue retention, and mungbean into the wheat–rice cropping system consistently improved all measured yield components compared with conventional tillage practices.

In wheat, the number of spikes per square metre varied significantly among the treatments, ranging from 346.26 m^{-2} under CE1 (CTPTR–CTW) to 390.67 m^{-2} under CE6 (ZTDSR–ZTW–ZTMB). The highest spike density recorded under CE6 was significantly superior to the conventional tillage treatment and was closely followed by CE4 (381.80 m^{-2}) and CE5 (378.84 m^{-2}). Spike length also increased markedly under conservation agriculture, with the longest spikes observed in CE6 (12.10 cm), whereas the shortest spikes were recorded under CE1 (9.40 cm). Similarly, the number of grains per spike was highest under CE6 (57.53), remaining statistically at par with CE4 (54.92), while the lowest number of grains per spike was observed in CE1 (43.14). Thousand-grain weight also followed a similar trend, with CE6 recording the highest value (40.90 g), followed closely by CE5 (40.49 g) and CE4 (40.07 g), whereas CE1 produced the lowest test weight (37.90 g).

Rice exhibited comparable improvements in yield attributes under conservation agriculture. The number of panicles (spikes) per square metre increased from 440.76 m^{-2} in CE1 to 471.44 m^{-2} in CE6. Panicle length was significantly enhanced under zero tillage and residue retention, with the highest value recorded under CE6 (27.95 cm), followed by CE4 (27.04 cm), whereas the shortest panicles were observed under CE1 (24.67 cm). Likewise, grains per panicle increased substantially from 109.39 in CE1 to 134.40 in CE6. Conservation agriculture had a significant positive effect on thousand-grain weight. The highest thousand-grain weight was obtained under CE6 (27.96 g), whereas the lowest value was recorded in the conventional tillage treatment, CE1 (22.63 g). The improvement in grain weight under CE6 suggests that the combined adoption of zero tillage, crop residue retention, and mungbean integration created favourable conditions for grain development. Overall, conservation agriculture-based treatments consistently enhanced important yield attributes in both wheat and rice, indicating their potential to improve crop productivity and support the long-term sustainability of the wheat–rice cropping system (Kumar *et al*., 2023; Ray *et al*., 2025).

The improved yield attributes observed under conservation agriculture are likely the result of the gradual improvement in soil physical, chemical, and biological properties brought about by reduced soil disturbance and long-term crop residue retention. Zero tillage helps preserve soil structure and pore continuity, facilitating better water infiltration, root growth, and soil aeration. At the same time, retained crop residues protect the soil surface, reduce moisture loss through evaporation, and buffer fluctuations in soil temperature, creating a more favourable environment for crop growth. These improvements enhance the availability and efficient use of water and nutrients, enabling plants to maintain vigorous vegetative growth and supply more assimilate to developing reproductive organs. As a result, crops grown under conservation agriculture produce superior yield attributes compared with those established under conventional tillage systems (Laxman *et al*., 2024; Kumar *et al*., 2022).

The inclusion of mungbean in the cropping sequence further enhanced the benefits of conservation agriculture. As a legume, mungbean contributed biologically fixed nitrogen and easily decomposable residues, which stimulated microbial activity and improved nutrient cycling. The resulting increase in nitrogen availability promoted leaf area development, chlorophyll synthesis, and photosynthetic activity, leading to greater assimilate production during grain filling. Consequently, treatments integrating mungbean with zero tillage produced longer spikes, more grains per spike, and heavier grains than the conventional tillage systems. The improved grain filling observed under CE6 is also indicative of prolonged photosynthetic activity and enhanced translocation of carbohydrates from source leaves to developing grains. (Nath *et al*., 2025).

The comparatively lower yield attributes under conventional tillage can be attributed to repeated soil disturbance, reduced soil organic carbon, and comparatively poor soil moisture conservation. Intensive tillage accelerates the oxidation of soil organic matter, weakens soil aggregation and limits microbial activity, thereby reducing nutrient availability during the critical reproductive stage. These conditions restrict spike development, reduce grain set, and limit grain filling, ultimately resulting in lower values for all yield attributes. The present findings therefore indicate that conservation agriculture creates a more favourable soil environment that enhances both vegetative growth and reproductive efficiency.

Table 5. Effect of tillage and residue-based conservation agriculture practices on yield attributes of wheat-rice cropping system in an Inceptisol

Treatments	Wheat				Rice			
	Spikes per meter square	Spike length	Grains per spike	1000 grain weight (g)	Spikes per meter square	Spike length	Grains per spike	1000 grain weight (g)
CE1: CTPTR-CTW	346.26 ± 1.99d	9.4 ± 0.15e	43.14 ± 1.72d	37.9 ± 0.59d	440.76 ± 4.27b	24.67 ± 0.71c	109.39 ± 1.09d	22.63 ± 0.66d
CE2: CTPTR-CTW-CTMB	374.39 ± 7.38bc	9.98 ± 0.19d	47.22 ± 0.97c	38.12 ± 0.66cd	442 ± 2.06b	24.86 ± 0.29c	116.46 ± 1.91c	25.35 ± 0.14bc
CE3: CTDSR-ZTW	367.55 ± 7.86c	11.15 ± 0.12c	45.95 ± 1.07cd	39.38 ± 0.58bc	445.82 ± 8.23b	25.23 ± 0.3bc	117.88 ± 1.34c	24.69 ± 0.28c
CE4: CTDSR-ZTW-ZTMB	381.8 ± 3.95ab	11.25 ± 0.09bc	54.92 ± 1.49a	40.07 ± 0.69ab	468.95 ± 8.75a	27.04 ± 0.46a	124.2 ± 2.73b	25.8 ± 0.34b
CE5: ZTDSR-ZTW	378.84 ± 2.77bc	11.54 ± 0.11b	50.23 ± 1.06b	40.49 ± 0.58ab	467.96 ± 7.58a	25.91 ± 0.38bc	128.14 ± 1.35b	25.6 ± 0.38b
CE6: ZTDSR-ZTW-ZTMB	390.67 ± 3.01a	12.1 ± 0.17a	57.53 ± 1.24a	40.9 ± 0.36a	471.44 ± 3.72a	27.95 ± 0.17a	134.4 ± 1.97a	27.96 ± 0.44a

*Abbreviations: CTPTR, conventional till puddled transplanted rice; CT, conventional till; DSR, direct-seeded rice; ZT, zero till; R, rice; W, wheat; MB, mungbean; CA, conservation agriculture. **Values are expressed as mean ± standard deviation (SD) (n = 4). Means within the same column followed by different lowercase letters differ significantly according to Duncan's Multiple Range Test (DMRT) after one-way analysis of variance (ANOVA) at $P \leq 0.05$*

Improved spike density, spike length, grains per spike, and thousand-grain weight under conservation agriculture have been widely reported as major contributors to increased grain yield in cereal-based cropping systems. Better crop establishment and higher tiller survival under zero tillage provide a larger number of productive spikes, while improved nutrient uptake and photosynthetic efficiency enhance grain formation and grain filling. Thus, the superior yield attributes recorded under CE6 demonstrate the synergistic effects of zero tillage, residue retention, and legume integration on crop productivity and resource-use efficiency (Kadiri Hassani *et al*., 2024).

The present results are in close agreement with earlier findings. Hamdy *et al*. (2016) and Hobbs *et al*. (2008) reported that conservation agriculture improves crop productivity by enhancing soil moisture conservation, nutrient availability, and root growth. Govaerts *et al*. (2009) observed significantly greater spike density, grain number, and grain weight under zero tillage with residue retention than under conventional tillage because of improved soil physical conditions. Jat *et al*. (2020) demonstrated that conservation agriculture-based wheat–rice systems in the Indo-Gangetic Plains significantly improved yield attributes and grain yield through enhanced soil health and efficient utilisation of water and nutrients. Kassam *et al*. (2019) emphasised that permanent residue cover and minimum soil disturbance improve crop performance by sustaining favourable soil conditions throughout the growing season. Lal (2015) further highlighted that increased soil organic carbon and biological activity under conservation agriculture improve nutrient cycling and crop productivity, resulting in superior yield components.

4. Conclusions

The present study demonstrated that tillage- and residue-based conservation agriculture practices significantly enhanced the growth and yield attributes of the wheat–rice cropping system in an Inceptisol. Among the evaluated crop establishment methods, the ZTDSR–ZTW–ZTMB treatment consistently outperformed the other treatments by recording the highest plant height, greenness index, initial plant population, tiller density, spikes or panicles per square metre, spike or panicle length, grains per spike or panicle, and 1000-grain weight in both wheat and rice. These results indicate that conservation agriculture creates more favourable conditions for crop establishment, vegetative growth, and grain development than conventional tillage. The superior crop performance observed under conservation agriculture was associated with the combined effects of reduced soil disturbance, crop residue retention, and mungbean integration, which improved soil moisture availability, soil structure, nutrient cycling, and microbial activity. The inclusion of mungbean further enriched the system through biological nitrogen fixation and the addition of easily decomposable residues, promoting better crop growth and grain development. Overall, the findings demonstrate that integrating zero tillage, residue retention, and mungbean is an effective strategy for enhancing crop productivity while maintaining soil health. Therefore, the ZTDSR–ZTW–ZTMB system can be considered a sustainable conservation agriculture practice for improving resource-use efficiency and ensuring the long-term productivity of wheat–rice cropping systems in Inceptisols.

5. Limitations

The findings are based on a single experimental site and the two study years reported in the manuscript, so transferability to other soils and agro-climatic conditions should be interpreted cautiously. The study focused on growth and yield attributes of wheat and rice under six crop-establishment practices; therefore, the conclusions are limited to the variables evaluated. Longer-term, multi-location evaluation would be needed to determine whether the observed treatment ranking remains consistent across contrasting Inceptisols and production environments.

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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. Grammarly and ChatGPT 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.

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