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Soil physical properties and crop productivity as affected by long-term conservation agriculture under maize (*Zea mays*) – wheat (*Triticum aestivum*) system in Indo Gangetic Plains

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ABSTRACT

Conservation agriculture (CA) incorporates crop management practices that can enhance productivity while conserving natural resources and improving soil physical properties. To assess this, an experiment was conducted during 2021–22 and 2022–23 at ICAR-Indian Agricultural Research Institute, New Delhi to evaluate soil physical properties and their impact on crop productivity in a long-term CA-based maize (*Zea mays* L.)–wheat (*Triticum aestivum* L.) system, initiated in 2010. The CA-based treatments were zero tillage with and without residue (ZT and ZT + R); permanent broad bed with and without residue (PBB and PBB + R); permanent narrow bed with and without residue (PNB and PNB + R) and conventional tillage (CT). The treatments were laid out under a randomised complete block design (RCBD) with three replications. Over the top 15 cm of soil, there was a 7.8% reduction in bulk density (BD) across the residue plots over non-residue plots. Although the highest porosity was observed in PNB + R (36.7%), all CA-based treatments were statistically comparable. Residue application had improved mean weight diameter (MWD) by 34.3% over CT, whereas a 22.6% increase in K_{sat} was reported in the study due to CA. At the plough layer, the highest soil organic carbon (SOC) was recorded under PBB + R (9.98 g/kg). A decreasing trend in soil properties (i.e. SOC, MWD and K_{sat}) was observed with increasing depth. Moreover, retaining residue in treatments PBB + R, ZT + R, and PNB + R caused a 13% rise in grain yield compared to treatments where residue was removed (PBB, ZT, PNB, CT). So, the outcomes of the experiment conclude that CA-based farming of maize– wheat cropping system could be practiced as a sustainable option to conserve soil and improve crop productivity in the long run.

Keywords: Bulk density, Hydraulic conductivity, Soil organic carbon, Soil physical health, Yield

The global inhabitants are projected to reach 11 billion by 2100 (Adam 2021). To provide sufficient and nutritious food, world food production must increase by approximately 70% by 2050 (ELD 2015). However, current intensive farming contributes to the degradation of soil, including loss of organic matter and biodiverdity, erosion, deterioration of soil structure, acidification, salinisation, deterioration of soil fertility, and rise in greenhouse gas emissions (Mandal *et al.* 2025). Crop production has become unsustainable and less profitable because of these issues. The most common farming practice in the Indo Gangetic Plains (IGP) region is rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.), which is currently facing significant challenges that threaten its long-term viability, including natural resource depletion, soil quality degradation (Bhattacharyya *et al.* 2013, Das *et al.* 2018), rapidly falling water tables, ecological imbalance, and reduced nutrient productivity. Food security in the region is under constant threat, exacerbated by global environmental changes.

In response, alternative crops and cultivation practices that are more eco-friendly and resource-efficient are being developed. The maize (*Zea mays* L.)–wheat system (MWS) is gaining attention as a replacement for the rice–wheat system due to its suitability across diverse ecologies and higher yields and better input-use efficiency. The transition to maize-centric crop rotations is driven by several factors, including maize's superior adaptability owing to its C4 photosynthetic pathway, rising demand for maize in the poultry, pig farming, and aquaculture industries, and a contracting export market for rice (Das *et al.* 2018). In India, maize is grown on approximately 9.5 mha, yielding about 24.5 mt each year. Following rice and wheat, it is the third most significant food crop (Das *et al.* 2018). The conventional practices for growing maize and wheat include multiple dry tillage processes (6–8 times), which result in issues such as water and labour scarcity, soil degradation, faster oxidation of soil organic carbon (SOC), heightened greenhouse gas emissions, depletion of essential plant

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nutrients, poor soil condition, and diminished agricultural sustainability (Bhattacharya *et al.* 2020).

Conservation agriculture (CA) has arisen as a solution to global agricultural sustainability concerns. CA has shown to enhance soil physical health (Jat *et al.* 2009, Indoria *et al.* 2017, Bhattacharya *et al.* 2023), soil organic carbon, hydraulic properties of soil (Maity *et al.* 2011), root water uptake, ecosystem services (Mandal *et al.* 2025), soil moisture conservation, and reduce water footprints (Bhattacharya *et al.* 2020). The total area under conservation agriculture in different parts of South Asia is around 2.5 mha (Jat *et al.* 2020) and the area area is mostly confined to rice–wheat based cropping system. The detailed knowledge of the long-term impacts of various tillage and planting methods, as well as of straw retention on soil physical properties and crop yield in MWS within the IGP, remains insufficient. This study was carried out to evaluate the effect of various tillage, residue management, and crop establishment options on crop productivity and soil physical properties of an MWS in the IGP region. The findings from this study are unique and will provide a basis for expanding opportunities for CA within the IGP.

MATERIALS AND METHODS

The current study was carried out during 2021–22 and 2022–23 at ICAR-Indian Agricultural Research Institute, New Delhi (28°35´N, 77°12´E; at an elevation of 229 m amsl) on a long-term maize–wheat field experiment initiated in 2010 based on conservation agriculture. The experimental location is characterised by a semi-arid subtropical climate, featuring dry, hot summers and cold, wet winters. The highest temperatures are recorded in May while the lowest occurs in January. The experimental site's soil is categorised as Typic Haplustept. At the start of the experiment, the top 0–15 cm layer had a *p*H of 7.8 and a sandy clay loam texture. Available P was at 24.3 kg/ha, available K was at 251.5 kg/ha, oxidisable SOC was at 5.3 g/kg, EC was 0.63 dS/m and oxidisable N content was at 183.3 kg/ha.

The experimental design used was a randomised complete block design (RCBD) with three replications. In addition to conventional tillage (CT), the treatments included three distinct crop establishment techniques with and without residue (R): (1) Permanent broad bed (PBB), which is 110 cm wide and 15 cm high, with a 30 cm furrow; (2) Permanent narrow bed (PNB), which is 40 cm wide and 15 cm high, with a 30 cm furrow and (3) Zero-till flatbed (ZT), which is assessed by retaining and removing residue. Permanent beds were laid out in 2010, the first year of the experiment, and maintained as such throughout the remainder of the experiment. Tillage was applied only to CT and 20% of the previous crop was left as residue in the residue-retained plots. Maize variety 'PMH 1' was planted in the first week of July 2021 and 2022 with a spacing of 70 cm × 30 cm and cultivated throughout the rainy (*kharif*) season from July to October with harvest taking place at the end of October each year. Wheat (cultivar HDCSW 18) was then sown during the first week of November 2021 and 2022. There were six raised beds in the PBB plot and twelve on the PNB plot. Using a core sampler, soil samples were collected at three depths (0–15, 15–30 and 30–45 cm) in April, which coincided with the wheat harvest.

The core auger method, as described by Blake and Hartge (1986), was used to estimate soil bulk density (BD). To measure saturated hydraulic conductivity (K_{sat}), core samples were collected in triplicate form from each plot. The K_{sat} was measured by the Constant Head method using a constant head permeameter (Mishra and Ahmad 1987). Soil clods that had been air-dried and moved through a 8 mm sieve while still withheld on a 4 mm sieve were utilised for aggregate analysis employing a nest of sieves (4, 2, 1, 0.50, 0.25, 0.10 and 0.05 mm sizes) using the wet sieving technique with a Yoder apparatus. The Mean Weight Diameter (MWD) of aggregates (Kemper and Roseneau 1986) was calculaued as:

$$\mathrm{MWD} = \sum_{i=1}^{n} W_i \times D_i$$

Where W_i, Proportion of aggregates withheld on the sieves in relation to the entire sample; D_i, Mean diameter of the aggregate class in millimetres (mm).

The organic carbon level in the soil was determined using the Wet Oxidation technique developed by Walkley and Black (1934). Grain yield of both maize and wheat crops was assessed on a plot area measuring approximately 3.2 m × 3.0 m. Soil properties and crop yields were analysed using ANOVA for a three-replication RCBD (Gomez and Gomez 1984). Tukey's HSD test was utilised for post hoc mean differentiation ($p<0.05$) using the 'Agricola' package (Mendiburu and Simon 2007) in R Studio (Version 4.2.1).

RESULTS AND DISCUSSION

Effect of conventional tillage (CT) and conservation agriculture (CA)-based practices on soil physical properties

Bulk density and porosity: Tillage, residue and crop establishment practices had a notable impact on soil bulk density (BD) across all soil depths (Fig. 1A). With increasing soil depth, BD increased significantly. BD in the 0–15cm soil layer ranged from 1.36 (PBB + R) to 1.59 Mg/m^3 (CT) with an average of 1.45 Mg/m^3. PBB + R registered a 14.2% lower value than CT, whereas other CA-based treatments demonstrated significantly lower BD (5.5–12.5%) than CT. Most significantly, ZT + R and PNB + R showed 11.1% and 12.5%, respectively lower BD than CT but there was no substantial ($p<0.05$) difference between the two. Similar outcomes have been reported by Raj *et al.* (2023) for bed-planting systems under long-term conservation practices. Over the top 15 cm of soil, there was a 7.8% decrease in BD across the residue plots over non-residue plots including CT. Similarly, in the 15–30 cm soil layer, the maximum BD was observed in CT (1.75 Mg/m^3) and the lowest in PBB + R (1.57 Mg/m^3). PBB + R showed a 10.3% lower BD than CT and a 5.6% decrease compared with PBB; however, it was comparable to PNB+R (1.60 Mg/m^3). In 15–30 cm soil, due to residue retention, BD decreased by

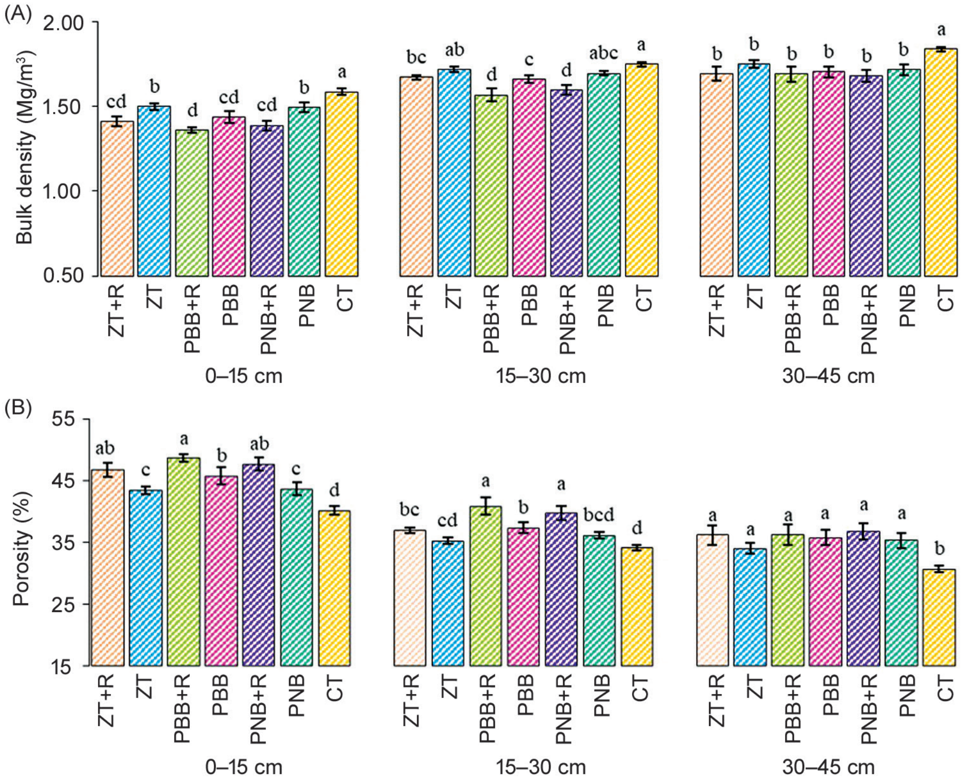

Fig. 1 Effect of CT and CA-based practices on (A) soil bulk density and (B) porosity. ZT, Zero tillage; ZT + R, Zero tillage with residue; PBB, Permanent broad bed; PBB + R, Permanent broad bed with residue; PNB, Permanent narrow bed; PNB +R, Permanent narrow bed with residue; CT, Conventional tillage; CA, Conservation agriculture. Bars along with similar letters for different treatments within different columns for a particular depth are not significantly different at $p<0.05$ level of significance according to Tukey's HSD mean separation test.

4.7%. The average BD in 30–45 cm soil depth was 1.72 Mg/m^3. The lowest BD value in this layer was under PBB + R, which was 8.7% lower than CT. All other CA-based treatments, i.e. ZT + R, ZT, PBB + R, PBB, and PNB were statistically comparable. At lower depths, the residue effect became insignificant, although there was a 3.7% decrease in BD value in residue retention plots relative to non-residue. Improvements in the soil physical properties under CA-based management practices have been reported in Nepal by Laborde *et al.* (2019).

As for the depth-wise porosity distribution (%) across seven treatments, in the topsoil layer (0–15 cm), the maximum porosity was documented in PBB + R (48.7%) and the lowest in CT (40.2%), with a mean of 45.2% (Fig. 1B). The PBB + R showed a 21.2% increase in porosity over CT and remained at par with ZT + R and PNB + R. Residue retention in plots increased porosity by up to 9.8% compared to non-residue plots, including CT. At a soil depth of 15–30 cm, average porosity decreased relative to the upper layer. In the 15–30 cm soil layer, the maximum porosity was noted in PBB + R (40.9%) and the lowest in CT (34.1%), with an average of 37.2%. At a depth of 30–45 cm, the total porosity decreased significantly, with a mean of 35.0%. Although the highest porosity was recorded in PNB + R (36.7%), all CA-based treatments were statistically comparable. The adaptation of CA significantly improved soil porosity compared with CT. Due to substantially lower soil disturbance in CA plots, there is a tendency toward a more stable soil structure, characterised by increased pore volume and connectivity compared with CT plots, where tillage disrupts the pore structure (Ghosh *et al.* 2020).

Mean weight diameter: The capacity of an aggregate to withstand various stresses, including rainfall and tillage, is a useful measure of the soil's structural stability. The MWD ranged from 1.02 (CT)–2.00 mm (PBB + R) (mean=1.65 mm), 0.73 (CT)–1.07 mm (PBB + R) (mean=0.91 mm) and 0.59 (CT)–0.72 mm (PBB+R) (mean=0.66 mm) for 0–15, 15–30 and 30–45 cm soil depths, respectively. At the plough layer (0–15 cm), a 52–97% increase in MWD was observed under CA over CT (Fig. 2). Several investigations have shown that the use of CA techniques has improved the resilience of soil aggregates (Sithole *et al.* 2019). Research in Zambia found that methods such as residue retention and crop rotation increased aggregate stability (41–45%) compared to traditional ploughing systems, which had a stability of 24% (Thierfelder and Wall 2010). In the present study, ZT + R, PBB + R, and PNB + R registered 21.4, 23.9, and 21.5% higher MWD over ZT, PBB, and PNB, respectively. Overall, residue application improved MWD by 34.3% compared with non-residue plots, including CT. Previous studies in various regions of the IGP have also reported similar results under CA practices, showing greater aggregate MWD than soil under CT (Sarkar *et al.* 2023). In 15–30 cm soil depth, MWD followed the following trend: PBB + R (1.07 mm)> ZT + R (1.03 mm)> PNB + R (1.01 mm)> PBB (0.88 mm)> ZT (0.85 mm)> PNB (0.83 mm)> CT (0.72 mm). Although ZT + R, PBB + R, and PNB + R were statistically comparable, they showed significant improvements of 39.5–47.2% in MWD over CT and around a 22% increase over the respective non-residue plots. Owing to the application of crop residue mulch, MWD at 0–15 and 15–30 cm soil depths significantly increased by 34.3% and 26.2%, respectively, compared with the non-residue treatment. However, CA-based management was non-significant for MWD at lower depths. Likewise, at a

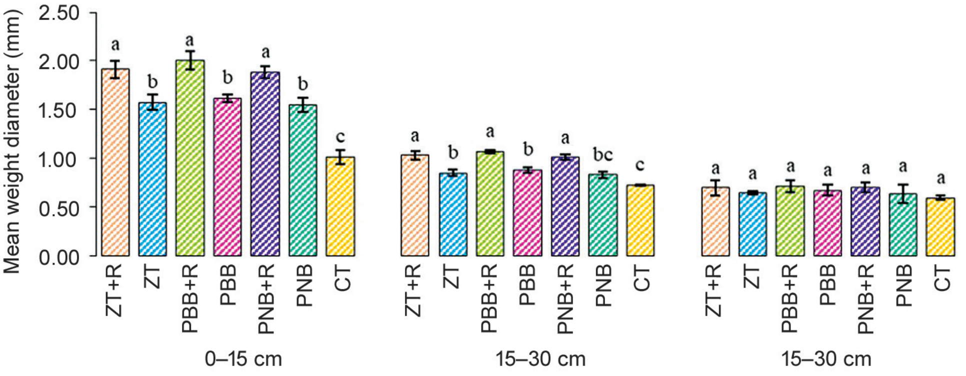

Fig. 2 Effect of CT and CA-based practices on soil mean weight diameter.
ZT, Zero tillage; ZT + R, Zero tillage with residue; PBB, Permanent broad bed; PBB + R, Permanent broad bed with residue; PNB, Permanent narrow bed; PNB + R, Permanent narrow bed with residue; CT, Conventional tillage; CA, Conservation agriculture. Bars along with similar letters for different treatments within different columns for a particular depth are not significantly different at $p< 0.05$ level of significance according to Tukey's HSD mean separation test.

soil depth of 30–45 cm, MWD decreased significantly, but all treatments were comparable.

Saturated hydraulic conductivity (K_{sat}): Irrespective of management practices, the mean K_{sat} of 0–15, 15–30 and 30–45 cm soil depths were 2.25, 1.82 and 1.42 cm/h, respectively. In 0–15 cm soil depth, maximum K_{sat} of 2.60 cm/h was obtained under PBB + R and the lowest K_{sat} of 1.78 cm/h was observed in CT. In 0–15 cm, the trend of K_{sat} was as follows: PBB + R (2.60 cm/h) >ZT + R (2.54 cm/h) >PNB + R (2.43 cm/h) >PBB (2.22 cm/h) >ZT (2.18 cm/h) >PNB (2.04 cm/h) >CT (1.78 cm/h). Residue-retained plots such as PBB + R, ZT + R and PNB + R showed 45.7, 42.3 and 36.2% improvements in K_{sat} over CT and 17.2, 16.4 and 18.9% increases over PBB, ZT and PNB, respectively. Overall, K_{sat} increased by 22.6% in residue-retaining plots compared with non-residue plots, including CT (Fig. 3). These improvements are attributed to increased soil porosity under CA (Abdallah *et al.* 2021) and to improved pore geometry, including pore continuity, pore diameter and the presence of many macropores (Ghosh *et al.* 2023). Several researchers have uncovered a complex relationship: Increased fungal activity, resulting from greater SOC accumulation through crop residue, is responsible for the heightened HC in conservation agriculture (Ghosh *et al.* 2020). A decreasing trend of K_{sat} was recorded with increasing depth. Similar to surface soil, the lowest K_{sat} of 1.47 cm/h was recorded in CT, which was significantly lower (40.7 and 39.3%) than PBB+R (2.07 cm/h) and ZT + R (2.05 cm/h) at 15–30 cm soil depth. A notable difference (16.5–18.9%) was observed between residue retention plots (ZT + R, PBB + R, PNB + R) and their corresponding non-residue plots (ZT, PBB, PNB). In 30–45 cm, the trend of K_{sat} was as follows: PBB + R (1.55 cm/h) >PNB + R (1.52 cm/h) >ZT + R (1.49 cm/h) >PBB (1.46 cm/h) >PNB (1.45 cm/h) >ZT (1.41 cm/h) >CT (1.42 cm/h). All CA-based treatments were comparable but showed significant differences relative to CT.

Soil organic carbon: The practices of tillage, residue management and bed planting significantly affected the concentration of SOC at soil depths of 0–15 cm, 15–30 cm, and 30–45 cm (Table 1). Retaining crop residue notably increased the SOC concentration in the top soil layer by approximately 40%. In this layer, the SOC was recorded as highest under PBB + R (9.98 g/kg) and lowest under CT (6.04 g/kg). ZT + R, PBB + R, and PNB + R treatments registered a significantly higher SOC not only over CT (53.7–65.1%) but also over their respective non-residue treatments (ZT, PBB, PNB), though the differences were comparable. Tripathi *et al.* (2015) reported SOC improvements of 3.6–6.1% in bed-planting systems along with residue retention, similar to ours. Results indicated a decrease in SOC concentration with increasing soil depth. In the 15–30 cm soil layer, the highest SOC was reported in PBB + R (6.27 g/kg), which

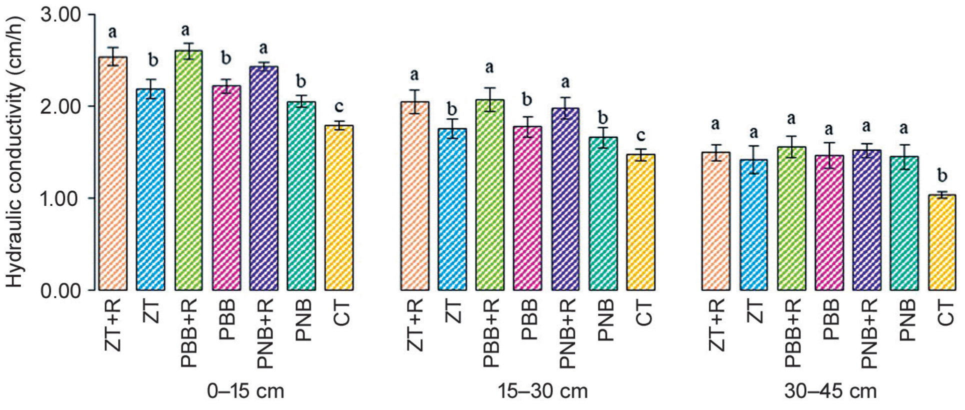

Fig. 3 Effect of CT and CA-based practices on saturated hydraulic conductivity.
ZT, Zero tillage; ZT + R, Zero tillage with residue; PBB, Permanent broad bed; PBB + R, Permanent broad bed with residue; PNB, Permanent narrow bed; PNB + R, Permanent narrow bed with residue; CT, Conventional tillage; CA, Conservation agriculture. Bars along with similar letters for different treatments within different columns for a particular depth are not significantly different at $p<0.05$ level of significance according to Tukey's HSD mean separation test.

Table 1 Effect of CT and CA-based practices on soil organic carbon

Treatment	Soil organic carbon (g/kg)		
	0–15 cm	15–30 cm	30–45 cm
ZT + R	9.47^{a*}	6.20^{a}	4.78^{a}
ZT	7.21^{b}	5.59^{c}	4.65^{a}
PBB + R	9.98^{a}	6.28^{ab}	4.84^{a}
PBB	7.24^{b}	5.69^{b}	4.71^{a}
PNB + R	9.29^{a}	6.13^{ab}	4.73^{a}
PNB	6.89^{b}	5.49^{c}	4.57^{a}
CT	6.04^{c}	4.97^{d}	4.53^{a}

ZT, Zero tillage; ZT + R, Zero tillage with residue; PBB, Permanent broad bed; PBB + R, Permanent broad bed with residue; PNB, Permanent narrow bed; PNB + R, Permanent narrow bed with residue; CT, Conventional tillage; CA, Conservation agriculture. *When comparing means within a column using Tukey's HSD test, only groups sharing the same letter are considered statistically similar at $p<0.05$

Table 2 Effect of CT and CA-based practices on crop productivity

Treatments	Maize yield (t/ha)			Wheat yield (t/ha)		
	2021	2022	Pooled	2021–22	2022–23	Pooled
ZT + R	6.40^{a*}	6.36^{a}	6.38^{ab}	5.91^{ab}	6.27^{a}	6.09^{a}
ZT	5.82^{bcd}	5.78^{b}	5.80^{cd}	5.40^{bcd}	5.65^{bc}	5.53^{bc}
PBB + R	6.51^{a}	6.62^{a}	6.57^{a}	6.12^{a}	6.39^{a}	6.25^{a}
PBB	5.99^{abc}	5.82^{b}	5.91^{c}	5.55^{abc}	5.69^{bc}	5.62^{bc}
PNB + R	6.27^{ab}	6.20^{ab}	6.23^{b}	5.62^{ab}	6.00^{ab}	5.81^{ab}
PNB	5.51^{cd}	5.73^{b}	5.62^{d}	4.99^{cd}	5.42^{c}	5.20^{cd}
CT	5.28^{d}	5.18^{c}	5.23^{e}	4.88^{d}	5.15^{c}	5.01^{d}

ZT, Zero tillage; ZT + R, Zero tillage with residue; PBB, Permanent broad bed; PBB + R, Permanent broad bed with residue; PNB, Permanent narrow bed; PNB + R, Permanent narrow bed with residue; CT, Conventional tillage; CA, Conservation agriculture. *When comparing means within a column using Tukey's HSD test, only groups sharing the same letter are considered statistically similar at $p<0.05$.

was statistically similar to that of ZT + R, PNB + R and PBB, and the lowest was under CT (4.97 g/kg). Residue retention in ZT + R and PNB + R increased SOC by around 11% compared with ZT and PNB. The SOC decreased significantly at depths of 30–45 cm. At 30–45 cm depth, SOC was similar across treatments, with an average of 4.69 g/kg. Reduced tillage can minimise SOC loss by forming macro aggregates that protect particulate organic material (Bhattacharya *et al.* 2020, Gora *et al.* 2024). In contrast, tillage can increase soil disturbance and expose SOC, thereby accelerating the mineralisation of SOM (Das *et al.* 2018).

Effect of CT and CA–based practices on crop productivity: Crop establishment methods significantly ($p<0.05$) influenced the grain yield of maize and wheat (Table 2). Practices utilising CA enhanced maize grain yields by 10.6–27.8% in 2021 and by 4.3–23.3% in 2022 compared to CT, which is the typical method used by farmers.

In a similar vein, wheat grain yield increased by 5.3–24.2% and 2.2–25.4% when comparing CA-based practices to CT in 2021–22 and 2022–23, respectively. When pooled across both years, the PPB + R method significantly outperformed the others, increasing maize and wheat grain yields by 25.6% and 24.7%, respectively compared to CT. The treatments involving PBB (both with and without residue), ZT (both with and without residue) and PNB (both with and without residue) also produced significantly higher grain yields (pooled) than the CT plots by 19.3%, 16.4% and 13.3%, respectively for maize and 18.5%, 16.0% and 6.2%, respectively for wheat. Additionally, retaining residue (in treatments PBB + R, ZT + R, PNB + R) led to a 13.4% and 13.3% increase in grain yield over treatments where residue was removed (PBB, ZT, PNB, CT) for maize and wheat, respectively. These results aligned with earlier studies on IGP, which showed that conservation agriculture (CA) yields exceed those of CT in MWS (Das *et al.* 2018). The higher yields from CA are attributable to factors such as nutrient addition, fewer weeds (Ghosh *et al.* 2023), improved soil conditions (Raj *et al.* 2023) and more efficient nutrient use than in CT. The PBB treatments, regardless of residue presence, resulted in higher productivity than the PNB (with and without residue) treatments. In maize, establishing two rows of corn along the edges of the beds or near the furrows within the PBB system may have alleviated water stress. Additionally, the consistent application of residue to the broad bed surface in PBB enhanced soil microbial activity, controlled weed development, decreased runoff and erosion, improved water infiltration and conservation and regulated temperature. These elements together promoted biological tillage (Das *et al.* 2018). This also resulted in a higher number of wheat tillers per unit area in PBB compared to narrow beds (Das *et al.* 2018). In this investigation, three rows of wheat were planted with an estimated spacing of 14 cm on each narrow bed. While this setup might have led to overcrowding and limited tillering, it proved more efficient at inhibiting weed growth.

The conventional maize–wheat system in the Indo Gangetic plains region is becoming increasingly unsustainable due to poor economic returns and deteriorating soil health. Implementing conservation agriculture practices such as minimal soil disturbance, preservation of crop residues and crop diversification can enhance soil characteristics, increase productivity and mitigate the impacts of climate change. This research supports our hypotheses by showing that conservation agriculture and bed-planting treatments significantly improved soil aggregate size, porosity, saturated hydraulic conductivity and soil organic matter while simultaneously decreasing soil bulk density. Further investigation root water uptake, nutrient loads and radiation productivity in relation to crop geometry across various management practices could yield valuable insights to enhance crop productivity.

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