Conservation agriculture based integrated crop management sustains productivity and economic profitability along with soil properties of the maize-wheat rotation

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Field experiments were conducted to evaluate eight different integrated crop management (ICM) modules for 5 years in a maize-wheat rotation (MWR); wherein, ICM1-2 ‘business-as-usual’ (conventional flatbed maize and wheat, ICM3-4 = conventional raised bed (CTRB) maize and wheat without residues, ICM5-6 = conservation agriculture (CA)-based zero-till (ZT) flatbed maize and wheat with the residues, and ICM7-8 = CA-based ZT raised bed maize and wheat with the residues. Results indicated that the ICM7-8 produced significantly (p < 0.05) the highest maize grain yield (5 years av.) which was 7.8–21.3% greater than the ICM1-6. However, across years, the ICM5-8 gave a statistically similar wheat grain yield and was 8.4–11.5% greater than the ICM1-4. Similarly, the CA-based residue retained ICM5-8 modules had given 9.5–14.3% (5 years av.) greater system yields in terms of maize grain equivalents (MGEY) over the residue removed CT-based ICM5-8. System water productivity (SWP) was the highest with ICM5-8 being 10.3–17.8% higher than the ICM1-4. Nevertheless, the highest water use (TWU) was recorded in the CT flatbed (ICM1-2) ~ 7% more than the raised bed and ZT planted crops with or without the residues (ICM5-8). Furthermore, the ICM1-4 had produced 9.54% greater variable production costs compared to the ICM5-8, whereas, the ICM5-8 gave 24.3–27.4% additional returns than the ICM1-4. Also, different ICM modules caused significant (p < 0.05) impacts on the soil properties, such as organic carbon (SOC), microbial biomass carbon (SMB), dehydrogenase (SDH), alkaline phosphatase (SAP), and urease (URE) activities. In 0.0–0.15 m soil profile, residue retained CA-based (ICM5-8) modules registered a 7.1–14.3% greater SOC and 10.2–17.3% SMB than the ICM1-4. The sustainable yield index (SYI) of MWR was 13.4–18.6% greater under the ICM7-8 compared to the ICM1-4. Hence, this study concludes that the adoption

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of the CA-based residue retained ICMs in the MWR could sustain the crop yields, enhance farm profits, save water and improve soil properties of the north-western plains of India.

Globally, maize (Zea mays L.) is the 3rd most important cereal, and across ecologies, being grown in ~ 155 nations; called ‘Queen of cereals’ (maize), the back bone of American food or a miracle crop. The United State produced ~ 31% of the maize grains, subsequently China (24%), Brazil (8%) and India (2.2%)12. In India, the maize-wheat rotation (MWR) is the 5th leading cropping rotation, occupying ~ 2 million ha in the Indo-Gangetic Plains (IGP), the heart land of the rice–wheat rotation (RWR)3. The relatively greater yields of the RWR in the upper IGP, materialized at the costs of the over utilization of the natural resources4,5, which caused nutrient imbalances, greater energy use and increased labour demands, weed shift/resistance and more GIEG emissions6,7. Further, rice residue burning is one of the realised threats of the RWR sustainability, which resulted in the extensive impacts on the losses of soil organic matter (SOM) and nutrients, reduced biodiversity, lowered water and energy efficiency, and of course the declined air quality. In India’s capital and other adjoining north Indian cities, the residue burning reduces air quality, with severe impacts on human and animal health8,9. Hence, these ruinous factors have given impetus to pursue alternative crops/rotations or to follow the integrated sustainable strategies in the line of UN Sustainable Development Goals, i.e., more environmentally sound and efficient utilization of resources10-12.

The maize adaptability to diverse agro-ecologies or across seasons is unmatched to any other crops. It can be a feasible alternative to the rice in RWR, and a potential driver for the crop diversification13,14. In India, it covers ~ 9.5 million hectares with 24.5 million tonnes annual production, and 3rd most important food crop next to rice and wheat. It is consumed in the form of grains, green cobs, sweet corn, baby corn and popcorn, besides its use as animal feed, fodder and raw material for the industrial products such as food (25%), animal feed (12%), poultry feed (49%), starch (12%), brewery and seed15. The intensive tillage with crop establishment accounts ~ 25% of the total production cost, leading to the reduced net income16. Here, the major challenge is to develop the alternative production system that should be climate and resource resilient, and can help to sustain the crop yields in the long-run17. Recently, the CA-based crop management, such as no-till or zero-till and bed plantings with residue retention and judicious crop rotations, is gaining more attention with the rising concerns pertaining to the over degradation of the natural resources, to offset the production cost18. Both the crops (maize, wheat) could be well fitted, and may prove input responsive in the CA-based practices19,20. A great potential exists to raise the yields and sustainability of the maize-wheat rotation (MWR) further by combining the CA-based production with certain integrated crop management (ICM) practices. Thus, need was felt to find out the best combinations of the ICM practices to accomplish the sustainability of the MWR. It is reported that these ICM practices can help in the initial crop establishment with greater input efficiency, and open up avenues for CA-based ICMs which could further help in the timely seeding of the both crops, hence may lead to the sustained yields without compromising the degradation of the natural resources.

Recently, the Food and Agriculture Organisation (FAO) has suggested that the ICM is of much significance and relevance than the individual agronomic management approach. The ICM is fundamentally based on the understanding of the interactions between the biology, environment and the land management systems apart from conserving the natural resources and producing the food on an economically viable and sustainable platform21. Adoption of the ICM practices significantly improved the crop yields to the tune of 20–30% in India22, and 13.5% in China23 over the farmers’ practice, while minimizing the production costs simultaneously24,25. In RWR, a recent long-term study showed the superiority of the ICM-based modules, with 10–13% greater system yields, saved 8–12% irrigation water, and gave 19–22% additional economic returns over the CT-based modules3.

Therefore, the integration of the ICM practices along with the CA-background needs to be developed in a holistic manner so as to achieve the long-term sustainability and profitability of the MWR. With this hypothesis, we have evaluated the different ICM modules for five years in a MWR of the north-western India, chiefly aimed to improve the crop and water productivity, economic profitability, sustainability and soil biological properties.

Results

Five years’ trends and pooled maize grain and straw yields. During the initial year, the maize grain yield did not differ significantly among the ICM modules, although the highest yield was recorded under the ICM5. Nevertheless, from the second year onwards, the different ICM modules had the significant (p < 0.05) impacts on the maize grain yield (Fig. 1a). The ICM1 consistently produced the highest yield across the years, which was closely followed by the ICM5. Similarly, the highest stover yield across the years was recorded with ICM5, except first year (Fig. 1b). The highest pooled grain (5.2 Mg ha⁻¹) and stover (8.7 Mg ha⁻¹) yields were recorded with the ICM5, being close to the ICM3,4,6,8. On an average, the ICM5 had produced 5.9–21% and 5.8–18.4% greater grain and stover yields, respectively, over the ICM1 (Table 1).

Five years’ trends and pooled wheat grain and straw yields. The different ICM modules did not impact the wheat grain yield significantly during the first three years. While, at the fourth year, the ICM5 had the highest yield, being significantly higher than the ICM1,3, and subsequently in the fifth year, it was ICM4 which outperformed significantly (p < 0.05) over the ICM1 (Fig. 1c). Similarly, the straw yield did not differ significantly among the ICM modules in the initial three years, but significantly a greater yield was registered with the ICM3 in the fourth and fifth years (Fig. 1d). However, the mean grain and straw yields under the ICM5 (CA-based ZT) was 8.4–11.5% and 7–14% greater than the CT-based residue removed (ICM1) modules (Table 1).

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System yields in terms of maize grain equivalents. The ICM modules had a significant impact on the maize grain equivalents (MGEY) across the years, except during the initial two years (2015–16 and 2016–17), wherein the ICM7 produced the highest yield during the 2017–18 and 2019–20, which was significantly greater than the ICM1-4 to the tune of 19–22% and 17–26%, respectively. While, in 2018–2019, the highest yield was recorded with the ICM8, which was significantly higher than the ICM1-4 by 16–22%. Averaged across the five years, the ICM5-8 had 6–15% system MGEY advantage over the ICM1-4 (Table 2).

System water use and productivity. The system water use (TWU) (irrigation + Ep) differed across the years. The highest water was consumed (1434–1753 kg ha−1 mm−1) in the ICM1&2, while it was relatively lesser under the ICM3-8 (1324–1663 kg ha−1 mm−1). On an average, the ICM3-8 saved 6.5% system water use compared to the ICM1&2 (Fig. 2a). In contrast, the highest water productivity (WP) was observed with the ICM3 (2015–16), ICM7 (2016–17, 2017–18), and ICM8 (2018–19). While, in 2019–20, the ICM7&8 produced the similar WP, but significantly higher than the ICM1-4. The average WP under CA-based residue retained modules (ICM5-8) was 7.7–19.6% greater than the CT (ICM1-4) practices (Fig. 2b).

Figure 1. Five years’ maize grain and stover (a,b); wheat grain and straw (c,d) yield trend under different ICM modules in maize-wheat rotation. The vertical bars indicate LSD at p = 0.05.

Table 1. Five years’ pooled grain and stover / straw (Mg ha−1) (± S.D.) yields of maize-wheat rotation under different ICM modules. Means followed by a similar lowercase letters within a column are not significantly different at p < 0.05 according to Tukey’s HSD test. # ICM1&2 = conventional flatbed maize & wheat (CTB); ICM3&4 = conventional raised bed maize & wheat (CTB); ICM5&6 = zero-till (ZT) flatbed maize with wheat residue at ~ 3 Mg ha−1 (ZT_M + WR) & ZT wheat with maize residue at ~ 5 Mg ha−1 (ZT_W + MR), and ICM7&8 = ZT raised bed maize with wheat residue (ZT_M + WR) & ZT wheat with maize residue (ZT_W + MR). *RDF = recommended fertilizers for maize / wheat 150:26.2:50 / 120:26:33 NPK kg ha−1; LBFs = NPK liquid bio-fertilizer; AMF = arbuscular mycorrhizal fungi.
Across the years, the variable input costs differed among the ICM modules. The highest system input cost was incurred with the ICM3 ($1001–1145 ha⁻¹ yr⁻¹), while the least was under the ICM6 ($868–991 ha⁻¹ yr⁻¹). On an average, the ICM1-4 had 9.54% greater variable production costs compared to the ICM5-8 (Fig. 3a). Furthermore, the ICM7&8 gave the highest net economic returns, resulting chiefly due to greater yields and lesser production costs incurred. The average increment in the net returns under the ICM7&8 was 23.6–29.5% compared to the ICM1-4 (Fig. 3b).

**Soil properties.** The ICM modules had a significant impact on the variable soil properties i.e., soil organic carbon (Soc), microbial biomass carbon (SMBC), dehydrogenase activity (SDH), alkaline phosphatase (SAP) and soil urease (URE) activities (Fig. 4, Table 3).

**Soil organic carbon (Soc).** In the top 0.00–0.05 m soil depth, the highest Soc was recorded with the ICM7, which was significantly higher than the ICM2&4. The increment in Soc under the ICM7&8 over the ICM1-4 was to the tune of 10.2–16.2%. Further, in the 0.05–0.15 m soil depth, the highest Soc was recorded with the ICM6, wherein it was significantly more than the ICM3, but statistically (p < 0.05) similar to the ICM1,2,4,5,7&8. While, there were no significant differences among the ICM modules, with respect to the Soc, in the 0.15–0.30 m soil depth (Fig. 4a).

**Soil microbial biomass carbon (SMBC).** The highest SMBC in the 0.00–0.05 m soil depth was observed under the ICM7, wherein it was similar to the ICM7&8, and significantly higher than the ICM4-8. The SMBC had 6–23% greater SSMBC than the ICM1-4. While, in the 0.05–0.15 m soil depth, the highest SSMBC was recorded in the ICM6, being significantly greater than the ICM1-4 to the tune of 12–22.8%, but similar to the ICM7&8. In contrast, at lower soil depth (0.15–0.30 m), the highest SSMBC was observed under the ICM5, and being greater than that of the ICM1,2,4,8 (Fig. 4b).

### Table 2. Five years’ trend of system productivity (Mg ha⁻¹) (± S.D.) in terms of maize grain equivalent yield (MGEY) of maize-wheat rotation under different ICM modules. Means followed by a similar lowercase letters within a column are not significantly different at p < 0.05 according to Tukey’s HSD test.

| Treatment | System maize grain equivalents (MGEY) |
|-----------|--------------------------------------|
|           | 2015–16  | 2016–17  | 2017–18  | 2018–19  | 2019–20  |
| ICM1      | 8.5±0.94 | 9.9±0.68 | 8.5±0.25 | 9.3±0.65 | 9.7±0.54 |
| ICM2      | 9.6±0.95 | 9.2±1.01 | 8.4±0.58 | 9.0±0.63 | 9.1±0.53 |
| ICM3      | 10.5±0.21| 9.1±1.38 | 8.6±0.30 | 9.5±0.23 | 9.8±1.53 |
| ICM4      | 9.6±0.80 | 9.7±1.09 | 8.6±0.36 | 9.7±0.26 | 8.7±0.90 |
| ICM5      | 9.7±1.36 | 9.8±1.45 | 10.3±1.11| 11.4±0.62| 10.9±0.71|
| ICM6      | 10.0±1.95| 8.8±1.16 | 10.1±0.70| 10.8±0.55| 11.9±0.66|
| ICM7      | 10.1±0.66| 10.2±0.66| 10.8±0.83| 11.5±0.45| 11.8±1.15|
| ICM8      | 10.2±1.50| 10.0±0.14| 10.9±0.51| 11.6±0.64| 11.7±1.03|

**Figure 2.** Five years’ water use (a) and system water productivity (b) trend under different ICM modules in maize-wheat rotation. The vertical bars indicate LSD at p = 0.05.
Soil dehydrogenase activity (SDH). The ICM6 had the highest SDH which was similar with the ICM7&8, but significantly greater than the ICM1-5 to the tune of 7.8–21% in the top 0.00–0.05 m soil depth. Further, in the second depth (0.05–0.15 m), the ICM8 recorded the highest SDH, wherein it was similar to the ICM6&7, but shown 17–36.6% greater SDH than the ICM1-5. In the 0.15–0.30 m soil depth, ICM5 resulted in the highest SDH. Averaged across the soil depths, the ICM6-8 gave 4–21% higher SDH than the ICM1-5 (Table 3).

Table 3. Effect of different ICM modules on soil dehydrogenase activity (SDH), alkaline phosphatase (SAP) and urease (URE) at the flowering of 5th season wheat under MWR. Means followed by a similar lowercase letters within a column are not significantly different at p < 0.05 according to Tukey’s HSD test.

| Treatment | 0.0–0.05 m | 0.05–0.15 m | 0.15–0.30 m | 0.0–0.05 m | 0.05–0.15 m | 0.15–0.30 m | 0.0–0.05 m | 0.05–0.15 m | 0.15–0.30 m |
|-----------|------------|-------------|-------------|------------|-------------|-------------|------------|-------------|-------------|
| ICM1      | 58.3b      | 26.1cd      | 13.2ab      | 54.3d      | 44.6bc      | 27.1c       | 14.2c       | 11.8c       | 7.6c        |
| ICM2      | 53.2d      | 22.0d       | 15.7a       | 49.8e      | 38.9b       | 30.2a       | 15.6b       | 12.6bc      | 6.5c        |
| ICM3      | 57.4cd     | 26.5cd      | 15.7a       | 61.8g      | 44.9bc      | 32.8a       | 14.7c       | 12.3bc      | 6.1c        |
| ICM4      | 62.0bc     | 28.7bc      | 13.4ab      | 52.9e      | 43.5a       | 28.9a       | 16.3bc      | 11.7c       | 8.4c        |
| ICM5      | 60.9bc     | 26.5cd      | 16.4a       | 60.9c      | 31.9a       | 30.6a       | 18.5d       | 13.5bc      | 8.6c        |
| ICM6      | 65.3a      | 31.9ab      | 13.8a       | 70.4a      | 56.3b       | 28.9a       | 19.4c       | 14.7bc      | 7.7c        |
| ICM7      | 63.3ab     | 34.7b       | 11.7b       | 73.6a      | 42.6a       | 31.4a       | 19.5c       | 16.7b       | 7.7c        |
| ICM8      | 65.2ab     | 37.2b       | 11.7b       | 73.6a      | 42.6a       | 31.4a       | 19.5c       | 16.7b       | 7.7c        |

Soil dehydrogenase activity (SDH). The ICM8 had the highest SDH which was similar with the ICM7&8, but significantly greater than the ICM1-5 to the tune of 7.8–21% in the top 0.00–0.05 m soil depth. Further, in the second depth (0.05–0.15 m), the ICM8 recorded the highest SDH, wherein it was similar to the ICM6, but shown 17–36.6% greater SDH than the ICM1-5. In the 0.15–0.30 m soil depth, ICM8 resulted in the highest SDH. Averaged across the soil depths, the ICM6-8 gave 4–21% higher SDH than the ICM1-5 (Table 3).
Soil alkaline phosphatase ($S_{AP}$). The highest $S_{AP}$ in the top 0.00–0.05 m soil depth was recorded with the ICM₅, being significantly higher than the ICM₁–₅, but similar to the ICM₆–₇. Indeed, the ICM₇&₈ resulted in 8.3–32.3% higher $S_{AP}$ compared to the ICM₁–₅. While, in the 0.05–0.15 m soil depth, the highest $S_{AP}$ was observed with the ICM₇, where it was significantly more than the ICM₁–₅₈, but at par with the ICM₅₈. Further, at 0.15–0.30 m, no significant difference in $S_{AP}$ was noticed among the ICM modules (Table 3).

Soil urease ($U_{RE}$). The $U_{RE}$ in the 0.00–0.05 m soil depth was the highest with the ICM₆, in which it was similar to the ICM₄–₅, but significantly greater than the ICM₁–₃. The increment in $U_{RE}$ under ICM₇&₈ over the ICM₄–₅ (CT modules) was to the tune of 12.7–27.2%. Similarly, in the 0.05–0.15 m, the highest $U_{RE}$ was recorded with the ICM₇, which was significantly greater than the ICM₁–₃, but similar to the ICM₅–₇. As expected, the ICM₇&₈ produced 8–27% higher $U_{RE}$ compared to the ICM₄–₅. However, in the lowest soil layer (0.15–0.30 m), no significant differences in $U_{RE}$ were observed among the ICM modules (Table 3).

Sustainable yield index ($SYI$). Among the ICM modules in the maize, the ICM₇ had the greatest SYI, but being at par to the ICM₇₅₈, which was 12–15.2% greater than the ICM₂₄. Again, SYI in wheat was the highest under the ICM₇, similar with ICM₅₆, being 17.9–25.3% greater than the CT-based ICM₁–₄ modules. In the case of $M_{WY}$, the SYI was the highest under the ICM₇₅₈, which was 13.4–18.6% higher than the ICM₁–₄ and similar to ICM₅.

Discussion

The rice–wheat is the commanding rotation in northern India’s ecologies. However, of late, from the resource exploitation to their judicious use for sustained yield, save water and improve soil-based properties is the focus, besides achieving SDGs. Seeing the degradation of natural resources, stagnation in crop yields and other constraints in adoption of rice–wheat rotation (RWR), it is thus noteworthy to identify the alternative crops and cropping rotations to sustain the food security. Maize ‘Queen of cereals’ being a C₄ plant, has wider adaptability under the diverse climate, thus could be a striking substitute of rice. Every year, in the rice–wheat belt of north western India, the ground water falls off by 0.30–0.40 m and, therefore, acreage under maize is likely to increase with the time. It is clearly evident that rice is the main water consumer, maize could be a potential choice for accompanying wheat in this area, as it saves irrigation water, fulfills demand for palatable fodder and industries. Rice residue burning rather than returning to the soil, is another concern which not only deteriorates the air quality, but also have acute effects on human health. Thus, the MWR has a potential to replace the water industries. Rice residue burning rather than returning to the soil, is another concern which not only deteriorates the air quality, but also have acute effects on human health. Thus, the MWR has a potential to replace the water industries. Rice residue burning rather than returning to the soil, is another concern which not only deteriorates the air quality, but also have acute effects on human health. Thus, the MWR has a potential to replace the water industries. Rice residue burning rather than returning to the soil, is another concern which not only deteriorates the air quality, but also have acute effects on human health. Thus, the MWR has a potential to replace the water industries.
considerable rhizo-depositions through hidden half and lower decaying rates. Our results showed that the SOC changed remarkably in the top soil layers, and ICM5-8 increased the SOC storage by 12.1% in the top soil layer over the CT-based ICM1-4 (Fig. 4a), as intensive tillage operations facilitate the loss of SOC, which is undesirable for the global C balance.

The SMBC is the living component (i.e., bacteria and fungi) of SOM, being the key indicator for SOC. In spite of small size, being a labile pool of SOM, it contributes to the transformation or cycling of SOM. In this study, the CA-based residue retained modules had 13.7% greater SMBC in the 0.0–0.15 soil layers than the modules where residues were removed (Fig. 4b), as regular residue addition accumulated the soil C that enhanced the SMBC and other microbial activities. Moreover, the ZT conditions with sufficient crops residue are more conducive for the fungal hyphae growth, with additional supply of AMF along with LBFs further enhanced the fungal population and diversity, which could play an important role in the C/N cycling through their hyphal networks. The SDH is the most intuitive bioindicators, describing the soil fertility. It is associated with the SOM oxidation, and its activity depends on the microorganisms’ abundance and activity. Current results showed a 10.1% improvement in the SDH activity under the CA-based modules, over CT-based practices (Table 3). The SMBC and SDH activities are directly linked with the recycling of the organic amendments, such as, the crops residues.

Phosphatase activity is needed for P-mineralization and release of the PO$_4^{3-}$ for the plant uptake. Often it is stated that the phosphatase activities (alkaline / acid) are greater in the P deficient soils, and the current study soils are alkaline in nature (pH 7.9) with only 13 kg ha$^{-1}$ available P. The P deficiency, residue addition and stoichiometric changes would exhilarate the phosphatase activity under the CA-based modules. The urease activity responsible for the N mineralization and NH$_3$ release through hydrolysing the C–N bond of the amides. The residue based ICMs recorded greater urease, as residues acts as a substrate for the urease, and eventually help in increasing the N availability for plant uptake. The SOC, SMBC, SDH, APA and URE activities are directly linked with

**Figure 5.** Effect of ICM modules on sustainable yield index (SYI) of the maize, wheat and maize-wheat rotation. Means followed by a similar lowercase letter within a bar are not significantly different at p < 0.05 using Tukey’s HSD test.

**Figure 6.** Initial establishment of ZT maize under residue retained CA-based ICM6 (a); 27 d old maize under CA-based ICM5 (b); raised bed wheat in ICM4 (c); soil conditions of CT-based ICM4 (water stagnation, left side) and CA-based residue retained ICM7 (no water stagnation, right side), photo clicked after 4–5 h of rain (d).
and the soil biological properties, and hence the soil fertility. We conclude that the CA-based residue retained modules of MWR improved crops yields, farm economic profitability, and conserved the soil moisture. Such practices could also supplement the nutrients, sustain the crop yields, conserve natural resources, especially water and boost up the soil microbial functions for the long-term sustainability.

**Conclusions**

The five years’ results clearly indicated the superiority of the CA-based residue retained ICM$_{5-8}$ modules, which produced 9.5–14.3% greater system maize grain equivalents (MGEY) over the CT-based modules (ICM$_{1-4}$). Further, the ICM$_{5-8}$ saved 6.5–8.0% irrigation water, and ICM$_{5-8}$ recorded 10.3–17.8% higher system WP than the residue removed (ICM$_{1-4}$) modules. Of course, the conventional modules (ICM$_{1-4}$) were expensive, however, ICM$_{5-8}$ gave 24.3–27.4% extra returns than the ICM$_{1-4}$, eventually made them economically more profitable. The residue retained modules (ICM$_{5-8}$) registered 7.1–14.3% (0.0–0.15 m) greater SOC than the ICM$_{1-4}$, indicating the positive impacts of the residue addition which would be useful in sustaining the soil health in long-run. On an average, in 0.0–0.15 m depths, the soil biological activities i.e., S$_{MBC}$ (10.1–16.7%), S$_{MBH}$ (10–15.6%), S$_{AP}$ (14.8–18.1%), and U$_{S}$ (16.5–20%) increased in the ICM$_{5-8}$ compared to the ICM$_{1-4}$, thus the effect of residue retention was more pronounced in the upper soil layers than in lower depths. Further, there is a need to change regional growers’ perceptions towards the adoption of maize, it could be a potential choice for accompanying wheat in this area. Therefore, the ZT residue retained modules either ICM$_{7&8}$ or ICM$_{5&6}$ could be acceptable for their adoption in the MWR for improving the yields, economic profitability and soil biological properties in the northwestern India and probably in other similar agro-ecologies.

**Materials and methods**

**Experimental site, location and climate.** Five years’ field experimentation on ICM was started in 2014–15 at the ICAR-Indian Agricultural Research Institute (28°35′N latitude, 77°12′E longitude, 229 m MSL), New Delhi, India. The study site comes under the ‘Trans IGPs’, being semi-arid with an average annual rainfall of 650 mm, of which ~ 80% occurs in July–September (south-west monsoon). The mean max. / min. air temperature ranges between 20–40°C and 4-28°C, respectively. The five years (2014–2019) weather data were recorded from the observatory adjoining to the experimental field, and presented in Supplementary Table 1. Before start of the experiment, a rainy season Sesbania was grown in 2014 to ensure the uniform fertility across the blocks. Initial soil samples (0.0–0.15 m depth) were collected in October 2014 after incorporating the Sesbania residues in soil. The soil samples were processed for the chemical analysis. The study site had a pH of 7.9 (1:2.5 soil and water ratio)88, 3.8 g kg$^{-1}$ soil organic-C89, 94.1 kg ha$^{-1}$ KMnO$_4$ oxidizable N$^{70}$, 97 μg g$^{-1}$ soil microbial biomass carbon$^{71}$, 51.3 μg PNP g$^{-1}$ soil h$^{-1}$ alkaline phosphatase$^{72}$, 53.0 μg TPF g$^{-1}$ soil d$^{-1}$ dehydrogenase$^{73}$, and 13.5 μg NH$_4$-N g$^{-1}$ soil h$^{-1}$urease$^{74}$.

**Description of different ICM modules.** The eight ICM modules were tested, comprising of four conventional tillage (CT)-based (ICM$_{1-4}$) and four conservation agriculture (CA)-based (ICM$_{5-8}$) modules, replicated thrice in a complete randomized block design with the plot size of 60 m$^2$ (15 m × 4.5 m) (Table 4). The crop residues were completely removed in the CT-based modules (ICM$_{1-4}$), while in the ICM$_{5-8}$ modules, in-situ wheat (~ 3 Mg ha$^{-1}$ on dry weight basis) and maize (~ 5 Mg ha$^{-1}$, on dry weight basis) residues were retained on the soil surface during all the seasons of crops cultivation (Footnote Table 4, Fig. 6a,b).

| Treatment notations | Maize | Wheat |
|--------------------|-------|-------|
| ICM$_1$            | CT$_{fb}$ + 100% RDF | CT$_{fb}$ + 100% RDF |
| ICM$_2$            | CT$_{fb}$ + 75% RDF + AM + LBM | CT$_{fb}$ + 75% RDF + AM + LBM |
| ICM$_3$            | CT$_{fb}$ + 100% RDF | CT$_{fb}$ + 100% RDF |
| ICM$_4$            | CT$_{fb}$ + 75% RDF + AM + LBM | CT$_{fb}$ + 75% RDF + AM + LBM |
| ICM$_5$            | ZT$_{fb}$ + W$_b$ + 100% RDF | ZT$_{fb}$ + W$_b$ + 100% RDF |
| ICM$_6$            | ZT$_{fb}$ + W$_b$ + 75% RDF + AM + LBM | ZT$_{fb}$ + W$_b$ + 75% RDF + AM + LBM |
| ICM$_7$            | ZT$_{fb}$ + W$_b$ + 100% RDF | ZT$_{fb}$ + W$_b$ + 100% RDF |
| ICM$_8$            | ZT$_{fb}$ + W$_b$ + 75% RDF + AM + LBM | ZT$_{fb}$ + W$_b$ + 75% RDF + AM + LBM |

Table 4. Description of integrated crop management (ICM) modules adopted in maize and wheat crops during the five years’ fixed plot experimentation. ¹ICM$_{1&2}$ = conventional flatbed maize & wheat (CT$_{fb}$); ICM$_{3&4}$ = conventional raised bed maize & wheat (CT$_{rb}$); ICM$_{5&6}$ = zero-till (ZT) flatbed maize with wheat residue at ~ 3 Mg ha$^{-1}$ (ZT$_{w}$ + W$_b$) & ZT wheat with maize residue at ~ 5 Mg ha$^{-1}$ (ZT$_w$ + M$_b$), and ICM$_{7&8}$ = ZT raised bed maize with wheat residue (ZT$_{rb}$ + W$_b$) & ZT wheat with maize residue (ZT$_{rb}$ + M$_b$).

²RDF = recommended fertilizers for maize / wheat 150:26.2:50 / 120:26:33 NPK kg ha$^{-1}$; LBFs = NPK liquid bio-fertilizer; AMF = arbuscular mycorrhizal fungi. ³Integrated weed management (maize): ICM$_{1-4}$ = atrazine-pre-emergence (P) fb 1 hand weeding (HW) mulch; ICM$_{5-8}$ = glyphosate-preplant (P) + atrazine-P$_b$ fb HW mulch. HW (wheat): ICM$_{1-4}$ = sulfo-sulfuron 75 + metsulfuran-methyl (total)-P$_b$; ICM$_{5-8}$ = glyphosate-P$_b$ fb pendimethalin-P$_b$ & total P$_b^E$. ⁴Need-based integrated pest management (I$_{ipm}$) and disease management (I$_{idm}$) were followed in all the ICM modules.
In the ICM$_{1-4}$ modules, the field preparation was carried out by sequential tillage operations, such as, deep ploughing using the disc harrow, cultivator/rotavator twice (0.15–0.20 m), followed by levelling in each season. In the ICM$_{5-8}$, the raised beds of 0.70 m bed width (bed top 0.40 m and furrow 0.30 m) were formed during each cropping cycle using the disc harrow, cultivator/rotavator twice (0.15–0.20 m), followed by levelling in each season. In the case of maize, ridges (0.67 m length) were prepared using the ridge maker. In the CA-based ICM$_{5-8}$ modules, the tillage operations, such as, seed and fertilizer placement were restricted to the crop row-zone in maize and wheat both. In the ICM$_{9-16}$, the permanent raised beds (0.67 m mid-furrow to mid-furrow, 0.37 m wide flat tops, and 0.15 m furrow depth), were prepared (Fig. 6d). However, these beds were reshaped using the disc coulter at the end of each cropping cycle without disturbing the surface residues. The sowing was accomplished using the raised bed multi-crop planter.

**Cultural operations and the fertilizer application.** During every season, the maize (cv. PMH 1) was sown in the first week of July using 20 kg seed ha$^{-1}$. The wheat (cv. HD 2967) crop was sown in the first fortnight of November using the seed-cum fertilizer drill (ICM$_{1-4}$), bed planter (ICM$_{5-8}$) and zero-till seed drill (ICM$_{9-16}$) at 100 kg seed ha$^{-1}$. The chemical fertilizers (N, P and K) were applied as per the modules described in the footnote of Table 4. At sowing, the full doses of phosphorous (P) and potassium (K) were applied using the di-ammonium phosphate (DAP) and muriate of potash (MOP), and the nitrogen (N) supplied through DAP. The remaining N was top-dressed through urea in two equal splits after the first irrigation and tasseling / silking stages of wheat, and crown root initiation and tillering stages of wheat. In the modules receiving ¾ fertilizers (ICM$_{1,4,6,8}$), the seeds were treated with the NPK liquid bio-fertilizer (LBFs) (diluted 250 ml formulation 2.5 L of water ha$^{-1}$), and an arbuscular mycorrhiza ($A_{arb}$) was broadcasted at 12 kg ha$^{-1}$ as has been described by$^{76}$. This $A_{arb}$ had the microbial consortia of N-fixer (Azotobacter chroococcum), P (Pseudomonas) and K (Bacillus decolorationis) solubilizers, procured from the commercial biofertilizer production unit of the Microbiology Division, ICAR-Indian Agricultural Research Institute, New Delhi (Patentee: ICAR, Govt. of India). Weeds were managed by integrating the pre- and post-emergence herbicides, and their combinations along with the hand weeding-mulching, as mentioned in the concerned modules (Footnote Table 4). However, in the CA-based modules (ICM$_{5-8}$), the non-selective herbicide glyphosate (1 kg ha$^{-1}$) was used 10 days before the sowing. The need-based integrated insect-pests and disease management practices were followed uniformly across the modules.

**Soil sampling and analysis.** Before start of the experiment, the soil sampling was done from 0.0–0.15 m soil depth. Afterwards, five random samples from each module from 0.0–0.30 m soil depth were collected at the flowering stage of 5th season wheat. These samples were taken from the three soil depths (0.0 to 0.05, 0.05–0.15 and 0.150–0.30 m) using the core sampler. The ground, air-dried soil samples, passed through a 0.2 mm sieve were used for the determination of the Walkley and Black organic carbon ($S_{OBC}$), as described by$^{76}$. For the soil biological properties, the soil samples were processed, and stored at 5ºC for 18–24 h, then analyzed the soil microbial biomass carbon (SMBC), dehydrogenase (SDH), alkaline phosphate (SAP) and the urease (URE) activities.

The soil microbial biomass carbon ($S_{MBC}$). The $S_{MBC}$ was measured using the fumigation extraction method as proposed by$^{71}$. The preweighed samples from the respective soil depths were fumigated with the ethanol-free chloroform for the 24 h. Separately, a non–fumigated set was also maintained. Further, 0.5 M K$_2$SO$_4$ (soil: extractant 1:4) was added, and kept on a reciprocal shaker for 30 min. and then filtered through a Whatman No. 42 filter paper. OC of the filtrate was measured through the dichromate digestion, followed by the back titration with 0.05 N ferrous ammonium sulphate. The $S_{MBC}$ was then calculated using the equation:

$$S_{MBC} = EC \times 2.64$$

where, $EC = (C_{org} \cdot fumigated \ soil - C_{org} \cdot non\-fumigated \ soil)$, and expressed in $\mu$g C g$^{-1}$ soil.

The dehydrogenase activity ($S_{DH}$). The $S_{DH}$ activity ($\mu$g TPF g$^{-1}$ soil d$^{-1}$) was assessed using the method of$^{71}$. The soil sample (~6 g) was saturated with 1.0 ml freshly prepared 3% triphenyltetrazolium chloride (TTC), and then incubated for 24 h under the dark. Later on, the methanol was added to stop the enzyme activity, and the absorbance of the filtered aliquot was read at 485 nm.

The alkaline phosphatase activity ($S_{AP}$). The $A_{ph}$ activity was estimated in 1.0 g soil saturated with 4 ml of the modified universal buffer (MUB) along with 1 ml of p-nitrophenol phosphate followed by incubation at 37 $^\circ$C for 1 h. After incubation, 1 ml of 0.5 M CaCl$_2$ and 4 ml of NaOH were added and the contents filtered through Whatman No. 1 filter paper. The amount of p-nitrophenol in the sample was determined at 400 nm$^{72}$ and the enzyme activity was expressed as $\mu$g p-NP g$^{-1}$ soil h$^{-1}$.

The urease activity. Urease activity was measured using 10 g soil suspended in 2.5 ml of urea solution (0.5%). After incubating for a day at 37 $^\circ$C, 50 ml of 1 M KCl solution was added. This was kept on a shaker for 30 min and the aliquot was filtered through Whatman No. 1 filter paper. The filtrate (10 ml), 5 ml of sodium salicylate and 2 ml of 0.1% sodium dichloro-isocyanide solution were added and the green color developed was measured at 690 nm$^{73}$. These values are reported as $\mu$g NH$_4$-N g$^{-1}$ soil h$^{-1}$.

**Water application and productivity.** In experimental modules, water was given through the controlled border irrigation method. The current meter was fixed in the main lined rectangular channel, and the water
velocity was measured. To get the flow discharge, then multiplied with area of cross section of the channel. The following formulae were used to calculate the applied irrigation water quantity and depth:

\[
\text{Irrigation water applied (L)} = F \times t (i)
\]

\[
\text{Depth (mm)} = L \div A/1000
\]

where, \(F\) is flow rate (\(m^3\ s^{-1}\)), \(t\) is time (s) taken in each irrigation in each module and \(A\) is area (\(m^2\)).

The effective precipitation (\(E_p\), difference between total rainfall and the actual evapotranspiration) was calculated, and then \(E_p\) was added to the irrigation water applied to calculate the total water applied in each module. Across the maize and wheat modules (ICM1-8), irrigations were given at the critical growth stages, such as, knee high and silking / tasseling (maize) and crown root formation, maximum tillering, flowering, heading / milking (wheat) stages, and after long dry spell (≥ 10-days).

On the basis of the soil water depletion pattern (at the depth of 0.60 m), in each season, 3–6 irrigations were given to maize, while wheat received 5–8 irrigations per season or crop including the pre-sowing irrigation. The rainfall data were obtained from the meteorological observatory located in the adjoining field. The water productivity (kg grains ha\(^{-1}\) mm\(^{-1}\) of water) was measured as per the equation given below:

\[
\text{Water productivity} = \frac{\text{economic yield (kg ha}^{-1}\text{)}}{\text{total water applied (mm)}}
\]

Additionally, the systems water productivity (\(S_{\text{WP}}\)) was also estimated by adding the water productivity (\(W_P\)) of both maize and wheat crops grown under the \(M_{\text{WR}}\).

**Yield measurements.** In each season, the maize and wheat crops were harvested during the months of October and April, respectively, leaving 0.75 m border rows from all the corners of each module. The crops were harvested from the net sampling area (6 m × 3 m, 18 m\(^2\)) located at the center of each plot. Maize crop was harvested manually and the wheat by using the plot combine harvester. All the harvested produce was sun dried before threshing and the grain and straw / stover yields were weighed separately. The stover/straw yields were measured by subtracting the grain weight from the total biomass. To compare the total (system) productivity of the different ICM modules, the system yield was computed, taking maize as the base crop, i.e., the maize equivalent yield (\(M_{\text{GEY}}\)) using the equation:

\[
M_{\text{GEY}}(\text{Mg ha}^{-1}) = Y_m + \left\{ \left( Y_w \times \frac{P_w}{P_m} \right) \right\}
\]

\[
\text{where, } Y_m = \text{maize grain yield (Mg ha}^{-1}\text{)}, Y_w = \text{wheat grain yield (Mg ha}^{-1}\text{)}, P_m = \text{price of maize grain (US$ Mg}^{-1}\text{)}\text{, and } P_w = \text{price of wheat grain (US$ Mg}^{-1}\text{)}\text{.}
\]

**Farm economics.** Under different ICM modules, the variable production costs and economic returns were worked out based on the prevailing market prices for the respective years. The production costs included the cost of various inputs, such as, rental value of land, seeds, pesticides, LBFs / consortia, AMF, labor, and machinery; tillage / sowing operations, irrigation, mineral fertilizers, plant protection, harvesting, and threshing etc. The costs for the crops’ residues were also considered. The system total returns were computed by adding the economic worth of the individual crop, however, the net returns were the differences between the total returns to the variable production costs of the respective module. The Govt. of India’s minimum support prices (MSP) were considered for the conversion of grain yield to the economic returns (profits) during the respective years. Further, the system net returns (\(S_{\text{NI}}\)) were worked out by summing the net income from both maize and the wheat in Indian rupees (INR), and then converted to the US$, based on the exchange rates for different years.

**Sustainable yield index (\(S_{\text{VI}}\)).** The \(S_{\text{VI}}\) as a quantitative measure of the sustainability of agricultural rotation/practice. The sustainability could be interpreted using the standard deviation (\(\sigma\)) values, where the lower values of the \(\sigma\) indicate the greater sustainability and vice-versa. Total crop productivity of maize and wheat under the different ICM modules was computed based on the five years’ mean yield data. \(S_{\text{VI}}\) was calculated using equation:

\[
S_{\text{VI}} = \frac{\left( \bar{Y}_n - \sigma_{n-1} \right)}{\bar{Y}_m}
\]

where, \(\bar{Y}_n\) is the average yield of the crops across the years under the specific management practice, \(\sigma_{n-1}\) is the standard deviation and \(\bar{Y}_m\) is the maximum yield obtained under the set of an ICM module.

**Statistical analysis.** The GLM procedure of the SAS 9.4 (SAS Institute, 2003, Cary, NC) was used for the statistical analysis of all the data obtained from different ICM modules to analyze the variance (ANOVA) under the randomized block design. Tukey’s honest significant difference test was employed to compare the mean effect of the treatments at \(p = 0.05\).

Authors have confirmed that all the plant studies were carried out in accordance with relevant national, international or institutional guidelines.

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Author contributions
V.P., R.R.Z., N.B., A.K.C., led the research work, planned, supervised, and conducted field experiments, read and edited the manuscript. N.B., R.R.Z., K.D., M.M.P., R.L.C., R.D.J., M.K., H.R., G.M., K.K.L., L.M., collected soil and...
plant samples and performed chemical analysis, also wrote the initial draft of the manuscript, prepared figures, and tables. D.K. Y.S., A.K., R.D.J., H.R., M.K.K., K.S., R.L.C., A.K.C., R.K.J., project supervision, reviewed, read and edited the manuscript with significant contributions. A.L. performed statistical analysis.

**Competing interests**
The authors declare no competing interests.

**Additional information**

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