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**Review Article**

# Integrated Crop Management in Cereal-based Rotations: Enhancing Productivity, Profitability and Agricultural Sustainability

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**ABSTRACT**

Integrated crop management (ICM) modules in cereal-based rotation have been developed to enhance productivity, profitability, and agricultural sustainability in the upper Indo-Gangetic Plains (IGPs). As the available options are often used singly or with few combinations, these studies evaluated eight distinct ICM modules. wherein, ICM$_{1\&2}$- conventional transplanted rice/ maize *fb* flatbed wheat, ICM$_{3\&4}$- conventional direct seeded rice (DSR)/ bed planted maize *fb* furrow irrigated raised bed wheat without residues, ICM$_{5\&6}$- conservation agriculture (CA)-based modules [zero tilled (ZT) DSR/ maize and ZT wheat] with the wheat and rice/ maize residues, and ICM$_{7\&8-}$ CA-based modules (ZT DSR/ maize and ZT (wheat) with the wheat, mungbean, and rice/ maize residues. In case of rice, ICM$_8$ achieved the highest mean rice grain yield, statistically similar to ICM$_{1\&7}$, but 10.1-20.7% higher than ICM$_{2–6}$. Additionally, ICM$_7$ recorded a 14-16% higher wheat grain yield than ICM$_{1–6}$, similar to ICM$_8$. Modules ICM$_{7-8}$ also produced 10-13% rice equivalents over ICM$_{1-2}$(5 yrs. mean). Water use was the highest in ICM$_{1-2}$, 8-12% greater than in ICM$_{3–8}$. Conversely, the highest water productivity was recorded in ICM$_{7-8}$, 14-16% greater than in ICM$_{1-2}$. Further, ICM$_{1-2}$ incurred the highest variable production costs, *fb* ICM$_{7-8}$. Nevertheless, ICM$_{7-8}$ generated 19-22% additional returns compared to ICM$_{1-2}$. The ICM modules also had a significant positive impact on soil carbon within the 45 cm depths. Across soil layers, residue retained modules recorded 10-25% higher total organic carbon stock than ICM$_{1-4}$. This article highlights that integrated inputs and adopting conservation agriculture-based ICM modules in different cropping systems are important for improving crop yields, farm profitability, soil fertility, water savings, and agricultural sustainability.

**Key words:** Rice-/maize-wheat rotation, Crop productivity, Profitability, Water savings, Soil properties

## Introduction

Recently, the Food and Agriculture Organization (FAO) has adopted integrated crop management (ICM) approach in agriculture. This method combines sustainable practices for crop establishment with integrated nutrient, weed, water, and pest management (Kumar and Shivay, 2008; Das *et al.*, 2018; Biswakarma *et al.*, 2021) to overcome emerging resource-, production- and climatic vulnerabilities. Integrated crop management is a holistic, site-specific strategy designed to provide optimal and safe outputs for long-term benefits (Das *et al.*, 2018). It focuses on conserving and enhancing natural resources while producing food that takes into account the interactions between biology, environment, and land management systems

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(Biswakarma *et al*., 2021). This promotes better crop establishment, increases farm yields and profitability, and ensures greater environmental safety (Kumar and Shivay, 2008). Moreover, ICM integrates traditional agricultural methods with modern technology, reducing the need for expensive external inputs and making efficient use of existing farm resources (Varatharajan *et al*., 2019). Lancon *et al*. (2007) reported that this approach is particularly well-suited for small farm holdings.

Integrated crop management is made up of three words -*integrated, crop, and management*; the term *"integrated"* refers to the management of the entire production system on a site-specific and holistic level, *"crop"* involves all aspects of crop husbandry; and planning, setting goals and objectives, executing, monitoring, evaluating, and achieving goals are all aspects of *"management"* (Das *et al*., 2018; Biswakarma *et al*., 2021). It is founded on a thorough understanding of how biology, ecology, and land management systems interact. There are five major principles of the integrated crop management approach– (i) Food Security, (ii) Environmental Security, (iii) Economic Viability, (iv) Social Acceptability, and (v) Food Safety and Quality (Kumar and Shivay, 2008; Das *et al*., 2018), however, in practical terms, ICM means good agronomy or crop management. It is defined as the integrated use of compatible technologies that meet farmer's needs and ecologically improve the productivity of crops with its key elements as suggested in Table 1. It is a "*site-specific whole farm approach*" that includes - the use of crop rotations, appropriate cultivation techniques, careful choice of seed varieties, minimum reliance on synthetic inputs such as fertilizers, pesticides and fossil fuels, maintenance of the landscape, and enhancement of wildlife habitats.

The rice-wheat rotation (RWR), South Asia's most extensive and productive system, covers 413.5 million hectares and provides staple grain to millions (Ladha *et al*., 2003) in the upper Indo-Gangetic Plains (IGPs). This system is critical for India's food and nutritional security, contributing ~75% to the national food chain (Benbi and Senapati, 2010). However, over the past two decades, the RWR has shown signs of fatigue due to increasing labour, capital, and energy demands (Bhushan *et al*., 2007; Das *et al*., 2018), along with a declining groundwater table by 30-40 cm per year (Mahajan *et al*., 2012). Additionally, paddy straw burning has led to significant emissions, adversely affecting air quality in northern India and causing health issues (Abdurrahman *et al*., 2020). Conventional transplanted rice has also had detrimental effects on subsequent wheat crops, including soil structural degradation (Mandal *et al*., 2003; Tripathi *et al*., 2005; Biswakarma *et al*., 2021), sub-soil compaction (Kukal and Aggarwal, 2003), and delayed seeding (Jat *et al*., 2020).

Similarly, Maize (*Zea mays* L.) is grown in ~155 nations; called the '*Queen of Cereals*', the backbone of America. The US produced ~31% of the maize, subsequently China (24%), Brazil (8%) and India (2.2%). In India, the maize-wheat rotation (MWR) is the 5$^{th}$ leading rotation, occupying ~2 million ha in the IGPs (Jat *et al*., 2009). Rice residue burning is one of the realized threats to RWR sustainability,

**Table 1.** Key elements of integrated crop management

| Component | Aim |
|---|---|
| 1. Minimum tillage and soil conservation techniques | 1. Low-cost maintenance of soil structure and fertility |
| 2. Use of bio-fertilizers, nitrogen-fixing plants, manures and agro-forestry techniques | 2. Improvement in soil fertility |
| 3. IPM for pests and disease control | 3. Cheap and sustainable plant protection |
| 4. Crop diversification and crop rotation | 4. Prevent the build-up of pests, diseases and weeds |
| 5. Rational use and disposal of plant and animal residues | 5. Resource recycling for better soil, plant, and human health |
| 6. Maintenance and improvement of ecological diversity | 6. Avoid loss of soil and ecological biodiversity |
| 7. Minimum use of purchased inputs and non-renewable fuel resources | 7. Reduce production costs and environmental damage |

which resulted in extensive impacts on the losses of soil organic matter (SOM) and nutrients, reduced biodiversity, lowered water, and energy efficiency, and declined air quality have given impetus to pursue alternative crops/ rotations or to follow the integrated sustainable strategies (Keesstra *et al*., 2016, 2018; Visser *et al*., 2019).

Therefore, sustainable interventions are necessary to maintain the system and ensure food security (Das *et al*., 2018; Biswakarma *et al*., 2021). Research should prioritize cost-effective, resource-conserving approaches to address these challenges. In this context, promoting zero-tilled (ZT) DSR/ maize *fb* ZT wheat with the wheat, mungbean, and rice/ maize residues could be a viable alternative. This approach aligns with the UN Sustainable Development Goals (SDGs), particularly land degradation neutrality and land restoration, emphasizing the transition from resource exploitation to sustainable use (Keesstra *et al*., 2016, 2018) and addressing soil property deterioration (Visser *et al*., 2019). Direct seeded rice (DSR) establishes crops by sowing seeds directly into unpuddled soil, bypassing the need for transplanting (Liu *et al*., 2015). For zero-tilled (ZT) maize and wheat, seeds and fertilizers are drilled into undisturbed soil in a single tractor pass (Laxmi *et al*., 2007). The DSR-ZT wheat rotation offers significant advantages over traditional practices, such as reduced production costs (Jat *et al*., 2019), and a 20-25% saving in irrigation water (Raj *et al*., 2017). This method also enhances crop water productivity and overall system productivity (Jat *et al*., 2009; IRRI, 2014; Biswakarma *et al*., 2021). Additionally, it creates a favourable soil environment, provides a longer window for residue management, and allows timely sowing of subsequent wheat. Dr. Khush, a World Food Prize Laureate, has recommended DSR for addressing northwest India's water crisis due to its lower water usage (Indian Express, 2020). Nonetheless, to fully realize the potential of DSR, it is crucial to address production constraints such as poor crop establishment, high weed infestation, and inefficient nutrient management through robust agronomic interventions (Jat *et al*., 2014, 2019). Thus, a significant shift in agricultural practices is essential for future productivity gains and the preservation of soil and agro-ecosystem resources.

Adoption of ICM enriches the soil, and can produce greater yields compared to the conventional methods (Suhas *et al*., 2017; Wani *et al*., 2017; Das *et al*., 2018; Pooniya *et al*., 2022; Biswakarma *et al*., 2021, 2023). The superiority of ICM in terms of crop yields over farmers' practices had also been reported in Nepal (Regmi and Ladha, 2006), and China (Wang *et al*., 2017). In upper IGPs of India, the impacts of ICM-based modules were evaluated with the hypothesis that these practices would improve the system yields and economics and conserve soil carbon and water resources over conventional systems.

## Material and Methods

The long-term trials consisted of eight ICM modules, four conventional tillage-(CT) based ($ICM_{1-4}$) and four conservation agriculture (CA)-based ($ICM_{5-8}$), each for rice/ maize and wheat in rice-/ maize-wheat rotation. The fixed plot experiments were laid out in a randomized complete block design (RCBD) with three replications. The climate-smart, water-saving, fertilizer-responsive, short-duration, semi-dwarf, high-yielding cultivars/ genotypes were utilized. In $ICM_{1-4}$, conventional methods of sowing/ planting were practiced and in $ICM_{3-8}$, conservation agriculture-based practices were followed to ensure a uniform crop stand. Fertilizers-nitrogen (N), phosphorus (P), and potassium (K)-were applied as per treatment, with no fertilizers applied to the summer mungbean crop. Before sowing, a full dose of phosphorus (P) and potassium (K), along with one-third of the nitrogen (N), was applied. The remaining N was top-dressed in two equal splits: after the first irrigation and active vegetative stages for rice/ maize; at maximum tillering and heading stages for wheat. For $ICM_2$, $ICM_4$, $ICM_6$, and $ICM_8$, seed treatment and root dipping with NPK liquid bio-fertilizer (diluted 250 ml formulation in 2.5 liters of water for 1 ha) were done before sowing/transplanting.

Weed infestation poses a significant challenge in both rice and wheat crops, particularly under direct-seeded rice, which can severely impact yield. Therefore, various pre-and post-emergence herbicides and their combinations were included in the modules. Integrated pest and disease management practices were uniformly followed across all ICM modules to manage insect pests and diseases as needed.

## Results and Discussion

### *A. Integrated crop management in rice-wheat rotation*

The trends of system productivity (Mg ha$^{-1}$) in terms of rice equivalent yield (REY) for a rice-wheat rotation under various integrated crop management treatments from 2015 to 2020 were highlighted in Table 2. The highest productivity was consistently observed in $ICM_7$ across the years, with peak yields reaching 10.7±0.25 Mg ha$^{-1}$ in 2015-16 and 10.2 ± 0.34 Mg ha$^{-1}$ in 2018-19. Also, $ICM_8$ showed the highest productivity, especially in 2017-18 with 10.1±0.31 Mg ha$^{-1}$. In contrast, $ICM_4$ frequently exhibited the lowest productivity, particularly in 2018-19 with 7.59±0.45 Mg ha$^{-1}$. Overall, $ICM_7$ demonstrated a clear trend of superior performance, yielding 16% to 34% more than the lowest-performing treatments in various years ($p<0.05$).In rice, ICM practices led to enhanced rice yields by 5-42% (Regmi and Ladha, 2006; Wang *et al*., 2017; Wani *et al*., 2017; Das *et al*., 2018; Biswakarma *et al*., 2021, 2023) over conventional practices. $ICM_{8\&7}$ produced the highest mean rice and wheat grain yield (Fig. 2) and yield increases of 10.1–20.7% and 14–16%, respectively for rice and wheat over $ICM_{1–6}$ (Biswakarma *et al*., 2021). It has been clearly outlined the superiority of the $ICM_{7\&8}$ in respect of the system yields as rice equivalents, which produced 10-13% greater yields than the $ICM_{1\&2}$.

The highest sustainable yield index (SYI) for rice was recorded under $ICM_8$, and for wheat under $ICM_{7–8}$. CA-based $ICM_{7\&8}$ outperformed conventional $ICM_{1–4}$ practices in terms of wheat equivalent yield, with increases of 10.8–14.7% (Biswakarma *et al*., 2023). These practices improved the properties governing the favourable soil environments in the rhizosphere regions (Jat *et al*., 2009). Further, the $ICM_{1\&2}$ consumed the largest amount of water, and

**Table 2.** Trend of system productivity (Mg ha$^{-1}$) (±S.D.) in terms of rice equivalent yield (REY) of rice-wheat rotation

| Treatment | System rice equivalent yield | | | | |
|---|---|---|---|---|---|
| | 2015–16 | 2016–17 | 2017–18 | 2018–19 | 2019–20 |
| $ICM_1$ | $9.25^{d}$±0.19 | $9.02^{ab}$±0.27 | $8.95^{bc}$±0.28 | $9.44^{ab}$±0.34 | $8.78^{b}$±0.02 |
| $ICM_2$ | $9.21^{d}$±0.15 | $8.63^{b}$±0.06 | $8.57^{c}$±0.21 | $9.14^{abc}$±0.22 | $8.79^{b}$±0.50 |
| $ICM_3$ | $9.84^{bcd}$±0.09 | $8.41^{b}$±0.24 | $8.25^{c}$±0.10 | $8.60^{bc}$±1.41 | $8.50^{b}$±0.04 |
| $ICM_4$ | $9.65^{cd}$±0.41 | $8.42^{b}$±1.33 | $8.24^{c}$±0.50 | $7.59^{c}$±0.45 | $8.28^{b}$±0.27 |
| $ICM_5$ | $10.2^{abc}$±0.29 | $9.07^{ab}$±0.61 | $9.70^{ab}$±0.43 | $9.07^{abc}$±0.36 | $8.33^{b}$±0.11 |
| $ICM_6$ | $9.91^{bc}$±0.84 | $9.28^{ab}$±0.51 | $9.16^{bc}$±0.37 | $9.16^{ab}$±0.36 | $8.68^{b}$±0.43 |
| $ICM_7$ | $10.7^{a}$±0.25 | $10.7^{a}$±0.14 | $9.15^{bc}$±0.24 | $10.2^{a}$±0.34 | $9.98^{a}$±0.15 |
| $ICM_8$ | $10.3^{ab}$±0.31 | $10.4^{ab}$±0.43 | $10.1^{a}$±0.31 | $10.5^{a}$±0.36 | $9.68^{a}$±0.16 |

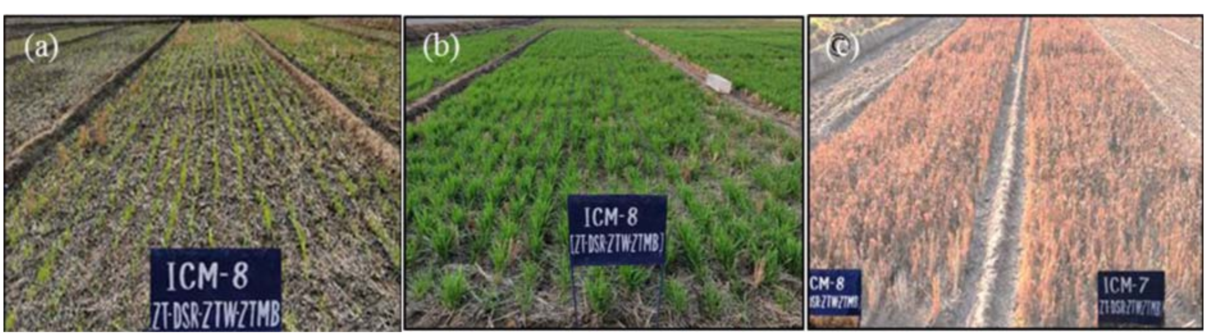


**Fig. 1.** Crop establishment in CA-based rice-wheat rotation experiment – ZT direct seeded rice (a), ZT wheat (b), and knocked down mungbean (c) (Biswakarma *et al*., 2021)

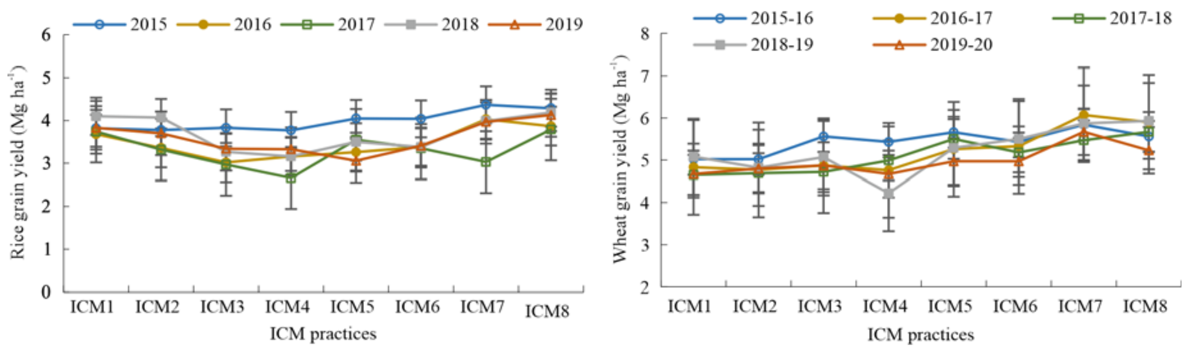


**Fig. 2.** Five years' rice grain and wheat grain yields trend under different ICM modules in rice-wheat rotation. The vertical bars indicate LSD at p=0.05 (Biswakarma *et al.*, 2021)

had the least system water productivity (SWP). The $ICM_{3-8}$ saved 8-12% water and $ICM_{7\&8}$ had 14-16% higher SWP than the $ICM_{1\&2}$. CA-based $ICM_{5-8}$ residue retained modules (0-15 cm layer) had 15-24% greater organic carbon (OC) stock than the $ICM_{1-4,}$ indicating changes in the organic carbon status of ICM modules and thereby, gets slowly decomposed for the long-run benefits. $ICM_{7\&8}$ improved the soil quality index (SQI) by 24.7% and 56.2% compared to $ICM_{5–6}$ and $ICM_{1–4}$, respectively. CA-based ICM practices also reduced carbon footprints by 9.1% to 47% compared to CT-based $ICM_{1–4}$. CA-based ICM practices proved to be environmentally safer, reducing greenhouse gas (GHG) emissions and promoting better soil health. Though, the $ICM_{1\&2}$ were costlier modules, however, the $ICM_{7\&8}$ gave the additional returns (19-22%) over the $ICM_{1\&2}$, as clearly been offset by its production costs and eventually made it more profitable. CA-based ICM practices such as minimal soil disturbance, crop residue retention, and crop rotation, improved soil structure, promotes better water infiltration and retention, which in turn supports root development and nutrient uptake. The increased soil organic carbon stocks in $ICM_{7-8}$ resulted from the decomposition of retained crop residues, which enrich soil fertility over time and provide a continuous nutrient supply (Das *et al.*, 2018; Biswakarma *et al.*, 2021, 2023).

### *B. Integrated crop management in maize-wheat rotation*

The trends of system productivity in terms of maize grain equivalent yield (MGEY) for various integrated crop management treatments over five years (2015-16 to 2019-20) in a maize-wheat rotation were highlighted in Table 3. Over the years, certain treatments consistently outperformed others. In 2015-16, $ICM_3$ recorded the highest MGEY with 10.5±0.21 Mg ha$^{-1}$, and in 2016-17, $ICM_8$ had the highest yield with 10.2±0.66 Mg ha$^{-1}$. $ICM_7$ showed superior performance in 2017-18 with a yield of

**Table 3.** Trend of system productivity (Mg ha$^{-1}$) (±S.D.) in terms of maize grain equivalent yield (MGEY) of maize-wheat rotation (Pooniya *et al.*, 2022)

| Treatment | System maize grain equivalent yield (MGEY) | | | | |
|---|---|---|---|---|---|
| | 2015–16 | 2016–17 | 2017–18 | 2018–19 | 2019–20 |
| $ICM_1$ | $8.5^{a}$±0.94 | $9.9^{a}$±0.68 | $8.7^{bcd}$±0.25 | $9.3^{bc}$±0.65 | $9.7^{bc}$±0.54 |
| $ICM_2$ | $9.6^{a}$±0.95 | $9.2^{a}$±1.01 | $8.4^{d}$±0.58 | $9.0^{c}$±0.63 | $9.1^{c}$±0.53 |
| $ICM_3$ | $10.5^{a}$±0.21 | $9.1^{a}$±1.38 | $8.6^{cd}$±0.30 | $9.5^{bc}$±0.23 | $9.8^{bc}$±1.53 |
| $ICM_4$ | $9.6^{a}$±0.80 | $9.7^{a}$±1.09 | $8.6^{cd}$±0.36 | $9.7^{bc}$±0.26 | $8.7^{c}$±0.90 |
| $ICM_5$ | $9.7^{a}$±1.36 | $9.8^{a}$±1.45 | $10.3^{ab}$±1.11 | $11.4^{a}$±0.62 | $10.9^{ab}$±0.71 |
| $ICM_6$ | $10.0^{a}$±1.95 | $8.8^{a}$±1.16 | $10.1^{abc}$±0.70 | $10.8^{ab}$±0.55 | $11.0^{ab}$±0.66 |
| $ICM_7$ | $10.1^{a}$±0.66 | $10.2^{a}$±0.66 | $10.8^{a}$±0.83 | $11.5^{a}$±0.45 | $11.8^{a}$±1.15 |
| $ICM_8$ | $10.2^{a}$±1.50 | $10.0^{a}$±0.14 | $10.0^{abc}$±0.51 | $11.6^{a}$±0.64 | $11.7^{a}$±1.03 |


**Fig. 3.** Initial establishments of ZT maize under residue retained CA-based $ICM_6$ (a); 27 days old maize under CA-based $ICM_7$ (b); raised bed wheat in $ICM_4$ (c) (Pooniya *et al*., 2022)

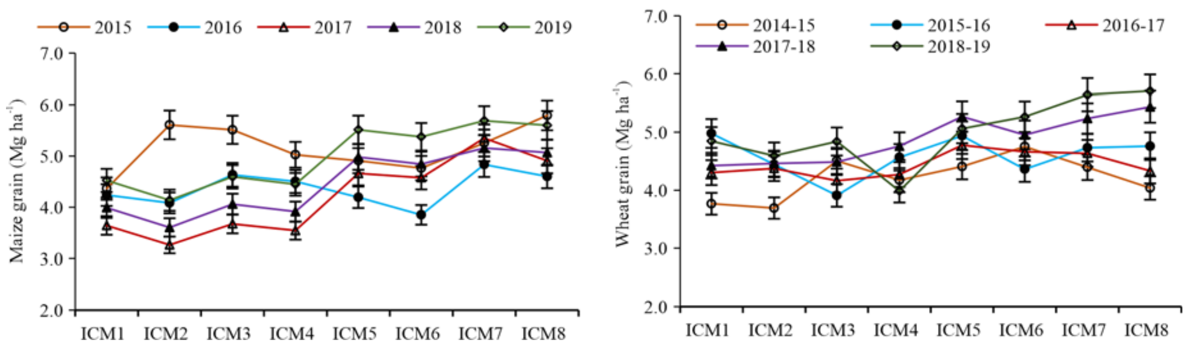


**Fig. 4.** Five years' maize and wheat grain yields trend under different ICM modules in maize-wheat rotation. The vertical bars indicate LSD at p=0.05 (Pooniya *et al*., 2022)

10.8±0.83 Mg $ha^{-1}$ and maintained its position in 2018-19 with the $ICM_8$. In 2019-20, $ICM_{7\&8}$ performed the best, with $ICM_7$ having the highest yield of 11.8±1.15 Mg $ha^{-1}$. $ICM_7$ demonstrated a substantial 16.8% increase in yield from 2015-16 to 2019-20. This analysis highlights that $ICM_7$ consistently outperformed other treatments, particularly from 2017-18 onwards, making it an effective crop management strategy in maize-wheat rotations. The results of integrated crop management practices in maize-wheat rotation clearly indicated the superiority of the CA-based residue retained $ICM_{5\text{-}8}$ modules, which produced 9.5-14.3% greater MGEY over the CT-based modules ($ICM_{1\text{-}4}$) (Pooniya *et al*., 2022). $ICM_{7\&8}$ produced the highest maize grain yield, 7.8–21.3% greater than $ICM_{1\text{-}6}$ (Fig. 4). Wheat grain yield was statistically similar across $ICM_{5\text{-}8}$, with 8.4-11.5% higher yields than $ICM_{1\text{-}4}$. Further, the $ICM_{2\text{-}8}$ saved 6.5-8.0% irrigation water, and $ICM_{5\text{-}8}$ recorded 10.3-17.8% higher SWP than the residue removed ($ICM_{1\text{-}4}$) modules. Of course, the conventional modules ($ICM_{1\text{-}4}$) were expensive, however, $ICM_{5\text{-}8}$ gave 24.3-27.4% extra returns than the $ICM_{1\text{-}4}$, eventually made them economically more profitable.

The residue retained modules ($ICM_{5\text{-}8}$) registered 7.1-14.3% (0-15 cm) greater organic carbon (OC) than the $ICM_{1\text{-}4}$, indicating the positive impacts of the residue addition which would be useful in sustaining the soil health in the long run. On average, in 0-15 cm depths, the soil biological activities i.e., microbial biomass carbon (10.1-16.7%), dehydrogenase activity (10-15.6%), alkaline phosphatase (14.8-18.1%), and urease (16.5-20%) increased in the $ICM_{5\text{-}8}$ compared to the $ICM_{1\text{-}4}$, thus the effect of residue retention was more pronounced in the upper soil layers than in lower depths (Pooniya *et al*., 2022). Therefore, the ZT residue retained modules either $ICM_{7\&8}$ or $ICM_{5\&6}$ could be acceptable for their adoption in the maize-wheat rotation for improving the yields, economic profitability, and soil biological properties in the upper IGPs and probably in other similar agro-ecologies.

## Conclusion

Integrated Crop Management principles focus on aspects like food security, environmental security, economic viability, social acceptability, and food safety and quality, emphasizing good agronomic practices. CA-based ICM modules, particularly $ICM_{7\&8}$, demonstrate superior soil quality, water productivity, and carbon dynamics, leading to higher crop yields and profitability in rice-/ maize-wheat rotations. ICM components include minimum tillage, soil conservation, bio-fertilizers, IPM, crop diversification, residue management, and ecological diversity maintenance, promoting sustainable agriculture practices. Adoption of ICM practices can significantly reduce water usage, production costs, and enhance crop water productivity, benefiting both farmers and the environment. Integrating traditional and modern agricultural methods through ICM can lead to better crop establishment, increased yields, profitability, and environmental safety. Therefore, CA-based ICM modules may be recommended for adoption to enhance productivity and profitability while reducing water use, improving soil health, and enhancing agricultural sustainability in the upper Indo-Gangetic Plains.

Future research should focus on optimizing ICM practices further to enhance sustainability, productivity, and profitability in agricultural systems. Integration of advanced technologies like precision agriculture, remote sensing, and artificial intelligence can revolutionize ICM implementation, leading to more efficient resource utilization and improved decision-making processes. ICM should be tailored to address climate change challenges by including climate-resilient crop varieties, implementing water-saving techniques, and promoting biodiversity conservation to ensure long-term agricultural sustainability. Establishing knowledge-sharing platforms, farmer cooperatives, and extension services can facilitate the dissemination of best ICM practices, fostering collaboration and learning among farmers for continuous improvement.

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