Pak. J. Bot., 57(2): 755-770, 2025. DOI: http://dx.doi.org/10.30848/PJB2025-2(39)

ORGANIC WEED MANAGEMENT CAN IMPROVE RICE-MAIZE ROTATION PERFORMANCES UNDER CONSERVATION AGRICULTURE

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Abstract

A two-year field experiment was carried out to ascertain the influence of organic weed management (OWM) on the crop performance and productivity of rice–maize rotation under conservation agriculture. The experiment comprised of four tillage practices as main plots and five OWM treatments as subplots arranged in split-plot design with three replication. The tillage management treatments included ZTR *fb* ZTM: zero-tillage (ZT) direct seeded rice (DSR) followed by (fb) ZT-maize, PBDSR+R *fb* PBDSM+R: DSR fb maize both in permanent bed (PB) with residue incorporation, PBDSR-R *fb* PBDSM-R: DSR *fb* maize both in PB without residue and CTR *fb* CTM: conventionally tilled rice *fb* maize. In OWM, five treatments were as follows: UC: unweeded weed control, VM: vermicompost mulching, PVM: phosphorous (P) enriched VM, LM: live-mulch of *Sesbania* spp. in rice and *Pisum sativum* in maize, WF: weed-free check. The PBDSR+R *fb* PBDSM+R obtained a significantly higher plant height (18.9–19.7%), leaf area index (LAI) (24.0–24.6%), dry matter accumulation (DMA) (10.8–11.3%) and crop growth rate (CGR) over CTR *fb* CTM in both rice and maize in all the growth stages. Moreover, PBDSR+R *fb* PBDSM+R recorded significantly higher grain yield (63.6 and 66.0 q ha^{-1}) in rice and in maize (93.02 and 94.31 q ha^{-1}) over other treatments in both years. Among the various OWM, LM reported significantly superior growth attributes *viz.* plant height, number of tillers m^{-2}, leaf area index and dry matter accumulation in rice and maize and grain yield by 12.3–16% in rice and 7.4–8.5% in maize over VM across the years of study. The PBDSR+R *fb* PBDSM+R recorded and LM recorded significantly the highest net return and benefit-cost ratio throughout the study. The study highlights that residue incorporation under rice–maize rotation in PB led CA system along with LM enhanced productivity and profitability.

Key words: Live mulch, Net returns, Organic weed management, Permanent bed, Residue, Zero tillage.

Introduction

Rice (*Oryza sativa* L.) and maize (*Zea mays* L.) are major cereals that contribute commendably towards food security and income generation in Asia. Farmers often grow both crops on the same field, either as a monocrop or in rotation as some varieties of rice have adapted to free drainage conditions of upland soils, which can be grown under similar conditions as maize (Mohidem *et al.*, 2022). ORYZA 2000 and Hybrid Maize Models have projected that the yield potential of rice and maize can be anticipated to reach 15 and 22 t ha^{-1} respectively (Timsina *et al.*, 2010a; Zhou *et al.*, 2016). Considering the ever-growing demand for food to nourish the rapidly growing human population and feed for livestock and poultry, growing these crops as a sequence in double or triple-crop systems seems to be a promising solution (Timsina *et al.*, 2010a). A substantial gap is evident between biologically and climatically feasible potential yields, even though extensive research work has been directed to boost the productivity potential of these crops (Timsina *et al.*, 2010b). Regional food security and sustainability are the major concern that becomes apparent from the reports of decline or stagnant system productivity (Adak *et al.*, 2023). Even though the Indo-Gangetic plains have the highest percentage of land under cultivation, the crop productivity is still poor due to drought, sub-optimal soil fertility, and weed infestation (Nungula *et al.*, 2023).

At present, to act upon the burning issue of climate change, soil health deterioration, water, energy, and manpower scarcity associated with the widespread rice-based cropping system of IGPs, Conservation agriculture (CA)-based tillage practices, more precisely zero tillage (ZT), no-tillage (NT), and minimum tillage (MT) are encouraged (Kumar *et al.*, 2013; Dutta *et al.*, 2022; Saleem *et al.*, 2022). CA has been widely accepted and has gained immense popularity on a global scale in recent years (Dayal *et al.*, 2023; Alhammad *et al.*, 2023). The CA system shows a complete paradigm shift from the management of crops and resources for crop production (soil, water, nutrients, weed, farm machinery, etc.) over the traditional systems. The guiding principles of CA are specially premeditated to reinstate farm incomes and decrease yields of degraded ecologies. Moreover, the reduced or ZT systems slow down the rate of mineralization of organic matter, thus nutrients get released at a slower pace (Ranjan *et al.*, 2023). The practice of minimizing soil disturbance in combination with crop residues retained in soil boosts the soil biological processes and hence, improves the soil quality (Bhattacharyya *et al.*, 2018; Sohail *et al.*, 2021).

Weeds are the most significant biotic pests creating hinderance in minimizing the yield gaps and their dominance and abundance shift largely when management practices are changed. Weeds are often a challenge in CA especially when there is not enough residue to cover the soil (Fonteyne *et al.*, 2020; Nichols *et al.*, 2015). Traditional tillage practices allow the diffusion of atmospheric oxygen into the soil in exchange for carbon dioxide and increase the soil nitrate concentration, ideal for breaking seed dormancy (Buhler, 2014). Tillage also helps to expose old and dormant seeds to proper light and ambient climatic conditions that facilitate their germination and thus foster a higher weed population (Baral, 2012). Whereas, Pardo *et al.*, (2019) found that CT using mouldboard plough, caused a seedbank with lower weed density than under MT or ZT. Additionally, compared to traditional tillage system, ZT had the maximum shannon index, pieloús evenness index, and species richness, indicating a higher diversity of weed species and low weed control efficiency (Pratibha *et al.*, 2021). However, with CA, the status of the viable seed-bank in soil, weed seed distribution and dispersal mechanism, weed growth patterns, diversification, expression of weeds, and trends of crop-weed competition are complex and different from the traditional methods (Derrouch *et al.*, 2020; Cordeau, 2022). Conservation agriculture practices often create unsuitable conditions that hinder weed germination and competently decrease the weed population (Benech-Arnold *et al.*, 2000; Hossain *et al.*, 2021).

Weed management, adds to the cost of cultivation making it an expensive affair. Weeds are responsible for a reduction of almost 34% of the potential crop yield (Baral, 2012; Islam *et al.*, 2021). Synthetic herbicides are heavily used in modern traditional agriculture to control weeds credit to their affordability and high effectiveness (Tataridas *et al.*, 2022). Despite, their numerous benefits, undesirable effects on the environment and health are significant. Problems such as herbicide-resistant weeds, weed shifts, off-target movement, and herbicide misapplication are evident (Gage *et al.*, 2019). Attempts to reduce herbicide input in agriculture are being made in response to the rising environmental concerns like contamination of ground and surface water sources by the accumulation of herbicide residue runoff, reconsideration of unconventional methods to control weeds is essential to confirm a promising result as the problem of herbicide-resistant weeds has amplified considerably (Ofusu *et al.*, 2023). To overcome some limitations of an intensive herbicide system, conventional growers now need to understand the basics of organic production knowledge. The practice of organic weed management (OWM) is conceptualized from the combination of traditional methods along with modern innovation and science and has gained importance due to the increasing demand for alternative healthy food sources besides sustaining soil health and conserving the ecosystem (Herzog *et al.*, 2019). The OWM recognizes certain core functions of a good weed management system that includes various cultural and mechanical methods to control the weeds, by the use of mulch, crop residues, practices of ZT and MT, and use of compost extracts (Mhlanga *et al.*, 2015). Mulching seems to be a reliable method to manage the agroecosystem and address the concern of environmental protection associated with weed management (Rhioui *et al.*, 2023). Mulching is a simple and beneficial practice that helps to maintain soil temperature, enhance soil organic matter content, and control weeds by efficiently manipulating crop growth conditions to improve product quality and increase the yield (Ahmed *et al.*, 2020; Cabrera-Pérez *et al.*, 2023).

Although vermicompost enhances the decomposition rate of soil organic matter, improves soil structure, increases aeration, and soil moisture-retaining capacity (Rehman *et al.*, 2023; Wu *et al.*, 2023) but it was found that the application of vermicompost as mulch can also effectively control weeds and simultaneously enrich the soil with nutrients to sustain crop yield without deteriorating soil health (Devi & Khwairakpam, 2020; Ganguly *et al.*, 2022). Along with conventional mulch, the live mulch concept is gaining popularity where the plants grown with the main crop offer innumerable environmental assistance to the crop under consideration together with a considerable influence on pests, diseases, and soil organisms (Matkovic *et al.*, 2015). The review of past literature indicates that very little research has been conducted on organic weed management (OWM) under conservation agriculture (CA) systems. Thus, a study has been hypothesized to explore the possibility of integrating the principles of CA and OWM to improve the growth performance, productivity, profitability, and macronutrient uptake of rice and maize under rotation.

Material and Methods

Experimental site and climatic conditions: The field experiment was conducted for two years during the summer and winter seasons of 2019-20 and 2020-21 at the Crop Research Centre of Dr. Rajendra Prasad Central Agricultural University (20º 58' 49.0" N latitude, 85º 40' 33.41" E longitudes, at an altitude of 173 m above the mean sea level), Pusa, Bihar, India. The soil of the experimental site was clay loam in texture, with pH (1:2 soil: water) 8.3, organic C content 7.1 g ha^{-1} (Walkley and Black, 1934), $KMnO_4$-oxidizable N 320 kg ha^{-1} (Subbiah and Asija, 1956), 0.5M $NaHCO_3$ extractable P 13 kg ha^{-1} (Olsen *et al.*, 1954), and NH_4OAc-exchangeable K 140 kg ha^{-1} (Prasad, 1998). The climate of the experimental site is characterized by a hot sub-humid eco-region that experiences cold and dry winters and hot and humid summers. The mean annual rainfall is 1344 mm and its distribution is unimodal, 70% of which is received between July to September. The amount of rainfall received during the study period was 1045.7 and 1326.6 mm during 2019-20 and 2020-21, respectively (Fig. 1).

Treatment details*:* The field experiment consisted of four main treatments and five sub-treatments in a split-plot design with three replications. The main plot treatments consisted of zero-tillage direct seeded rice and zero-tillage maize (ZTR *fb* ZTM); ZTDSR and maize both on permanent raised beds with residue (PBDSR+R *fb* PBDSM+R); PBDSR and PBM without residue (PBDSR-R *fb* PBDSM-R) and conventional tillage puddled transplanted rice and conventional tillage maize (CTR *fb* CTM). The subplots comprised unweeded control (UC); vermicompost mulch (VM); P- enriched vermicompost mulch (PVM); live mulch with *Sesbania* spp. in rice and *Pisum sativum* in maize (LM) and weed-free (WF). The details of the management practices followed in different treatments are given more specifically in Table 1. The study was conducted on an elementary plot size of 7.0 m × 3.6 m with a net plot size of 6.0 m × 2.6 m during each year in the same plot. During the two years of experimentation, about 3.0–5.0 and 3.5–4.8 Mg ha^{-1}, of rice residues were retained in PBM and ZTM treatments on the soil surface in maize plots, and maize residue of 2.7–5.0 and 2.2–4.8 Mg ha^{-1} were retained in PBDSR and ZTDSR plots of rice, respectively. All the remaining residues were utilized as fodder for cattle. Among the organic weed management strategies, the physicochemical composition of the vermicompost was 2.21, 1.11, and 1.25 % N, P, and K respectively whereas in P-enriched vermicompost it was 2.30, 1.23, and 1.37 % N, P and K respectively.

Crop management: Rice cv. Rajendra Mahsuri was sown with seed rates of 25 kg ha^{-1}, 20 kg ha^{-1}and 12 kg ha^{-1} under ZTR, PBDSR, and conventional treatments, respectively. Winter maize cv. DKC 9081 was sown with a uniform seed rate of 25 kg ha^{-1} in all the treatments. In the case of ZT/PBR rice was sown on 8th June 2019, 3rd June 2020 and harvested on 23rd November 2019 and 15th November 2020; whereas in CTR was sown on 30th June 2019, 27th June 2020, and harvested on 25th November 2019, 18th November 2020 respectively. During the study period, the maize crops were sown on 5th December 2019 and 27th November 2020 and were harvested on 22nd May 2020 and 7th May 2021.

During the growing season, monsoon rice received a dose of N: P: K: Zn - 150: 26: 17.5: 10 kg ha^{-1} and winter maize received a dose of N: P: K: Zn- 200:35:26:10 kg ha^{-1}. During both years, 18% N and whole P, K, and Zn were applied as basal fertilizer using di-ammonium phosphate, muriate of potash, and zinc sulphate heptahydrate applied with seed cum-fertilizer drills. During tillering and panicle initiation in rice and V5 and VT phases in maize, the remaining N was applied as urea in two equal splits. Application of Zn fertilizer was made in alternate years.

Customarily, ZTR was sown using the residual soil moisture from the pre-monsoon showers and subsequent irrigation was scheduled if there was no rain for 7 days following seeding. While, each irrigation, about 6 cm of water was applied to the rice crop irrespective of treatments. A total of five irrigations were applied during both the years of the maize cycle. Irrigation was applied to the furrows between the beds and owing to the lateral movement of water in the soil, the entire bed would become wet.

Crop variables measurement: Leaving aside, the outermost border rows, ten randomly selected plants from each net plot area in each treatment were selected and tagged, and then various growth parameters were recorded. Similarly, by leaving the border rows of net plot, the plants were used for destructive sampling periodically for recording observations on plant dry matter. The plants that were tagged earlier during early growth stages were uprooted at harvest and were further used to record the post-harvest biometric observations and sampling was also done for biochemical analysis. The procedures followed to record the data for each parameter under study have been described below.

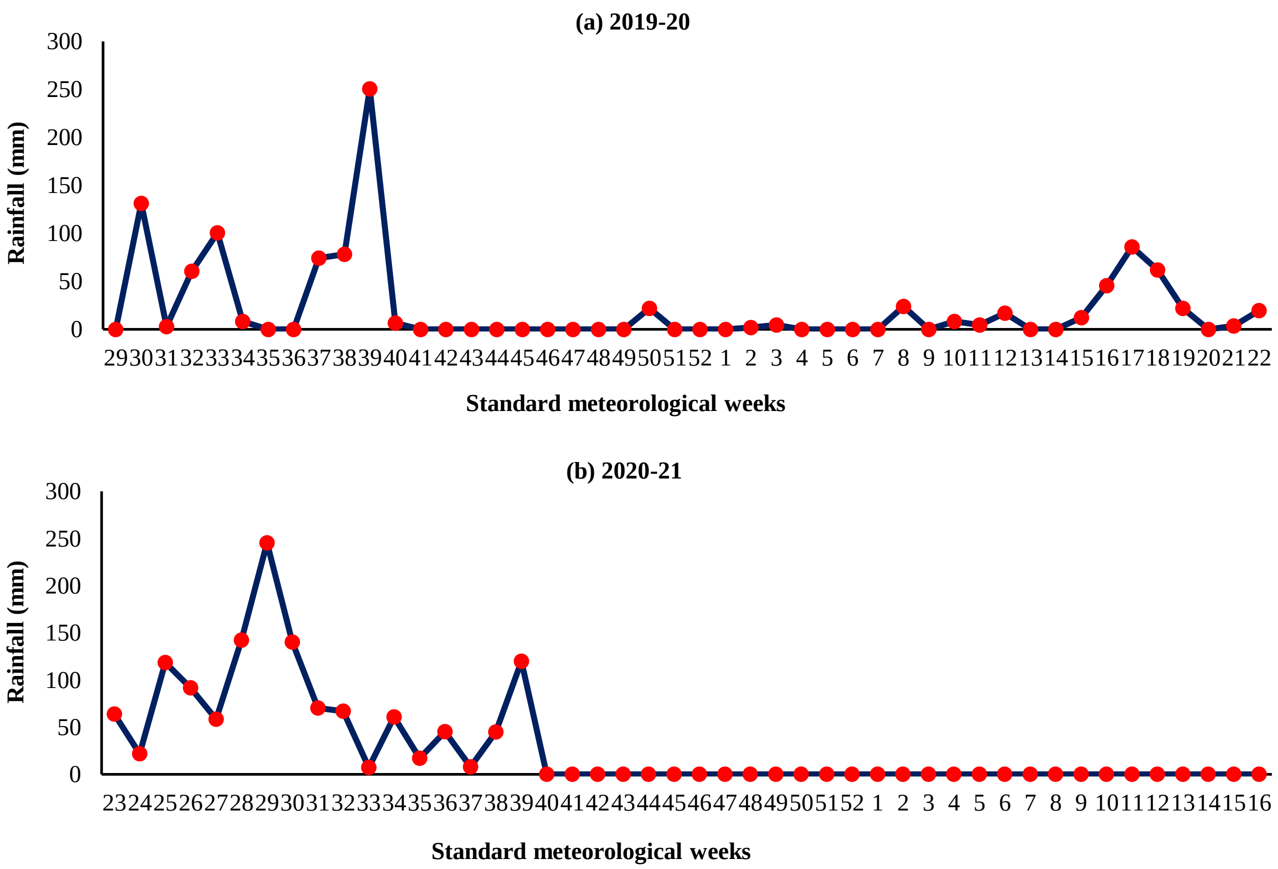

Fig. 1. The mean monthly rainfall (mm) for 2 crop years (a. 2019–20, b. 2020–21).

Table 1. Details of organic weed, tillage, and residue management practices under rice-maize rotations.

Treatment notations	Descriptions
Tillage practices	
ZTR *fb* ZTM	Zero-tillage laser leveled, 50% rice residue retention for maize, 25% maize residue retained for rice
PDSR+R *fb* PDSM+R	Zero-tillage on permanent bed, 50% rice residue retention for maize, 25% maize residue retained for rice
PDSR-R *fb* PDSM-R	Zero-tillage on the permanent bed without no residue retention
CTR *fb* CTM	Puddled transplanted rice was sown with 3 passes of dry tillage with harrow, 2 passes of cultivator in ponded water, and after 25 DAS seedlings were transplanted. Conventional till maize sown with 2 passes of harrow, 1 pass of cultivator followed by 1 planking
Organic weed management	
Unweeded control (UC)	No weed control
Vermicompost mulch (VM)	Vermicompost mulching before sowing/transplanting
P- enriched Vermicompost mulch (PVM)	P-enriched vermicompost mulching before sowing/transplanting
Live mulch (LM)	Seeds of *Sesbania spp.* and *Pisum sativum* were broadcasted with a seed rate of 40 kg ha^{-1}. Later, at 30 DAS of live mulching, the mulched plants were turned down and left as a mulch cover
Weed-free (WF)	Hand weeding at 20, 40, and 60 DAS

Crop growth parameters: The height of ten randomly selected tagged plants from each plot was measured using a metre scale from ground level to the tip of the last completely opened leaf at 30,60, and 90 DAS and at harvest, and the mean values of height at each stage were expressed in cm. The tillers per meter row length were recorded from the demarcated area at periodic intervals of 30, 60, and 90 DAS and harvest. The productive capacity of a plant can be quantified in terms of dry matter accumulation. Ten randomly selected plants were uprooted from the sampling row from each plot. The plants were then cleaned meticulously to remove adhering soil and then the fresh weight was recorded. The plants were sundried for 3-4 days and then placed in properly labelled brown paper bags and oven-dried at 60°C for 2 days till constant weight was realized. The oven-dry weight was then recorded according to treatment. The average weight per plant was then expressed in terms of g m^{-2} at periodical intervals. The leaf area of the photosynthetic apparatus was measured using a leaf area meter. The recorded leaf area values (cm^2) were divided by land area (cm^2) occupied by each plant to determine the LAI value (Watson, 1947). Crop growth rate quantifies the change in dry weight over a certain duration. It is expressed as g m^{-2} day^{-1} and is calculated using the formula given by Leopold & Kridemann (1975).

$$\text{Crop growth rate (CGR)} = \frac{W2-W1}{t2-t1} \times 1/P$$

where,
W_1 and W_2 are total dry matter at times t_1 and t_2, respectively and P is the ground area covered by plant

Crop yield: Rice grain yields (q ha^{-1}) were ascertained from a sampling area of 10 m^2 (5 m × 2 m) situated in the central region of each sub-plot, while maize crop in permanent raised beds was harvested from a width of 2.01 m (0.67 m × 3 m) and a length of 5 m. In contrast, in CT and ZT, harvest encompassed the entire net plot area of 10 m^2 (2 m × 5 m). Grain yield measurements were recorded at 14% moisture content. The straw harvested from each net plot was left in the field for 3-4 days and then weighed. The recorded data was in terms of kg plot^{-1} which was later converted into q ha^{-1}.

The Harvest index was computed using the formula given by Donald & Hamblin (1976).

$$\text{Harvest index} = \frac{\text{Grain yield}}{\text{Grain yield + Straw yield}} \text{ x } 100$$

For estimating stone yield, the grain yield was subtracted from the recorded cob yield from each treatment. It was then expressed as q ha^{-1}. Then, after separating the cob from each plant in the net plot, the cobs collected were weighed on a weighing scale and the value was noted in q ha^{-1}.

Nutrient uptake (kg ha^{-1}): Plant samples were collected at maturity to analyze macronutrient content. Subsequently, these samples underwent drying in an oven, grinding, and storage for subsequent chemical analysis. The total nitrogen (N) content in both grain and straw was determined through a process involving digestion followed by distillation, utilizing the Kel-Plus unit, and following the method outlined by Nelson and Sommers, 1980. For the analysis of phosphorus and potassium, samples underwent digestion with a diacid mixture ($HClO_4$: H_2SO_4 in a 4:1 ratio). Phosphorus content was determined through the vanadomolybdo phosphoric yellow color method using a spectrophotometer at 470 nm (Piper, 1966). Potassium content in the plant samples was determined via flame photometry (Piper, 1966) and expressed as a percentage. The amount of nutrients taken up by the plant was calculated by using the formula given below:

$$\text{Nutrient uptake} = \frac{\{\text{Nutrient content in sample x Yield (grain or straw)}\}}{\text{x } 100}$$

Economic analysis: The economic evaluation of the rice-maize cropping system was conducted for the fiscal years 2019-20 and 2020-21. Various economic parameters were computed based on the prevailing market prices of both inputs and outputs. The total cost of cultivation was determined by incorporating variable costs (except for land rent), encompassing expenditures on seeds, pesticide, fertilizer, human labour, machinery used for land preparation, transplanting, nursery raising, fertilizer application, irrigation, weeding, plant protection, harvesting, threshing, etc. Additionally, the time required per hectare to complete an individual field activity in each treatment was considered in the calculation. Labour costs associated with diverse field operations were quantified on a per hectare basis, following the person-days ha^{-1} metric (where 8 hours equate to 1 person-day, adhering to the labour law of the Indian government). The cost of labour was estimated by multiplying the labour input in all operations by the minimum wage rate prescribed by the Government of India's labour law (Minimum Wage Act, 1948).

Gross returns were computed by multiplying the grain yield (in quintals per hectare) of each crop by the minimum support price (MSP) stipulated by the Government of India (2022). Simultaneously, the value of straw was determined using prevailing local market rates. Net returns for each treatment were subsequently calculated by deducting the total cost of cultivation from the gross returns and were then recorded in Indian Rupees per hectare (INR ha^{-1}). Benefit: cost ratio was worked out by:

$$BCR = \frac{\text{Net returns (INR ha}^{-1}\text{)}}{\text{Cost of cultivation (INR ha}^{-1}\text{)}}$$

The value of 1 US$ = 74.13 and 73.93 INR as per 2020 and 2021 average exchange rates respectively (https://www.exchangerates.org.uk), was considered for economic analysis.

Statistical analysis: Analysis of variance (ANOVA) for the treatment effects on all the characters considered were then compared by using the 'F' test. Data analysis was conducted using SAS 9.3 (SAS Institute, Cary, NC), employing the PROC GLM procedure for the split-plot design. Post hoc mean separation was achieved through Tukey's honest significant difference test, where the significance level was set at ≤ 0.05. To evaluate differences between treatment means, the least significant difference (LSD) or critical difference (CD) approach was applied, as described in the work of (Gomez & Gomez, 1984).

Results

Physical growth characteristics of rice: Significantly higher plant height was observed under treatment PBDSR+R *fb* PBDSM+R (124.77 cm and 136.38 cm) at harvest which was statistically at par ($p \leq 0.05$) with ZTR *fb* ZTM but found to be significantly higher over CTR *fb* CTM by 18.9 and 19.7% in both the years, respectively (Table 2). A similar trend was observed in the 30, 60, and 90 DAS. Among the OWM, the maximum plant height was recorded by LM (124.47 and 135.64 cm) which was at par with the WF. In both years, the treatment PBDSR+R *fb* PBDSM+R (218.7 and 226.5) recorded a significantly higher number of tillers m^{-2} at 30 DAS which was significantly higher by 10.2–14.0 % as compared to PBDSR-R *fb* PBDSM-R and CTR *fb* CTM (Table 2). Similar trends were observed in the later growth stages as well. LM reported at par tiller numbers with WF but obtained significantly higher tillers by 9.3–10.8 and 11.9–13.3% over VM and PVM across the year at the harvest stage. The dry matter accumulation (DMA) in rice was significantly higher under PBDSR+R *fb* PBDSM+R by 11.1–13.2 and 10.8–11.3% over PBDSR-R *fb* PBDSM-R and CTR *fb* CTM (Fig. 2) at 90 DAS and harvest, respectively. Whereas, the PB+R system was found to be at par with the ZT system. Moreover, LM obtained a significantly higher DMA of 8.0–11.0% over VM at harvest whereas LM was found to be at par with PVM in the 1st year but recorded a significantly higher DMA by 7.4–8.2% in the 2nd year at 90 DAS and harvest. LM was found to be acquiring at par DMA with the WF at harvest.

At 60 DAS, PBDSR+R *fb* PBDSM+R (5.73 and 5.82) was reported at par LAI with ZTR *fb* ZTM (5.56 and 5.58) in both years but recorded significantly higher LAI by 9.1–10.4 and 24.0–24.6% over PBDSR-R *fb* PBDSM-R and CTR *fb* CTM, respectively (Table 3). Among the OWM, LM was found to be at par LAI with WF at all the stages but found to be significantly superior over PVM and VM by 6.3–7.4 and 14.1–14.7%, respectively at 60 DAS across the years. Similar patterns were observed at 30 and 90 DAS as well. Moreover, PBDSR+R *fb* PBDSM+R reported higher crop growth rate (CGR) of 18.39–19.67 and 15.87–17.01 g m^{-2} day^{-1} which was found to be at par with ZTR *fb* ZTM but significantly higher over PBDSR-R *fb* PBDSM-R and CTR *fb* CTM at 30–60 and 60–90 DAS in both years of study (Table 3). Similarly, LM reported at par CGR with WF but was found to be significantly higher over VM and PVM at all the phenological stages of rice.

Yield of rice: The grain yield of rice was influenced significantly by varied tillage practices with PBDSR+R *fb* PBDSM+R recorded significantly greater grain yield (63.6 and 66.0 q ha^{-1}) by 6.8–11.6%, 15.0–15.2% and 29.8–38.7% over ZTR *fb* ZTM, PBDSR-R *fb* PBDSM-R and CTR *fb* CTM, respectively across the years (Table 4a). Similarly, the straw yield of PBDSR+R *fb* PBDSM+R (76.9 and 79.4 q ha^{-1}) was found to be significantly higher by 10–11.7% and 11.9–14.7% over PBDSR-R *fb* PBDSM-R and CTR *fb* CTM, respectively but found to be at par with ZTR *fb* ZTM. Among the various OWM, LM reported at par grain yield and straw yield with WF and PVM but obtained a significantly superior grain and straw yield by 12.3–16.0% and 4.7–8.4% over VM, respectively. The grain and straw yield produced by LM was approximately twice that of UC. The 1000-grain weight of rice was not significantly affected by various tillage practices and OWM in both years of study. There was also a significant interaction effect between the tillage and OWM where the PBDSR+R *fb* PBDSM+R along with LM combinedly reported significantly higher grain yield (74.95 and 77.62 q ha^{-1}) by 151.8 and 52.2 in the 1st year and 155.9 and 59.3% in the 2nd year over CTR *fb* CTM with UC and CTR *fb* CTM with VM, respectively (Table 4b).

Table 2. Impact of CA-based tillage practices and organic weed management on plant height and tillers number of rice.

Treatments	Plant height (cm)							
	30 DAS		60 DAS		90 DAS		At harvest	
	2019	2020	2019	2020	2019	2020	2019	2020
	Tillage practices (TP)							
ZTR *fb* ZTM	31.3^{ab}	31.6^{ab}	79.4^{ab}	81.2^{a}	116.5^{ab}	126.7^{ab}	122.0^{ab}	131.2^{ab}
PBDSR+R *fb* PBDSM+R	32.4^{a}	32.8^{a}	79.8^{a}	81.4^{a}	121.4^{a}	131.9^{a}	124.8^{a}	136.4^{a}
PBDSR-R *fb* PBDSM-R	29.5^{b}	29.9^{b}	74.9^{bc}	75.3^{b}	111.1^{b}	121.1^{b}	117.0^{a}	124.3^{b}
CTR *fb* CTM	25.4^{c}	25.7^{c}	73.1^{c}	74.1^{b}	101.3^{c}	110.2^{c}	105.0^{b}	113.9^{c}
	Organic weed management (OWM)							
UC	25.6^{d}	25.9^{d}	54.6^{d}	55.5^{d}	96.0^{d}	104.7^{d}	96.6^{c}	108.3^{d}
VM	29.0^{c}	29.3^{c}	72.0^{c}	73.2^{c}	105.5^{c}	113.9^{c}	113.8^{b}	118.0^{c}
PVM	30.0^{bc}	30.3^{bc}	78.7^{b}	79.9^{b}	114.2^{b}	124.6^{b}	119.0^{b}	128.9^{b}
LM	31.7^{ab}	32.0^{ab}	87.5^{a}	89.2^{a}	120.4ab	131.2^{ab}	124.5^{ab}	135.6^{ab}
WF	32.0^{a}	32.3^{a}	91.3^{a}	92.3^{a}	126.7a	138.0^{a}	132.0^{a}	141.1^{a}
LSD (T)	2.7	2.8	4.83	5.8	8.6	9.8	11.9	9.7
LSD (W)	1.8	1.9	4.0	4.4	6.3	7.0	10.6	8.0
LSD (T × W)	NS	NS	NS	NS	NS	NS	NS	NS
Treatments	**No. of tillers m^{-2}**							
	30 DAS		60 DAS		90 DAS		At harvest	
	2019	2020	2019	2020	2019	2020	2019	2020
	Tillage practices (TP)							
ZTR *fb* ZTM	213.9^{ab}	221.5^{ab}	483.6^{ab}	486.7^{ab}	483.7^{a}	501.3a	478.1^{a}	482.3^{a}
PBDSR+R *fb* PBDSM+R	218.7^{a}	226.5^{a}	507.2^{a}	510.8^{a}	467.4^{a}	484.1a	456.6^{a}	466.4^{a}
PBDSR-R *fb* PBDSM-R	198.4^{bc}	205.8^{bc}	455.1^{b}	460.5^{b}	414.5b	428.9b	403.0^{b}	414.7^{b}
CTR *fb* CTM	191.6^{c}	198.6^{c}	379.8^{c}	384.5^{c}	408.7^{b}	423.6^{b}	402.0^{b}	409.6^{c}
	Organic weed management (OWM)							
UC	192.4d	199.3^{d}	356.2^{d}	359.7^{d}	394.5^{c}	408.7^{c}	383.1^{c}	393.0^{c}
VM	199.5cd	206.9^{cd}	435.2^{c}	438.0^{c}	434.5^{b}	450.3^{b}	429.0^{b}	433.6^{b}
PVM	206.2a^{bc}	213.4a^{bc}	464.7^{b}	466.2^{b}	423.5^{b}	438.3^{b}	419.1^{b}	423.8^{b}
LM	213.6^{ab}	221.3^{ab}	505.3^{a}	513.8^{a}	479.7^{a}	497.1^{a}	468.9^{a}	480.3^{a}
WF	216.5^{a}	224.5^{a}	520.8^{a}	525.4^{a}	485.6^{a}	503.2^{a}	474.5^{a}	485.6^{a}
LSD (T)	17.0	17.5	39.3	36.2	28.6	31.2	36.0	36.9
LSD (W)	12.2	12.6	28.4	25.4	23.5	24.8	29.2	30.5
LSD (T × W)	NS	NS	NS	NS	NS	NS	NS	NS

*The means with distinct letters within the same parameter indicate statistical significance, while identical letters denote non-significant at $p \leq 0.05$. "NS" represents non-significant

Table 3. Crop growth rate and leaf area index of rice as affected by CA-based tillage practices and organic weed management.

Treatments	Leaf area index						Crop growth rate (g m^{-2} day^{-1})					
	30 DAS		60 DAS		90 DAS		30–60 DAS		60–90 DAS		90–120 DAS	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
	Tillage practices (TP)											
ZTR *fb* ZTM	2.6^{a}	2.6^{a}	5.6^{a}	5.6^{b}	2.6^{a}	2.6^{a}	17.9^{a}	19.3^{a}	15.1^{a}	16.3^{a}	11.2^{b}	10.2^{b}
PBDSR+R *fb* PBDSM+R	2.7^{a}	2.7^{a}	5.7^{a}	5.8^{a}	2.7^{a}	2.7^{a}	18.4^{a}	19.7^{a}	15.9^{a}	17.0^{a}	12.6^{a}	11.4^{a}
PBDSR-R *fb* PBDSM-R	2.4^{b}	2.4^{b}	5.2^{b}	5.3^{c}	2.3^{b}	2.4^{b}	16.7^{b}	18.6^{a}	13.3^{b}	13.7^{b}	11.2^{b}	10.1^{b}
CTR *fb* CTM	2.0^{c}	2.0^{c}	4.6^{c}	4.7^{d}	2.0^{c}	2.0^{c}	15.7^{b}	16.9^{b}	12.7^{b}	13.6^{b}	11.1^{b}	10.3^{b}
	Organic weed management (OWM)											
UC	1.6^{d}	1.6^{d}	4.3^{d}	4.3^{d}	1.6^{d}	1.6^{d}	15.5^{b}	16.0^{d}	11.5^{c}	13.1^{c}	9.8^{c}	8.9^{c}
VM	2.4^{c}	2.4^{c}	5.0^{c}	5.1^{c}	2.4^{c}	2.4^{c}	17.3^{a}	18.2^{c}	13.1^{b}	14.5^{b}	11.2^{b}	9.6^{b}
PVM	2.5^{b}	2.5^{b}	5.4^{b}	5.4^{b}	2.5^{b}	2.5^{b}	17.6^{a}	18.6^{bc}	13.0^{b}	14.0^{bc}	11.4^{b}	10.2^{b}
LM	2.7^{a}	2.7^{a}	5.8^{a}	5.8^{a}	2.7^{a}	2.7^{a}	17.4^{a}	19.5^{ab}	16.7^{a}	16.8^{a}	12.4^{a}	11.4^{a}
WF	2.8^{a}	2.8^{a}	5.9^{a}	6.0^{a}	2.7^{a}	2.8^{a}	18.3^{a}	20.7^{a}	17.0^{a}	17.3^{a}	12.8^{a}	12.1^{a}
LSD (T)	0.1	0.1	0.2	0.2	0.1	0.1	1.2	1.4	1.1	1.1	0.8	0.8
LSD (W)	0.1	0.1	0.2	0.2	0.1	0.1	1.0	1.2	0.8	1.0	0.7	0.7
LSD (T × W)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

* The means with distinct letters within the same parameter indicate statistical significance, while identical letters denote non-significant at $p \leq 0.05$. "NS" represents non-significant

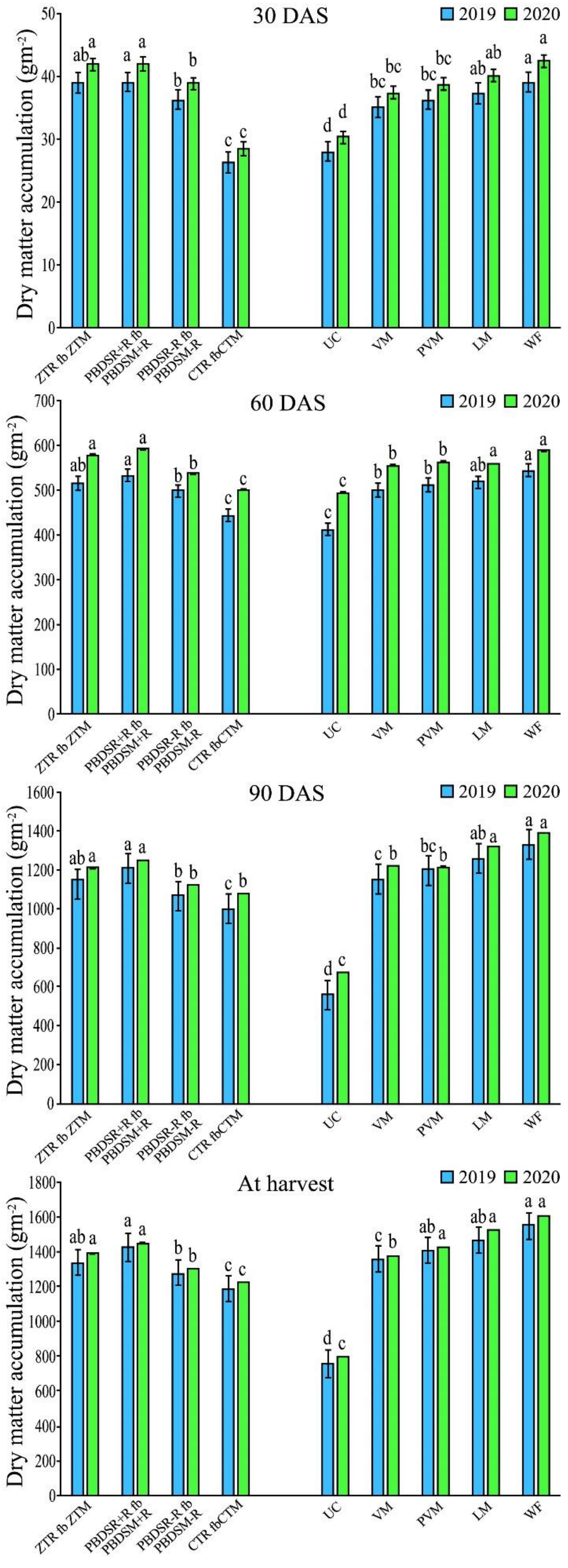

Fig. 2. Influence of CA-based tillage practices and organic weed management on plant dry matter accumulation in rice.

* The means with distinct letters within the same parameter indicate statistical significance, while identical letters denote non-significant at $p \leq 0.05$.

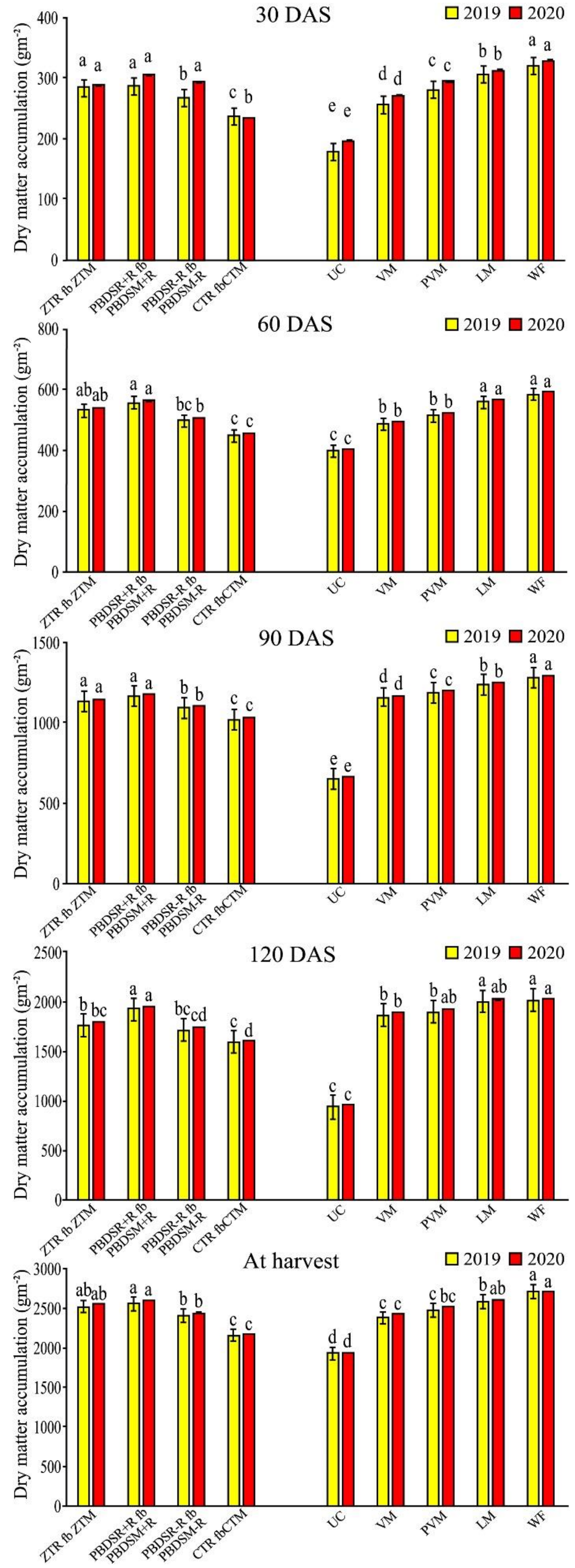

Fig. 3. Impact of CA-based tillage practices and organic weed management on plant dry matter accumulation in maize.

*The means with distinct letters within the same parameter indicate statistical significance, while identical letters denote non-significant at $p \leq 0.05$.

Table 4a. Influence of CA-based tillage practices and organic weed management on yield of rice.

Treatments	Grain yield (q ha^{-1})		Straw yield (q ha^{-1})		Harvest index (%)	
	2019	2020	2019	2020	2019	2020
	Tillage practices (TP)					
ZTR *fb* ZTM	57.0^{b}	61.8^{b}	74.3^{ab}	76.2^{ab}	43.3^{a}	44.58^{a}
PBDSR+R *fb* PBDSM+R	63.6^{a}	66.0^{a}	76.9^{a}	79.4^{a}	45.3^{a}	45.70^{a}
PBDSR-R *fb* PBDSM-R	55.2^{b}	57.4^{c}	69.9^{b}	71.1^{b}	44.1^{a}	44.62^{a}
CTR *fb* CTM	49.0^{c}	47.6^{d}	68.7^{b}	69.2^{b}	41.8^{a}	41.07^{a}
	Organic weed management (OWM)					
UC	30.8^{d}	33.1^{d}	40.4^{d}	41.8^{d}	43.6^{a}	44.6^{a}
VM	55.6^{c}	59.2^{c}	77.0^{bc}	77.3^{c}	41.9^{a}	43.2^{a}
PVM	63.1^{b}	61.4^{c}	78.8^{bc}	79.8^{bc}	44.4^{a}	43.4^{a}
LM	64.5^{ab}	66.5^{b}	80.6^{ab}	83.8^{ab}	44.3^{a}	43.9^{a}
WF	67.1^{a}	70.9^{a}	85.5^{a}	87.2^{a}	44.0^{a}	44.8^{a}
LSD (T)	4.3	3.8	2.4	5.9	7.3	NS
LSD (W)	3.6	3.1	6.1	4.9	6.1	NS
LSD (T × W)	S	S	NS	NS	NS	NS

* The means with distinct letters within the same parameter indicate statistical significance, while identical letters denote non-significant at $p \leq 0.05$. "NS" represents non-significant, "S" represents significant

Table 4b. Interaction effect of CA-based tillage practices and organic weed management on grain yield (q ha^{-1}) of rice.

Grain yield of rice	Rice 2020						Rice 2021					
	UC	VM	PVM	LM	WF	Mean	UC	VM	PVM	LM	WF	Mean
ZTR *fb* ZTM	30.9	57.3	64.7	65.3	66.9	57.0	32.6	63.6	64.3	74.2	74.3	61.8
PBDSR+R *fb* PBDSM+R	32.3	62.6	72.5	74.9	75.7	63.6	38.0	64.3	71.8	77.6	78.4	66.0
PBDSR-R *fb* PBDSM-R	30.2	53.1	62.9	64.4	65.4	55.2	31.6	60.0	60.6	65.0	69.9	57.4
CTR *fb* CTM	29.8	49.3	52.1	53.2	60.5	49.0	30.3	48.7	48.9	49.0	60.9	47.6
Mean	30.8	55.6	63.1	64.5	67.1		33.15	59.1	61.4	66.4	70.8	
	T		W		A	B	T		W		A	B
SEm±	1.2		1.0		2.8	2.2	1.1		0.9		2.4	2.0
LSD ($p \leq 0.05$)	4.4		3.0		6.3	6.9	3.8		3.1		5.6	6.1

*A: Subplot at the same level of main plot, B: Mainplot at the same level of subplot

Table 5. Impact of CA-based tillage practices and organic weed management on plant height in maize.

Treatments	Plant height (cm)							
	30 DAS		60 DAS		90 DAS		At harvest	
	2019	2020	2019	2020	2019	2020	2019	2020
	Tillage practices (TP)							
ZTR *fb* ZTM	18.6^{a}	20.9^{a}	31.9^{a}	33.9^{a}	65.1^{a}	67.8^{ab}	198.5^{a}	202.0^{a}
PBDSR+R *fb* PBDSM+R	18.8^{a}	21.2^{a}	32.6^{a}	34.7^{a}	67.0^{a}	70.3^{a}	201.7^{a}	205.4^{a}
PBDSR-R *fb* PBDSM-R	17.9^{a}	20.0^{a}	30.7^{a}	32.6^{a}	62.8^{a}	63.6^{bc}	190.5^{a}	194.0^{a}
CTR *fb* CTM	16.6^{b}	18.6^{b}	28.4^{b}	30.2^{b}	58.7^{b}	59.0^{c}	171.8^{b}	174.9^{b}
	Organic weed management (OWM)							
UC	15.5^{c}	17.4^{d}	27.3^{d}	29.0^{d}	55.2^{d}	57.5^{d}	170.4^{d}	173.4^{d}
VM	17.6^{b}	19.7^{c}	30.1^{c}	32.0^{c}	61.4^{c}	63.0^{c}	178.6^{cd}	181.7^{cd}
PVM	18.3^{ab}	20.4^{abc}	30.7^{bc}	32.6^{bc}	63.9^{bc}	65.1^{bc}	192.0^{bc}	195.6^{bc}
LM	19.1^{a}	21.6^{ab}	32.7^{ab}	34.8^{ab}	67.7^{ab}	69.3^{ab}	203.4^{ab}	207.1^{ab}
WF	19.4^{a}	21.8^{a}	33.8^{a}	35.9^{a}	68.8^{a}	70.0^{a}	208.6^{a}	212.5^{a}
LSD (T)	1.61	1.83	2.85	2.72	4.57	5.36	12.34	12.45
LSD (W)	1.21	1.50	2.38	2.35	4.20	4.23	16.22	15.93
LSD (T × W)	NS	NS	NS	NS	NS	NS	NS	NS

*The means with distinct letters within the same parameter indicate statistical significance, while identical letters denote non-significant at $p \leq 0.05$. "NS" represents non significant

Physical growth characteristics of maize: The maize plant height was significantly higher under treatment PBDSR+R *fb* PBDSM+R (201.73 and 205.41 cm) at harvest which was statistically at par ($p \leq 0.05$) with ZTR *fb* ZTM and PBDSR-R *fb* PBDSM-R but found to be significantly higher over CTR *fb* CTM by ~ 17.4% across the years (Table 5). A similar plant height trend witnessed in the 30, 60, and 90 DAS with PBDSR+R *fb* PBDSM+R reporting ~14%, ~15%, and ~17% higher values, respectively compared to CTR *fb* CTM. Among the various OWM, the maximum plant height was recorded by LM (203.45 and 207.08 cm) which was found to be at par with the WF. There was no statistically significant difference ($p \leq 0.05$) observed between VM, PVM, and LM in terms of plant height. The DMA in maize was significantly higher under PBDSR+R *fb* PBDSM+R by 6.2–12.7 and 18.4–21.9% over PBDSR-R *fb* PBDSM-R and CTR *fb* CTM, respectively (Fig. 3) at 120 DAS and harvest. Whereas, the

PB+R system was found to be at par with the ZT system. Moreover, LM obtained a significantly higher DMA of 7.5–8.6% over VM at harvest whereas the earlier was found to be at par with PVM in the 2nd year but recorded a significantly higher DMA by 4.6–5.4% in the 1st year at 120 DAS and at harvest. LM reported at par DMA with the WF at all the phenological stages of maize. The PBDSR+R *fb* PBDSM+R reported at par LAI with ZTR *fb* ZTM in both years but recorded significantly higher LAI by 15.7–16.8 and 49.1–49.6% at 60 DAS and by 13.9–15.2% and 35.5–36.6% at 90 DAS over PBDSR-R *fb* PBDSM-R and CTR *fb* CTM, respectively (Table 6).

Among the different OWM, LM was reported at par LAI with WF at all the stages but found to be significantly superior by 19.1–19.6 and 11.4–12.1% at 60 DAS and by 14.6–15.2% and 8.9–9.5% at 90 DAS over VM and PVM, respectively across the years. In line with the physical attributes like DMA and LAI, PBDSR+R *fb* PBDSM+R reported a higher CGR of 58.24–58.85 g m^{-2} day^{-1} which was found to be at par with ZTR *fb* ZTM but significantly higher over PBDSR-R *fb* PBDSM-R and CTR *fb* CTM at 90–120 DAS in both years of study in maize (Table 6). Similarly, LM reported at par CGR with WF but was found to be significantly higher over VM and PVM at all the phenological stages of maize.

Yield of maize: Different tillage practices significantly altered the grain yield of maize with PBDSR+R *fb* PBDSM+R recorded significantly greater grain yield (93.02 and 94.31 q ha^{-1}) by 15.1–15.2% and 17.0–17.3%, stone yield (20.38 and 20.80 q ha^{-1}) by 6.3–8.8% and 12.8–14.1%, cob yield (113.40 and 115.59 q ha^{-1}) by ~13.4–13.9% and ~16.2–18.1% along with stover yield (113.76 and 118.72 q ha^{-1}) by 8.2–10.3% and 12.7–16.3% over PBDSR-R *fb* PBDSM-R and CTR *fb* CTM, respectively across the years but found to be at par with ZTR *fb* ZTM (Table 7). Among the various OWM, LM reported at par grain yield and straw yield with WF and PVM but obtained a significantly superior grain yield, cob yield, and stover yield by 7.4–8.5%, 5.6–8.0% and 7.7–9.3% over VM, respectively. The grain yield, cob yield, and stover yield produced by LM was approximately twice that of UC. Also, there was no significant interaction effect between tillage practices and OWM across the years for different yield parameters of maize.

Table 6. Maize crop growth rate and leaf area index as influenced by CA-based tillage practices and organic weed management.

Treatments	Leaf area index						Crop growth rate (g m^{-2} day^{-1})							
	30 DAS		60 DAS		90 DAS		30–60 DAS		60–90 DAS		90–120 DAS		120 DAS–harvest	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
	Tillage practices (TP)													
ZTR *fb* ZTM	0.5^{a}	0.5^{a}	1.9^{a}	2.3^{a}	3.1^{a}	3.2^{a}	4.7^{ab}	4.7^{ab}	6.4^{ab}	6.6^{ab}	58.0^{ab}	58.5^{ab}	5.8^{a}	5.9^{a}
PBDSR+R *fb* PBDSM+R	0.5^{a}	0.5^{a}	2.0^{a}	2.4^{a}	3.2^{a}	3.3^{a}	4.9^{a}	4.9^{a}	6.5^{a}	6.7^{a}	58.2^{a}	58.8^{a}	5.8^{a}	5.9^{a}
PBDSR-R *fb* PBDSM-R	0.5^{a}	0.5^{b}	1.7^{b}	2.1^{b}	2.8^{b}	2.9^{b}	4.5^{bc}	4.5^{bc}	6.1^{ab}	6.1^{b}	55.9^{ab}	56.8^{ab}	5.3^{bc}	5.5^{b}
CTR *fb* CTM	0.4^{b}	0.4^{c}	1.3^{c}	1.6^{c}	2.4^{c}	2.4^{c}	4.2^{c}	4.3^{c}	5.3^{c}	5.4^{c}	50.5^{c}	50.5^{c}	5.0^{c}	5.1^{c}
	Organic weed management (OWM)													
UC	0.3^{c}	0.3^{d}	1.0^{d}	1.2^{d}	1.9^{d}	2.0^{d}	3.9^{d}	4.0^{d}	5.3^{d}	5.4^{d}	44.5^{d}	44.5^{d}	4.9^{d}	5.1^{d}
VM	0.5^{b}	0.5^{c}	1.7^{c}	2.1^{c}	2.9^{c}	2.9^{c}	4.3^{c}	4.4^{c}	6.0^{bc}	6.1^{bc}	55.6^{bc}	56.7^{bc}	5.2^{d}	5.4^{c}
PVM	0.5^{b}	0.5^{b}	1.8^{b}	2.2^{b}	3.0^{b}	3.1^{b}	4.4^{c}	4.4^{c}	6.1^{bc}	6.1^{bc}	57.2^{bc}	58.3^{abc}	5.6^{c}	5.7^{b}
LM	0.5^{a}	0.5^{ab}	2.1^{a}	2.5^{a}	3.3^{a}	3.3^{a}	4.9^{b}	5.0^{b}	6.3^{b}	6.4^{b}	59.2^{ab}	59.7^{ab}	5.7^{bc}	5.8^{b}
WF	0.6^{a}	0.6^{a}	2.1^{a}	2.6^{a}	3.3^{a}	3.4^{a}	5.3^{a}	5.4^{a}	6.8^{a}	6.9^{a}	61.6^{a}	61.6^{a}	6.1^{a}	6.1^{a}
LSD (T)	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.3	0.4	0.5	4.2	4.0	0.4	0.3
LSD (W)	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.4	0.4	3.6	3.5	0.3	0.2
LSD (T × W)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

* The means with distinct letters within the same parameter indicate statistical significance, while identical letters denote non-significant at $p \leq 0.05$. "NS" represents non-significant

Table 7. Maize yield under the influence of CA-based tillage practices and organic weed management.

Treatments	Grain yield (q ha^{-1})		Stone yield (q ha^{-1})		Cob yield (q ha^{-1})		Stover yield (q ha^{-1})		Harvest index	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
	Tillage practices (TP)									
ZTR *fb* ZTM	88.5^{a}	90.2^{a}	19.5^{ab}	20.4^{ab}	108.1^{a}	110.8^{a}	109.32^{ab}	114.2^{ab}	40.8^{a}	40.2^{a}
PBDSR+R *fb* PBDSM+R	93.0^{a}	94.3^{a}	20.4^{a}	20.8^{a}	113.4^{a}	115.6^{a}	113.76^{a}	118.7^{a}	41.1^{a}	40.4^{a}
PBDSR-R *fb* PBDSM-R	80.8^{b}	81.9^{b}	18.7^{bc}	19.6^{abc}	99.6^{b}	101.9^{b}	103.1^{bc}	109.7^{abc}	39.6^{a}	38.3^{a}
CTR *fb* CTM	79.5^{b}	80.4^{b}	18.1^{c}	18.2^{c}	97.6^{b}	97.8^{b}	100.9^{c}	102.0^{c}	39.7^{a}	39.8^{a}
	Organic weed management (OWM)									
UC	50.0^{d}	51.7^{d}	11.4^{d}	12.3^{d}	61.5^{d}	63.6^{d}	65.0^{d}	67.8^{d}	38.6^{a}	38.3^{a}
VM	89.0^{c}	90.6^{c}	20.2^{bc}	21.2^{bc}	109.2^{c}	112.3^{c}	110.9^{c}	113.8^{c}	40.4^{a}	39.5^{a}
PVM	93.6^{abc}	94.9^{abc}	20.1^{c}	21.1^{bc}	113.8^{bc}	115.7^{bc}	116.0^{bc}	121.1^{abc}	39.5^{a}	39.4^{a}
LM	96.6^{ab}	97.3^{ab}	21.4^{ab}	21.3^{b}	118.0^{ab}	118.6^{ab}	119.4^{ab}	124.4^{ab}	40.0^{a}	39.9^{a}
WF	98.0^{a}	99.0^{a}	22.7^{a}	22.8^{a}	120.8^{a}	122.6^{a}	122.7^{a}	128.7^{a}	39.5^{a}	39.3^{a}
LSD (T)	6.3	5.7	6.0	1.4	1.6	6.6	5.7	7.8	NS	NS
LSD (W)	5.3	4.8	5.0	1.2	1.4	5.5	4.7	6.5	NS	NS
LSD (T × W)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

*The means with distinct letters within the same parameter indicate statistical significance, while identical letters signify non-significant at $p \leq 0.05$. "NS" represents non-significant. "NS" represents non-significant

Table 8. N, P, and K uptake by rice as influenced by CA-based tillage practices and organic weed management.

Treatments	N uptake (kg ha^{-1})				P uptake (kg ha^{-1})				K uptake (kg ha^{-1})			
	Grain		Straw		Grain		Straw		Grain		Straw	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
	Tillage practices (TP)											
ZTR *fb* ZTM	92.3^{b}	102.5^{ab}	57.9^{ab}	61.0^{ab}	12.6^{ab}	14.1^{b}	9.1^{ab}	9.9^{ab}	43.5^{b}	48.6^{b}	125.2^{ab}	129.7^{ab}
PBDSR+R *fb* PBDSM+R	103.9^{a}	110.3^{a}	61.0^{a}	64.3^{a}	13.9^{a}	15.1^{a}	9.6^{a}	10.5^{a}	49.4^{a}	52.5^{a}	130.0^{a}	136.4^{a}
PBDSR-R *fb* PBDSM-R	88.9^{b}	96.9^{b}	53.7^{bc}	55.6^{bc}	12.0^{b}	12.8^{c}	8.4^{bc}	9.1^{bc}	41.6^{b}	45.3^{b}	116.9^{bc}	120.0^{bc}
CTR *fb* CTM	77.4^{c}	86.8^{c}	52.0^{c}	53.8^{c}	10.5^{c}	10.5^{d}	8.1^{c}	8.7^{c}	36.2^{c}	40.5^{c}	112.6^{c}	114.3^{c}
	Organic weed management (OWM)											
UC	49.1^{d}	54.2^{c}	30.5^{d}	32.4^{d}	6.6^{d}	7.3^{d}	4.8^{e}	5.2^{d}	21.^{d}	25.1^{c}	66.4^{d}	69.6^{d}
VM	89.0^{c}	102.3^{b}	59.1^{bc}	60.4^{c}	12.0^{c}	13.1^{c}	9.2^{d}	9.9^{c}	43.2^{c}	47.76^{b}	128.0^{bc}	130.0^{c}
PVM	101.3^{b}	106.3^{b}	61.0^{bc}	63.0^{bc}	13.7^{b}	13.8^{c}	9.6^{cd}	10.3^{bc}	45.4^{c}	50.0^{b}	131.4^{bc}	134.7^{bc}
LM	104.3^{ab}	115.2^{a}	62.8^{ab}	66.9^{ab}	14.1^{ab}	15.3^{b}	9.9^{bc}	10.9^{ab}	48.9^{b}	55.0^{a}	135.5^{ab}	142.6^{ab}
WF	109.5^{a}	117.7^{a}	67.3^{a}	70.6^{a}	14.7^{a}	16.2^{a}	10.6^{a}	11.4^{a}	51.7^{a}	55.8^{a}	144.6^{a}	148.7^{a}
LSD (T)	8.3	9.0	4.8	7.1	1.3	0.9	0.8	1.1	4.7	3.4	11.3	13.2
LSD (W)	6.3	6.4	4.6	4.5	0.8	0.9	0.7	0.8	2.6	3.1	9.1	9.3
LSD (T × W)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

* The means with distinct letters within the same parameter indicate statistical significance, while identical letters denote non-significant at $p \leq 0.05$. "NS" represents non-significant

Table 9. N, P, and K uptake by maize as affected by CA-based tillage practices and organic weed management.

Treatments	N uptake (kg ha^{-1})				P uptake (kg ha^{-1})				K uptake (kg ha^{-1})			
	Grain		Stover		Grain		Stover		Grain		Stover	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
	Tillage practices (TP)											
ZTR *fb* ZTM	125.5^{a}	128.6^{a}	52.9^{ab}	55.6^{a}	34.5^{b}	35.51^{b}	22.58^{ab}	25.7^{b}	52.9^{b}	55.6^{a}	129.4^{b}	135.5^{b}
PBDSR+R *fb* PBDSM+R	132.7^{a}	135.6^{a}	57.4^{a}	58.2^{a}	36.8^{a}	38.1^{a}	24.3^{a}	27.6^{a}	57.4^{a}	58.2^{a}	140.0^{a}	144.6^{a}
PBDSR-R *fb* PBDSM-R	112.4^{b}	115.1^{b}	48.81^{bc}	49.4^{bc}	30.8^{c}	31.9^{c}	21.4^{bc}	24.2^{bc}	48.8^{bc}	49.4^{b}	115.9^{c}	128.8^{b}
CTR *fb* CTM	108.6^{b}	110.5^{b}	47.0^{c}	47.5^{c}	29.7^{c}	30.8^{c}	20.7^{bc}	22.6^{c}	47.0^{c}	47.5^{b}	116.1^{c}	117.3^{c}
	Organic weed management (OWM)											
UC	69.2^{c}	72.2^{c}	27.6^{d}	30.81^{c}	18.8^{d}	19.9^{d}	13.3^{d}	14.9^{c}	27.6^{d}	30.8^{c}	77.0^{d}	79.5^{c}
VM	124.27^{b}	126.8^{b}	53.7^{c}	54.57^{b}	34.02^{c}	35.2^{c}	22.3^{c}	26.0^{b}	53.7^{c}	54.6^{b}	122.1^{c}	135.5^{b}
PVM	130.4^{b}	133.3^{b}	55.7^{bc}	56.49^{b}	35.8^{b}	37.2^{b}	24.2^{b}	26.5^{b}	55.7^{bc}	56.5^{b}	132.2^{b}	137.1^{b}
LM	135.9^{ab}	138.2^{ab}	59.5^{ab}	60.0^{a}	37.5^{ab}	38.6^{ab}	25.2^{ab}	28.4^{a}	59.5^{ab}	60.0^{a}	149.1^{a}	150.6^{a}
WF	139.2^{a}	141.7^{a}	61.0^{a}	61.6^{a}	38.6^{a}	39.6^{a}	26.2^{a}	29.3^{a}	61.0^{a}	61.58^{a}	146.4^{a}	154.9^{a}
LSD (T)	9.5	8.1	4.8	4.1	2.0	1.8	2.2	1.7	4.8	4.1	9.1	8.3
LSD (W)	8.1	6.9	4.0	3.4	1.7	1.6	1.7	1.3	4.0	3.4	8.4	6.4
LSD (T × W)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

* The means with distinct letters within the same parameter indicate statistical significance, while identical letters denote non-significant at $p \leq 0.05$. "NS" represents non-significant

Nutrient uptake in rice and maize: In rice, PBDSR+R *fb* PBDSM+R was found to be at par with ZTR *fb* ZTM in terms of N uptake but acquired significantly higher N uptake in grain (103.89 and 110.35 kg ha^{-1}) by 13.9–16.8% and 27.2–34.2% and in straw (61.03 and 64.34 kg ha^{-1}) by 13.6–15.6% and 17.4–19.7% over PBDSR-R *fb* PBDSM-R and CTR *fb* CTM, respectively (Table 8). Among OWM, LM reported at par grain and straw N uptake with WF and PVM but obtained a significantly superior grain and straw N uptake by 12.6–17.2% and 6.2–10.7% over VM, respectively (Fig. 2). The grain and straw N uptake reported by LM was approximately twice that of UC. A similar trend of uptake pattern was observed for P and K uptake in grain and straw for rice. Similar kind of nutrient uptake pattern was observed in the subsequent maize crop with PBDSR+R *fb* PBDSM+R was observed to be statistically at par with ZTR *fb* ZTM in terms of N uptake but acquired significantly higher N uptake in grain (132.72 and 135.58 kg ha^{-1}) by 17.8–18.0% and 22.3–22.7% and in stover (57.36 and 58.18 kg ha^{-1}) by 17.5–17.7% and 22.0–22.4% over PBDSR-R *fb* PBDSM-R and CTR *fb* CTM, respectively (Table 9). Among the various OWM, LM reported at par grain and stover N uptake with WF and PVM but obtained a significantly superior grain and stover N uptake by 9.0–9.4% and 9.9–10.9% over VM, respectively. The grain and stover N uptake reported by LM was approximately twice that of UC (Fig. 4). A similar trend of uptake pattern was observed for P uptake and K uptake in grain and stover for maize with PBDSR+R *fb* PBDSM+R obtaining significantly superior value among the tillage practices and LM among the OWM across the years of cropping.

Economics: A substantial amount of lesser cost of cultivation was associated with the ZT system with INR 14720 ha^{-1} lesser as compared to CT system and LM among the OWM recorded lesser cost of cultivation of ~ INR 40000 ha^{-1} compared to PVM and VM (Table 9). The PBDSR+R *fb* PBDSM+R recorded the highest system net returns (INR 190050 ha^{-1} or US$ 14088406 ha^{-1} and INR 230958 ha^{-1} or US$ 17074724 ha^{-1}) over other tillage practices whereas among the OWM, LM recorded significantly higher net return of INR 207787 ha^{-1} or US$ 15403250 ha^{-1} and INR 256301 ha^{-1} or US$ 18948332 ha^{-1} over VM and PVM but found to be at par with WF across the years (Table 10a). Along with this, significantly higher BCR was reported by PBDSR+R *fb* PBDSM+R (1.50 and 1.62) and LM (1.76 and 1.90), respectively. Interaction effect of CA-based tillage practices and OWM was significant and it is well perceived that the treatment PBDSR+R *fb* PBDSM+R with LM application enumerated the significantly higher BCR (Table 10b).

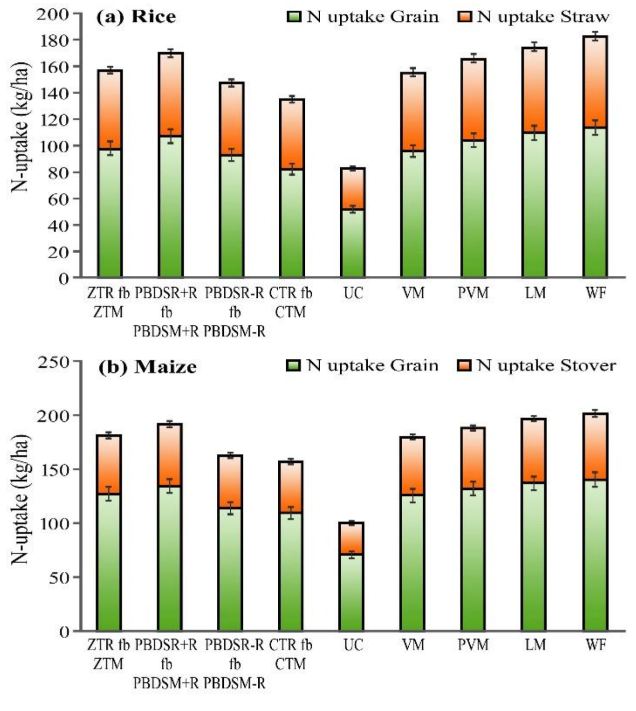

Fig. 4. N uptake (mean of two years) in grain and straw/stover of rice and maize as influenced by different tillage practices and organic weed management.

*Refer Table 1 for treatment details, the means with distinct letters within the same parameter indicate statistical significance, while identical letters denote non-significant at $p \leq 0.05$.

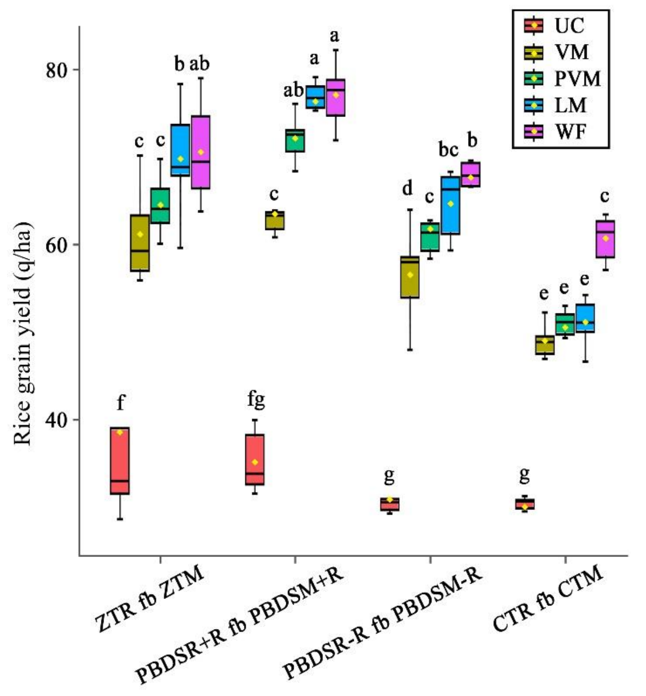

Fig. 5. Rice grain yield (mean of two years) as influenced by the interaction effect of various tillage practices and organic weed management (N=120)

*Refer Table 1 for treatment details, The means with distinct letters within the same parameter indicate statistical significance, while identical letters denote non-significant at $p \leq 0.05$.

Table 10a. Economic aspects of rice–maize system as influenced by CA-based tillage practices and organic weed management.

Treatments	Cost of cultivation (INR ha^{-1})		Net returns (INR ha^{-1})		BCR	
	2019	2020	2019	2020	2019	2020
	Tillage practices (TP)					
ZTR *fb* ZTM	89963	92711	168951^{b}	213469^{b}	1.34^{b}	1.49^{b}
PBDSR+R *fb* PBDSM+R	90033	92781	190050^{a}	230958^{a}	1.50^{a}	1.62^{a}
PBDSR-R *fb* PBDSM-R	91313	94061	140489^{c}	182661^{c}	1.01^{c}	1.12^{c}
CTR *fb* CTM	104683	107431	120873^{d}	160055^{d}	0.84^{d}	0.96^{d}
	Organic weed management (OWM)					
UC	86313	89061	70143^{e}	97083^{c}	0.76^{e}	0.88^{d}
VM	147593	150341	140778^{d}	190352^{b}	0.91^{d}	1.06^{c}
PVM	147593	150341	160059^{c}	195889^{b}	1.02^{c}	1.10^{c}
LM	108513	112221	207787^{a}	256301^{a}	1.76^{a}	1.90^{a}
WF	129513	132261	196687^{b}	244303^{a}	1.41^{b}	1.54^{b}
LSD (T)	-	-	12211	16060	0.09	0.11
LSD (W)	-	-	10165	13369	0.08	0.10
LSD (T × W)	-	-	NS	NS	S	S

* The means with distinct letters within the same parameter indicate statistical significance, while identical letters denote non-significant at $p \leq 0.05$. "NS" represents non-significant, "S" represents significant

Table 10b. Interaction effect of CA-based tillage practices and organic weed management in rice-maize rotation on BCR.

BCR	2019						2020					
	UC	VM	PVM	LM	WF	Mean	UC	VM	PVM	LM	WF	Mean
ZTR *fb* ZTM	1.0	1.0	1.1	2.0	1.6	1.3	1.1	1.2	1.2	2.2	1.8	1.5
PBDSR+R *fb* PBDSM+R	1.1	1.1	1.3	2.2	1.7	1.50	1.3	1.3	1.4	2.3	1.9	1.6
PBDSR-R *fb* PBDSM-R	0.6	0.8	0.9	1.5	1.2	1.0	0.7	1.01	0.9	1.6	1.3	1.1
CTR *fb* CTM	0.4	0.6	0.7	1.3	1.1	0.8	0.4	0.8	0.9	1.4	1.2	1.0
Mean	0.8	0.9	1.1	1.8	1.4		0.9	1.1	1.1	1.9	1.5	
	T		**W**		**A**	**B**	**T**		**W**		**A**	**B**
SEm±	0.03		0.02		0.06	0.06	0.03		0.02		0.08	0.06
LSD ($p \leq 0.05$)	0.09		0.08		0.17	0.18	0.11		0.10		0.16	0.18

*A: Subplot at the same level of main plot, B: Mainplot at the same level of subplot

Discussion

Crop growth: The results of this study indicated that the crop performance progressively increased with the advancement of crop duration and was significantly affected by tillage and weed management treatments throughout the life cycle. The permanent bed with residue reduced the weed population and thus provided better growth conditions for the crop. The reason behind this can be residue retention on the soil surface which inhibited weed seed germination due to the incidence of direct sunlight which inhibited weed seed germination. The increase in crop growth under PBDSR+R *fb* PBDSM+R as compared to CTR *fb* CTM might be because conventional tillage brought deeply buried weed seeds up to the surface, which facilitated their germination and growth of the rice and maize (Mitra *et al.*, 2019). CT resulted in inferior crop growth compared to the PBDSR+R *fb* PBDSM+R approach. The incorporation of organic matter from decomposed residue retained on the soil surface enhanced soil health, directly influencing crop growth positively. An additional factor contributing to this outcome could be the impact of tillage operations in the CTR *fb* CTM system on the vertical distribution of weed seeds, influenced by the frequency and type of tillage implement used. Soil pulverization in the CT system led to the burial of weed seeds at greater depths, preventing exposure to sunlight and subsequent germination. As a consequence, specific weeds emerged at the field scale, while the remaining seeds remained in the soil (Ranjan *et al.*, 2022). Our study's findings unequivocally demonstrate the advantages of transitioning from flats to PB in a rice-maize system with residue retention, attributing these benefits to enhanced weed control, reduced water and nutrient percolation losses, rapid seedling establishment, and improved nutrient availability.

Application of LM resulted in better crop growth as *Sesbania* and *Pisum sativum* mulch were able to provide soil cover, which lowered the weeds' biomass due to interference with light penetration up to weeds and release of phytotoxins due to decomposition of mulch suppressed weed growth and development (Modak *et al.*, 2020). The mulch proved very effective in decreasing weed emergence, and weed growth and ultimately provided a suitable environment for better crop growth and development. LM protected the soil from crusting and surface sealing, and reduced soil compaction and temperature. Moreover, it conserves soil moisture, improves soil aggregation, and promotes root growth (Lentz & Bjorneberg, 2003). According to the findings of Kocira *et al.* (2020), the utilization of a living legume cover crop has the potential to diminish weed infestation through niche pre-emption. Furthermore, the crop residues of these legumes act as a physical and chemical barrier, inhibiting or delaying weed emergence and growth. This mechanism has a positive impact on crop yield. Ezung *et al.* (2018) and Jamshidi *et al.* (2013) also reported that the application of cowpea mulch promoted crop growth by significantly reducing weed abundance.

Yield: The results of our investigation revealed elevated rice and maize yields in the PBDSR+R and ZT treatments compared to CTR, aligning with similar findings observed in the rice-wheat system within the region (Gathala *et al.*, 2011). Straw or stover yield is an amalgamation of growth parameters such as plant height and dry matter accumulation. The highest wheat straw yield is attributed to increased dry matter accumulation and plant height, particularly evident in PBDSR+R *fb* PBDSM+R and with the application of LM. This enhancement is likely linked to improved nutrient supply throughout the crop growth period, fostering favorable conditions for growth and development (Singh *et al.*, 2016; Tuti *et al.*, 2022). The Harvest index, representing the ratio of economic yield to biological yield, did not exhibit significant variation. These results closely align with the findings of Jain *et al.* (2022). Rapid disintegration of wastes aided in the easy nutrient availability by the residue retention and organic mulching treatments, which then enhanced yield attributes, resulting in better yields. Even, there was a negative impact by the CA-based tillage residue retained treatments and mulching on the weed population that eventually aided in an increase in yield of the crop under study (Singh *et al.*, 2016).

Amongst the OWM practices, UC resulted in the lowest grain yield due to heavy competition with weeds in DSR. The findings of Kumar and Ladha (2011), Rao *et al.*, (2014) and Nandan *et al.*, (2019) are also in agreement with the concept. Adoption of PBDSM+R with OWM practices, provides benefits, including higher grain yield in rice (Fig. 5). This might be ascribed to low weed density and less crop-weed competition during the initial crop growth stage in these treatments. Conventional and zero tillage treatments with residue retention resulted in higher straw or stover and grin yield under rice-maize rotation. This could be due to sustaining optimum soil moisture, moderate soil temperature, and improved nutrient availability (Jat *et al.*, 2019). The PB may have led to effective control of irrigation and drainage, reducing the short-term temporary aeration stress under high rainfall conditions. The yield of the two years showed that the maize grain yield in PBDSM and ZTM was significantly higher than in CTM.

The lower cob yield in the unweeded control may be due to increased weed infestation and interspecific competition. Similar results of increased yield using mulching practice were reported by Kwabiah (2004). The WF and LM treatments recorded maximum grain yield in contrast to the lowest obtained in UC. The increased yield with the application of LM can be due to the beneficial effects of mulching as compared to unmulched treatments. Additionally, manual weeding twice increased the grain yield (Rafenomanjato *et al.*, 2023). However, Chikoye *et al.*, (2004) found that weeding using manual labour (three times) was essential to achieve maximum grain yield. The significant enhancement in rice and maize yields could be attributed to a reduced weed presence during crucial growth stages of the crops. Additionally, the increased yield observed with LM as an organic source of plant nutrients may be attributed to the expansion of the photosynthetic area, greater dry matter accumulation per plant, enhanced translocation of photosynthates toward the sink, and improved yield attributes (Javed *et al.*, 2021; Babu *et al.*, 2023).

Economics: It is essential to understand how smallholder farmers can exploit their farm profits with the effective use of natural resources such as land, energy, water, and labor). The current study has demonstrated the effects of CA-based OWM options on profitability. It was observed that rice-maize rotations had higher net return due to the high yields of monsoon rice and winter maize. Further, maize cultivation had lower production costs, and required lower labor (due to less irrigation water application) as compared to winter rice. The higher net margin of the rice-maize system compared to the rice-rice system is consistent with other studies in South Asia (Jat *et al.*, 2020; Gathala *et al.*, 2021). A recent on-farm study spread over several hundred farmers in three countries of the eastern Gangetic plain demonstrated that the rice-maize rotation would be the most profitable cropping system for smallholder farmers (Hoque *et al.*, 2023). In this study, LM under CA-based practices attains the higher grain yield which leads to higher net returns and BCR (Roy *et al.*, 2023; Ghosh *et al.*, 2020).

Nutrient uptake: The crop's nutrient uptake is contingent on both the yield and the concentration of nutrients in various plant parts. In this study, there was an increase in the uptake of nitrogen, phosphorus, and potassium in plants under PBDSR+R- PBDSM+R compared to CTR-CTM. The proportional increase in nutrient uptake can be attributed to increased grain yield under permanent bed tillage practice with residue retention and mulching practices. This could be due to sustaining optimum soil moisture, moderate soil temperature, and improved nutrient availability due to reduced weed density during the initial crop growth stage. Moreover, the PB may have led to proper irrigation and drainage, reducing the short-term temporary aeration stress under high rainfall conditions (Jat *et al.*, 2018; Pooniya *et al.*, 2022). The PB with residue retained on the soil surface increased saturated and unsaturated hydraulic conductivities, microbial population, water holding capacity, and soil porosity which in turn increased nutrient availability (Jat *et al.*, 2013). On the other hand, in conventional tillage, the reduction in crop dry matter due to higher weed density lead to less competition for nutrient, light, and water at early growth stages, which reduces the nutrient uptake of the crop (Gul and Khanday, 2015). The increased availability of nutrients, influenced by residue retention and LM application, is likely responsible for enhancing physiological and metabolic functions within the plant, thereby promoting improved expression of growth parameters, yield, and nutrient uptake (Chesti *et al.*, 2013; Parihar *et al.*, 2017). The heightened biomass production can be identified as a significant factor contributing to the increased nutrient uptake. Additionally, the improved physical properties of the soil may have played a pivotal role in mobilizing nutrients, facilitating their availability, and enhancing nutrient uptake (Ghosh *et al.*, 2020; Singh *et al.*, 2016). Moreover, the elevated nutrient uptake might also be attributed to the higher availability of nutrients from the soil reservoir and the additional quantity of nutrients supplied by LM, resulting in a subsequent increase in grain yield.

Conclusion

In summary, our results showed significant variations in crop growth, yield, economics, and nutrient uptake induced by different tillage and weed management regimes in the rice-maize cropping system. Adoption of PB with residue retention enhanced nutrient uptake by increasing crop growth and yield. In contrast, conventional tillage reported poor growth, which ultimately led to less yield and nutrient uptake as compared to other treatments. Application of LM reported 110 and 90.6% increases in grain yield of rice and maize respectively as compared to UC. Our findings indicate a shift towards residue retention-based tillage practices and the adoption of suitable LM practices will be the key to enhancing crop growth, productivity, profitability, and nutrient uptake under rice-maize cropping systems. However, further research should be conducted to assess its influence on different rice-based cropping systems. Moreover, the effect on soil physicochemical properties and microorganisms should be studied, to further understand the additional benefits of adopting residue retention and organic weed management on the field crop growing environment for its large-scale adoption.

Acknowledgements

The authors extend their appreciation to Taif University, Saudi Arabia, for supporting this work through project number (TU-DSPP-2024-168)

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(Received for publication 07 September 2024)