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Research article

Conservation agriculture and weed management effects on weed community and crop productivity of a rice-maize rotation

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A R T I C L E I N F O

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A B S T R A C T

In recent years, an increase in weed infestation, which is adversely affecting crop growth and productivity has been a major challenge facing the farmers of South Asia. The adoption of a permanent bed in combination with residue retention-based crop management practices may reduce weed abundance and increase crop productivity. In a two-year field study, we evaluated the responses of different organic weed management practices with contrasting tillage and residue (R) management strategies to weed dynamics and crop productivity under rice-maize rotation. 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; vermicompost mulch; P- enriched vermicompost mulch; live mulch with *Sesbania* spp. in rice and *Pisum sativum* in maize and weed-free. Total weed density and biomass in rice and maize at 30 days after sowing (DAS) were minimum for PBDSR + R *fb* PBDSM + R compared to remaining tillage and residue management practices in both years. Apart from weed-free treatment, the highest weed control index was found with live mulch. Yield of rice and maize were found higher in permanent beds along with residue retention-based practices. In rice, the weed-free treatment showed the highest grain yield and live mulch reported 9.8 and 6.8 % higher grain yield than vermicompost mulch and P-enriched vermicompost mulch respectively. Our study shows that conservation agriculture practices under rice-maize rotation is one of the ways to reduce weed density and improve crop productivity in South Asia and other similar agro-ecologies.

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1. Introduction

Out of 1.5 Mha area under rice-maize cropping sytem in South Asia, India covers around 0.53 Mha [48]. As a component crop in rice-based systems, maize is rapidly gaining popularity among farmers in South Asia. These changes are primarily due to not only the increased productivity but also the lucrativeness of maize. Winter maize serves as a promising mitigation option in regions with limited water resources due to its lower water consumption than winter rice [27]. As a result of conventional crop management practices, cereal-based systems result in depletion and degradation of natural resources, greenhouse gas emissions, high production costs, low input efficiency, and weed shift, which threaten the viability of such cropping systems particularly in South Asia [25,38]. Traditionally, rice is planted by intensive dry and wet tillage, which is then followed by manual transplantation. This normally delays the rice transplantation process and reduces yield. As a substitute to the conventional tillage system, some of the conservation agriculture (CA)-based component routes including crop residue retention, zero tillage (ZT), and crop diversification have been assessed in South Asia [28,37]. Although most efforts in South Asia have been focusing on zero-tillage production in rice and wheat, the potential paybacks of CA-based strategies have yet to be fully realized in most cropping systems such as rice-maize rotation [15]. This results in a significant knowledge lacuna regarding the performance of CA-based practices in RM systems. Aside from the various benefits that have been gained from CA systems, weed control remains a major inhibition of its efficiency since weed infestations decrease crop yields [2,29,46]. Although surface retention of residues in CA-based systems suppresses to a certain extent, weed emergence, residues equally restrict mechanical or manual weed control [33]. Many studies have reported that modifications in crop establishment from puddled transplanted rice (PTR) to ZT-direct seeded rice (DSR) result in substantial variations in weed density, community composition, and competitiveness with the primary crops [7,20,34]. Kumar and Ladha [30] stated that a shift to ZT-DSR from PTR improved grass species abundance and richness, including *Leptochola chinensis*, *Dactyloctenium aegyptium* (L.) Willd., *Cyperus iria* L., *Fimbristylis quinquangularis* (Vahl) Kunth, and *Cyperus rotundus* L. High weed abundance, high costs and low availability of suitable herbicides, and insufficiently integrated weed management approaches can diminish farmers' acceptance of ZT-DSR. An enhanced understanding of the influence of weed dynamics and community composition on rice productivity could benefit the development of suitable weed management options. Such strategies would include cropping systems that utilize direct seeding of rice as well as the ones where the crop is rotated with other winter-season alternative crops like maize. Even though organic weed management strategies such as live mulch and the use of vermicompost are believed to be climate-resilient practice, which offers several benefits such as moisture conservation, weed suppression, improvement of soil health, and sequestration of carbon and nitrogen [17,43] however studies are inadequate to substantiate these paybacks. Furthermore, under the CA-based system, there is a huge application of chemical herbicides, which affects the environment and soil health. Therefore, there is a need to develop some efficient organic weed management

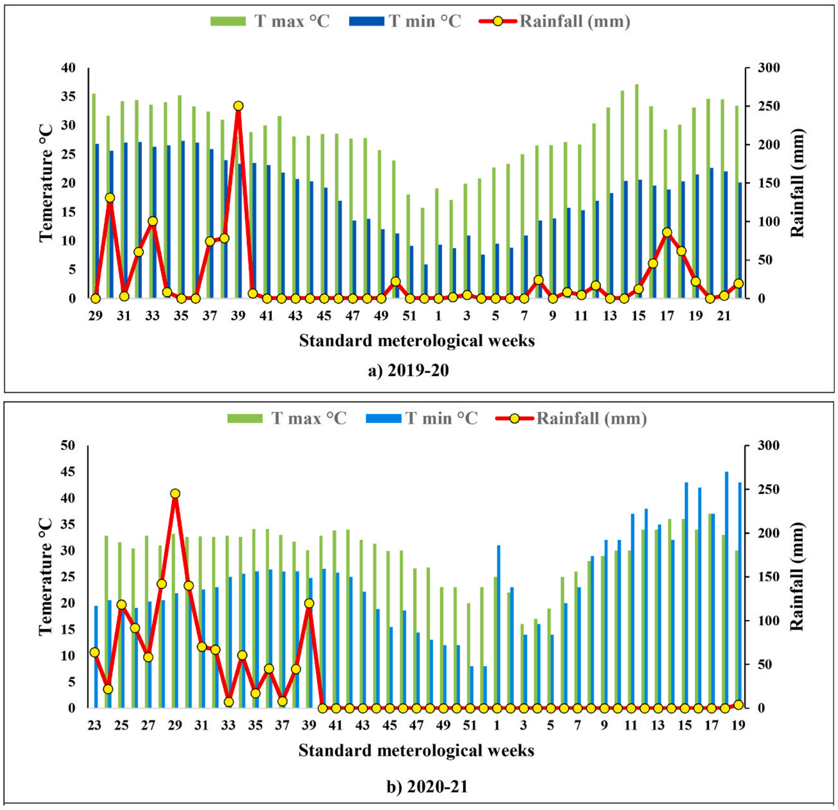

Fig. 1. The weekly minimum temperature, maximum temperature and rainfall during the study period of 2019–20 and 2020–21.

strategies under a CA-based system that not only control the weeds but also maintain crop productivity.

A significant amount of research has been directed at understanding the influence of weed management practices under CA-based systems on various crops. However, the integrated effects of these practices have not been thoroughly explored on an individual crop for the long-term. Most of the information explaining the effects on crop productivity and weed community is lacking. Furthermore, most of the studies in rice-based cropping systems are focused on DSR *fb* ZT in subsequent crops. Alternative rice establishment techniques like ZTDSR, and permanent bed with or without residue retention are important to explore. This will help to understand the best crop management practices to sustain the productivity of rice-based cropping systems. Based on these facts, the present study investigated the effectiveness of organic weed management practices under CA technologies (ZT with either permanent bed with and without residue retention or with residue retention).

Therefore, the current study aimed to assess the dynamics of weed populations and their effects on yield in response to organic weed management practices in contrasting tillage and residue management regimes in rice-maize rotation. We hypothesized that organic weed management strategies under ZT or residue retention and bed planting would result in less weed infestation and higher crop productivity compared with conventional practices.

2. Materials and methods

2.1. Site description 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 (located 20° 58′ N, 85° 40′ E, at an elevation of 173 m above the mean sea level), Pusa. The climate of the experimental site is characterized by a hot sub-humid (moist) 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 and September. The quantity of rainfall received during the experimental years was inconstant and was 1046 and 1327 mm during 2019–20 and 2020–21, respectively. January recorded the lowest mean minimum temperature of 9.4 °C in both years. During the 2019–20 cropping cycle, June had the highest maximum temperature of 37.5 °C, whereas in the cropping year 2020–21, April was the hottest month with a maximum temperature of 35.8 °C (Fig. 1).

Soil sampling was done from 0 to 15 cm layer using a steel auger of 5.0 cm internal diameter at the start of the experiment in May 2019. The soil was clay loam in texture, with pH (1:2 soil: water) of 8.3, organic C content of 7.1 g ha^{-1} [49], $KMnO_4$-oxidizable N of 320 kg ha^{-1} [47], 0.5 M $NaHCO_3$ extractable P of 13 kg ha^{-1} [39], and NH_4OAc-exchangeable K of 140 kg ha^{-1} [40].

2.2. Treatment details and experimental design

The field experiment consisted of four main treatments and five sub-treatments, which were replicated thrice in a split-plot design in plots measuring 6 m by 2.6 m. Four treatments of tillage and residue management practices and five treatments of weed control strategies (Table 1) in a rice-maize rotation were tested. During the two years of experimentation, about 3.0–5.0 and 3.5–4.8 Mg ha^{-1}, of rice residues were retained on the soil surface in maize plots in PBM and ZTM treatments, while maize residue of 2.7–5.0 and 2.2–4.8 Mg ha^{-1} was retained in PBDSR and ZTDSR rice plots, respectively. The remaining quantities of residues were utilized as fodder for cattle.

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

Used treatment notations	Treatment descriptions
Tillage and residue management	
ZTR *fb* ZTM	Zero-tillage laser leveled, 50 % rice residue retention for maize, 25 % maize residue retained for rice
PBDSR + R *fb* PBDSM + R	Zero-tillage on permanent bed, 50 % rice residue retention for maize, 25 % maize residue retained for rice
PBDSR-R *fb* PBDSM-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	No weed control
Vermicompost mulch	Vermicompost mulching before sowing/transplanting at the rate of 5t ha^{-1}. The chemical properties of vermicompost used in the experiment were pH- 7.8, N- 2.21 %, P- 1.11 % and K- 1.25 %.
P- enriched Vermicompost mulch	P-enriched vermicompost mulching before sowing/transplanting at the rate of 5t ha^{-1}. The chemical properties of vermicompost used in the experiment were pH- 7.8, N- 2.30 %, P- 1.23 % and K- 1.37 %.
Live mulch	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. The nutrient content of *Sesbania* spp. and *Pisum sativum* used in the experiment were N-3.50 %, P-0.60 %, K-1.20 % and N-0.90 %, P-0.30 %, K-0.40 % respectively.
Weed-free	Hand weeding at 20, 40 and 60 DAS

2.3. Crop and weed management

2.3.1. Crop geometry

The hardpan under the plough layer was broken using a chisel plough, and the field was then tilled deeply (to a depth of 30 cm) and laser leveled. For transplanted rice, 25-day-old seedlings were manually transplanted using random geometry at a density of 30 seedlings m^{-2}. Each raised bed (10–12 cm high) was planted directly with two rows (30 cm apart) of rice using a multi-crop raised bed planter with a top width of 37 cm and furrow spacing of 67 cm (ASS Foundry & Agri. Works, Jandiala Guru, Punjab, India). During the rice cycle, no reshaping was done. Seeds were direct drilled with a zero-tillage seed-cum-fertilizer planter fitted with an inclined-plate seed metering system (ASS Foundry & Agri. Works, Jandiala Guru, Punjab, India) at a row spacing of 20 cm in ZTDSR. Using the depth control wheel, the seeding depth was kept constant at 2–3 cm for all DSR treatments. Ploughing twice with disc harrows was followed by a single pass with a spring-tine cultivator via a multi-crop planter (A.S.S. Foundry & Agri. Works, Jandiala Guru, Punjab, India). The ZTM plots were established without any pre-tillage using a zero-till seed, fertilizer, and seed metering planter fitted with an inclined plate seed metering system. The sowing depth was kept between 3 and 5 cm using the depth control wheel. Each permanent raised bed was planted with one row of maize (67 cm apart) using a raised bed planter. During the maize cycle, raised beds were reshaped with the raised bed planter's reshaping shovel, i.e. sowing and reshaping occurred concurrently. Hand weeding with "khurpi" was done according to the treatments. Throughout the research, no herbicides were employed.

2.3.2. Seed rate, sowing time and cultivars

Rice cv. Rajendra Mashuri was sown with seed rates of 25, 20, and 12 kg ha^{-1} under ZTDSR, PBDSR, and conventional treatments, respectively. Whereas, for winter maize cv. DKC 9081, sowing was done at an even seed rate of 25 kg ha^{-1} across the treatments. ZT/PBR rice was sown on June 8, 2019, June 3, 2020, and harvested on November 23, 2019, and November 15, 2020, whereas CTR was sown on June 30, 2019, June 27, 2020, and harvested on November 25, 2019, and November 18, 2020, respectively. During the study period, the maize crops were sown on December 5, 2019 and November 27, 2020 and harvested on May 22, 2020 and May 7, 2021.

2.4. Fertilizer and irrigation management

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

Customarily, ZTDSR was sown using the residual soil moisture from the pre-monsoon showers and subsequent irrigation was scheduled whenever there was no rain for 7 days following seeding. While, each irrigation, around 60 mm 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.

2.5. Weed observations and measurement of yield

The data on weeds were recorded using a 0.5 m^2 quadrat, which was randomly placed four times in each plot. In this case, inside the quadrat, annual and perennial grasses were assessed and counted. In addition, the sedges and broad-leaved dicots that were observed were recorded and noted by species. The samples for weed biomass were collected and oven-dried for 72 h at 65 °C and, thereafter, weighed and expressed in g m^{-2}. Sampling for weed biomass and species count was done 30 days after sowing (DAS) during the growing season of each crop.

Weed control index (WCI) (%) was worked out using the formula given by Mishra and Tosh [35]

$$\text{Weed control index (\%)} = (\text{DWu} - \text{DWt})/\text{DWu} \times 100$$

where DWu is dry matter produced by weeds under unweeded control.

DWt is dry matter produced by weeds in the treated plot under consideration.

Rice grain yields (t ha^{-1}) were assessed from a 10 m^2 sampling area at the center of each subplot. For the maize crop in permanent raised beds harvesting was done from 2.01 m width (0.67 m × 3 m) of 5 m length while in CT and ZT harvesting was carried out from the whole net plot area of 10 m^2 (2 m × 5 m). Grain yield was recorded at 14 % moisture content.

2.6. Statistical analysis

Data analyses were performed on a year-wise basis for the weed density and aboveground weed biomass m^{-2} after transforming it using the square root $\left(\sqrt{x + 0.5}\right)$ (where x is the observed value and 0.5 is the constant) to lower the range of variation and were then statistically analyzed following the standard procedures. Using ANOVA for the treatment effects on all the characters considered were then compared by using the 'F' test. The analysis was then executed using SAS 9.3 (SAS Institute, Cary, NC) using PROC GLM procedure for the split-plot design. Post hoc mean separation was performed using Tukey's honest significant ($P \leq 0.05$) difference test [18]. The correlation study and weed density of individual weed for respective treatment were analyzed through principal component bi-plot analysis using the R 4.3.1 software.

3. Results

3.1. Weed density

The tillage and organic weed management treatments significantly influenced the weed density of rice-maize rotation during the years 2019–20 and 2020–21. Weed species belonging to different botanical families that emerged in both rice and maize were recorded at 30 DAS.

3.1.1. Grasses

Among tillage practices, at 30 DAS the CTR *fb* CTM recorded the highest density of *Echinochloa* spp. (3.15 and 3.00 m^{-2}) during both the years respectively as compared to all other treatments in rice. During both years of the study, PBDSR + R *fb* PBDSM + R recorded 26.9 and 18.6 % lower density as compared to CTR *fb* CTM respectively (Table 2). Similarly, in maize weed density of *Dactyloctenium aegyptium* is 14.8 and 8.6 % lower in the PBDSR + R *fb* PBDSM + R as compared to the CTR *fb* CTM. There was a 9.8, and 10.3 % reduction in weed density of other grasses in winter maize due to residue retention in PBDSR *fb* PBDSM as compared to PBDSR-R *fb* PBDSM-R during both the years of study.

During both years of experimentation, the maximum density of grassy weeds was observed in unweeded control and lowest in weed-free treatment in rice-maize rotation among different organic weed management strategies (Table 2). However, live mulch recorded 35.9 % less density of *Echinochloa* spp. as compared to unweeded control in rice during 2019 and 2020 respectively. Furthermore, in maize, the density of *Dactyloctenium aegyptium* was 12.3 and 13.9 % lower in live mulch treatment as compared to average of vermicompost mulch enriched with and without P treatment during 2019–20 and 2020–21 respectively. Whereas, there was no significant interaction effect between tillage practices and organic weed management practices across the years for weed density of grasses at 30 DAS of rice-maize rotation.

3.1.2. Sedges

Among the sedges, *Cyperus* spp. was found in rice-maize rotation during the study period (Table 3). In rice, the density of *Cyperus* spp. was the lowest under PBDSR + R *fb* PBDSM + R tillage practice (2.32 and 2.22 m^{-2}) which was 25.1 and 27.7 % lower than CTR *fb* CTM practice that showed the highest weed density during both of the years. Similarly, in maize, the CTR *fb* CTM recorded the highest (3.70 and 2.95 m^{-2}) weed density but it was statistically at par (2.84 and 2.75 m^{-2}) with PBDSR-R *fb* PBDSM-R tillage practice in 2019–20 and 2020–21 respectively.

The maximum and minimum density of *Cyperus* spp. among organic weed management treatments in rice was recorded under unweeded control and weed-free treatment respectively during both the years 2019 and 2020. Moreover, in maize, the unweeded plots

Table 2
Weed density of grasses at 30 DAS as influenced by contrasting tillage, residue, and organic weed management practices in rice-maize rotation.

Treatments	Rice (No. m^{-2})				Maize (No. m^{-2})			
	Echinochloa spp.		Other grasses		*Dactyloctenium aegyptium* (L.) Willd.		Other Grasses	
	2019	2020	2019	2020	2019–20	2020–21	2019–20	2020–21
Tillage and residue management (T)								
ZTR *fb* ZTM	2.76^{bc} (7.60)	2.61^{b} (6.80)	2.72^{b} (8.07)	2.66^{bc} (7.14)	2.68^{bc} (7.00)	2.58^{bc} (6.40)	2.87^{abc} (8.13)	2.80^{abc} (7.67)
PBDSR + R *fb* PBDSM + R	2.51^{c} (6.33)	2.31^{c} (5.60)	2.42^{c} (7.33)	2.50^{c} (6.27)	2.54^{c} (6.47)	2.67^{bc} (5.60)	2.67^{bc} (6.87)	2.61^{c} (6.60)
PBDSR-R *fb* PBDSM-R	2.97^{ab} (8.80)	2.77^{ab} (7.67)	2.85^{b} (9.00)	2.84^{ab} (8.06)	2.86^{ab} (8.00)	2.74^{ab} (7.27)	2.96^{ab} (8.67)	2.91^{ab} (8.33)
CTR *fb* CTM	3.15^{a} (9.87)	3.00^{a} (9.07)	3.31^{a} (10.27)	3.07^{a} (9.60)	2.98^{a} (8.80)	2.92^{a} (8.33)	3.12^{a} (9.60)	3.02^{a} (9.00)
Organic weed management (W)								
Unweeded control	3.84^{a} (14.33)	3.84^{a} (14.33)	4.12^{a} (16.59)	4.06^{a} (16.08)	3.51^{a} (12.33)	3.36^{a} (10.92)	3.76^{a} (13.75)	3.73^{a} (13.50)
Vermicompost mulch	3.14^{b} (9.42)	3.14^{b} (9.42)	3.06^{b} (9.17)	3.05^{ab} (9.03)	2.96^{b} (8.33)	2.87^{b} (7.83)	3.19^{b} (9.75)	3.07^{b} (9.00)
P- enriched Vermicompost mulch	2.94^{b} (8.25)	2.94^{b} (8.25)	2.71^{c} (8.17)	2.84^{bc} (7.70)	2.79^{bc} (7.33)	2.73^{b} (7.00)	2.86^{c} (7.75)	2.82^{c} (7.50)
Live mulch	2.46^{c} (5.75)	2.46^{c} (5.75)	2.25^{d} (6.50)	2.74^{c} (7.16)	2.52^{d} (6.00)	2.41^{c} (5.42)	2.54^{d} (6.00)	2.44^{d} (5.50)
Weed-free	1.86^{d} (3.00)	1.86^{d} (3.00)	1.98^{e} (2.92)	2.49^{d} (5.80)	2.06^{e} (3.83)	1.95^{d} (3.33)	2.18^{e} (4.33)	2.11^{e} (4.00)
LSD (T)	0.32	0.27	0.28	0.29	0.28	0.21	0.29	0.22
LSD (W)	0.20	0.21	0.21	0.21	0.26	0.22	0.19	0.16
LSD (T × W)	NS	NS	NS	NS	NS	NS	NS	NS

Prior to analysis, the original values presented in parentheses were subjected to square root transformation. Treatment means followed by the unlike lower-case letters are significantly diverse at $p \leq 0.05$ levels of significance as per Duncan's multiple range test. NS: Non-Significant.

Table 3
Weed density of sedges at 30 DAS as influenced by contrasting tillage, residue, and organic weed management practices in rice-maize rotation.

Treatments	Rice (No. m^{-2})		Maize (No. m^{-2})	
	Cyperus spp. L		*Cyperus* spp. L	
	2019	2020	2019–20	2020–21
Tillage and residue management (T)				
ZTR *fb* ZTM	2.38^{c} (5.33)	2.29^{c} (4.93)	2.60^{bc} (6.40)	2.51^{b} (5.93)
PBDSR + R *fb* PBDSM + R	2.32^{c} (5.07)	2.22^{c} (4.60)	2.39^{c} (5.40)	2.35^{b} (5.13)
PBDSR-R *fb* PBDSM-R	2.71^{b} (7.00)	2.63^{b} (6.53)	2.84^{b} (7.73)	2.75^{a} (7.40)
CTR *fb* CTM	3.10^{a} (9.33)	3.07^{a} (8.87)	3.70^{a} (8.80)	2.95^{a} (8.40)
Organic weed management (W)				
Unweeded control	3.17^{a} (9.75)	3.06^{a} (9.50)	3.17^{a} (9.58)	3.13^{a} (9.33)
Vermicompost mulch	2.75^{b} (7.25)	2.86^{ab} (8.25)	2.85^{b} (7.75)	2.78^{b} (7.33)
P- enriched Vermicompost mulch	2.54^{bc} (6.08)	2.72^{bc} (7.50)	2.76^{bc} (7.25)	2.70^{bc} (6.92)
Live mulch	2.46^{c} (5.76)	2.64^{cd} (7.17)	2.60^{c} (6.42)	2.52^{c} (6.00)
Weed-free	2.21^{c} (4.58)	2.51^{d} (6.17)	2.18^{d} (4.42)	2.11^{d} (4.00)
LSD (T)	0.32	0.25	0.28	0.23
LSD (W)	0.26	0.20	0.24	0.20
LSD (T × W)	NS	NS	NS	NS

Prior to analysis, the original values presented in parentheses were subjected to square root transformation. Treatment means followed by the unlike lower-case letters are significantly diverse at $p \leq 0.05$ levels of significance as per Duncan's multiple range test. NS: Non-Significant.

had the highest density of *Cyperus* spp. which was 31.2 and 32.6 % more as compared to weed-free treatment (Table 3). Whereas, live mulch reduced the *Cyperus* spp. by 8.7 and 9.3 % as compared to vermicompost mulch during 2019–20 and 2020–21 respectively.

3.1.3. Broadleaved weeds

During both the years of experiment in rice, the density of *Alternanthera philoxeroids* (Mart.) Griseb., *Eclipta alba* (L.) Hassk., *Achyranthes aspera* L., *Amaranthus viridis* L., and *Phyllanthus niruri* L. were found to maximum in CTR *fb* CTM treatment and minimum with PBDSR + R *fb* PBDSM + R treatment among the tillage and residue management practices (Tables 4 and 5). In rice, *Achyranthus aspera* was 11.4, and 8.9 % lower in PBDSR + R *fb* PBDSM + R as compared to PBDSR *fb* PBDSM during 2019 and 2020 respectively. Additionally, in maize density of broadleaved weed species such as *Chenopodium album* L., *Amaranthus viridis* L., *Alternanthera* spp. L. Br., *Melilotus alba* Medikus were found 21.1, 21.4, 15.1, and 14.6 % lower with PBDSR + R *fb* PBDSM + R as compared to CTR *fb* CTM during the year 2019–20, and a similar trend was witnessed in the year 2020–21. Moreover, there was 19.8, and 22.0 % higher weed density of other broadleaved weeds with CTR *fb* CTM as compared to PBDSR + R *fb* PBDSM + R during the two years of study respectively in maize (Table 5).

Among the organic weed management options, the unweeded control among various organic weed management treatments in rice-maize rotation recorded the maximum weed density of broadleaved weeds during the two years of study. In rice, *Phyllanthus niruri* recorded 23.9 % lower density with live mulch treatment than unweeded treatment during both years (Table 4). Vermicompost mulch recorded 17.6 and 17.5 % greater density of *Chenopodium album* relative to live mulch in maize during 2019–20 and 202–21 respectively. A similar trend was witnessed for *Amaranthus viridis*, *Alternanthera* spp., and *Melilotus alba* in maize during the study period. Weed-free treatment in maize showed minimum weed density of other broadleaved weeds (2.77 and 2.20 m^{-2}) i.e. 21.3 and 34.7 % lower as compared to unweeded control that recorded maximum weed density (Table 5).

3.1.4. Total weeds

Among tillage and residue management practices, the minimum weed density was found with PBDSR + R *fb* PBDSM + R, which was 19 and 20.5 % less as compared to CTR *fb* CTM in rice during 2019 and 2020 respectively. The total weed density in maize was increased by 7.6 and 8.7 %, and 22.9, and 25.8 % with ZTR *fb* ZTM and CTR *fb* CTM as compared to PBDSR + R *fb* PBDSM + R treatment in 2019–20 and 2020–21 respectively (Table 5).

Across the years of field experiment, the unweeded treatments showed maximum total weed density of 10.43 and 10.20 m^{-2} which was at par with vermicompost mulch (8.87 and 8.58 m^{-2}) under organic weed management practices in rice (Table 4). Similarly, in maize weed-free check showed 36.5 and 38 % lower density of total weeds relative to the unweeded treatment, which showed the highest total weed density. Furthermore, P– P-enriched vermicompost mulch recorded 11.9 and 11.5 % higher total weed density relative to live mulch treatment during both years of the study respectively.

3.2. Weed biomass and weed control index

Conservation agriculture based practices and organic weed management regimes resulted in a significant influence on weed biomass in rice-maize rotations during the years of the study. The total weed biomass at 30 DAS in rice crop was found maximum with CTR *fb* CTM which was 13.2, 23.3, and 18.6, 27.8 % higher in comparison to ZTR *fb* ZTM and PBDSR + R *fb* PBDSM + R in both the years respectively. Besides, in maize, the PBDSR + R fb PBDSM + R recorded 20.5 and 17.9 % lower weed biomass relative to CTR *fb* CTM in 2019–20 and 2020–21 respectively. Moreover, ZTR *fb* ZTM treatment recorded 5.2 and 5.8 % lower weed biomass than PBDSR-

Table 4
Weed density (No. m^{-2}) of broadleaved weeds at 30 DAS as influenced by contrasting tillage, residue, and organic weed management practices in rice.

Treatments	*Alternanthera* spp. L. Br.		*Achyranthus aspera* L.		*Eclipta alba* (L.) Hassk.		*Phyllanthus niruri* L.		*Amaranthus viridis* L.		Other broadleaved weeds		Total weeds	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
Tillage and residue management (T)														
ZTR *fb* ZTM	2.76^{bc} (7.47)	2.67^{bc} (7.00)	3.30^{bc} (6.40)	2.47^{bc} (6.00)	2.64^{bc} (6.67)	2.57^{bc} (6.33)	2.50^{bc} (5.93)	2.38^{bc} (5.47)	3.15^{bc} (9.80)	3.11^{abc} (9.53)	2.77^{bc} (7.40)	2.70^{bc} (7.07)	7.92^{c} (64.67)	7.64^{c} (60.27)
PBDSR + R *fb* PBDSM + R	2.63^{c} (6.73)	2.53^{c} (6.27)	3.04^{bc} (5.73)	2.34^{bc} (5.27)	2.50^{bc} (6.20)	2.43^{bc} (5.60)	2.32^{c} (5.07)	2.23^{c} (4.67)	2.93^{c} (8.33)	2.82^{c} (7.67)	2.54^{c} (6.13)	2.46^{c} (5.73)	7.41^{d} (56.66)	7.06^{d} (51.67)
PBDSR-R *fb* PBDSM-R	2.90^{ab} (8.33)	2.79^{ab} (7.73)	3.43^{b} (6.80)	2.57^{ab} (6.47)	2.75^{ab} (7.80)	2.69^{ab} (6.87)	2.68^{ab} (6.80)	2.62^{ab} (6.47)	3.31^{ab} (10.73)	3.25^{ab} (10.53)	2.93^{ab} (8.33)	2.91^{ab} (8.13)	8.46^{b} (73.20)	8.17^{b} (68.46)
CTR *fb* CTM	3.09^{a} (9.53)	3.01^{a} (9.00)	3.97^{a} (8.13)	2.76^{a} (7.40)	3.02^{a} (9.21)	2.99^{a} (8.67)	2.88^{a} (8.00)	2.83^{a} (7.67)	3.48^{a} (11.93)	3.41^{a} (11.47)	3.16^{a} (9.67)	3.08^{a} (9.13)	9.15^{a} (85.54)	8.88^{a} (80.87)
Organic weed management (W)														
Unweeded control	3.55^{a} (12.17)	3.47^{a} (11.58)	3.90^{b} (10.42)	3.22^{a} (9.92)	3.14^{a} (9.42)	3.21^{a} (9.75)	3.10^{a} (9.17)	2.99^{a} (8.58)	3.92^{a} (15.08)	3.89^{a} (14.75)	3.43^{a} (11.4)	3.43^{a} (11.2)	10.43^{a} (108.8)	10.24^{a} (104.9)
Vermicompost mulch	3.19^{b} (9.75)	3.10^{b} (9.17)	3.58^{c} (8.00)	2.83^{b} (7.58)	2.88^{b} (7.92)	2.90^{b} (7.33)	2.77^{b} (7.25)	2.72^{b} (7.00)	3.41^{b} (11.17)	3.41^{b} (11.25)	3.02^{b} (8.75)	3.02b (8.33)	8.87^{b} (78.67)	8.58^{b} (73.50)
P- enriched Vermicompost mulch	3.02 b (8.67)	2.92^{b} (8.08)	3.44^{c} (7.17)	2.63^{b} (6.50)	2.80^{bc} (7.42)	2.78^{bc} (7.00)	2.64^{b} (6.58)	2.58^{b} (6.25)	3.32^{b} (10.58)	3.26^{b} (10.17)	2.79^{bc} (7.42)	2.79^{c} (7.08)	8.39^{c} (70.33)	8.04^{c} (64.67)
Live mulch	2.67^{c} (6.67)	2.57^{c} (6.17)	5.75^{a} (3.30)	2.37^{c} (5.17)	2.69^{bcd} (6.84)	2.69^{bcd} (6.25)	2.36^{c} (5.17)	2.28^{c} (4.83)	2.93^{c} (8.17)	2.78^{c} (7.42)	2.68^{c}(6.83)	2.60^{c} (6.33)	7.56^{d} (57.08)	7.17^{d} (51.42)
Weed-free	1.80^{d} (2.83)	1.70^{d} (2.50)	2.95^{d} (2.50)	1.63^{d} (2.25)	2.58^{cd} (6.25)	2.58^{cd} (4.00)	2.12^{d} (4.08)	2.01^{d} (3.67)	2.51^{d} (6.00)	2.40^{d} (5.42)	2.32^{d} (5.00)	2.24^{d} (4.67)	5.93^{e} (35.17)	5.66^{e} (32.08)
LSD (T)	0.22	0.25	0.40	0.23	0.30	0.32	0.27	0.31	0.27	0.33	0.32	0.24	0.39	0.30
LSD (W)	0.19	0.21	0.29	0.21	0.24	0.28	0.21	0.26	0.24	0.26	0.25	0.19	0.26	0.21
LSD (T × W)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Prior to analysis, the original values presented in parentheses were subjected to square root transformation. Treatment means followed by the unlike lower-case letters are significantly diverse at $p \leq 0.05$ levels of significance as per Duncan's multiple range test. NS: Non-Significant.

Table 5
Weed density (No. m^{-2}) of broadleaved weeds at 30 DAS in response to contrasting tillage, residue, and organic weed management practices in maize.

Treatments	*Chenopodium album* L.		*Amaranthus viridis* L.		*Alternanthera* spp. L. Br.		*Melilotus alba* Medikus.		Other broadleaved weeds		Total weeds	
	2019–20	2020	2019–20	2020	2019–20	2020	2019–20	2020	2019–20	2020	2019–20	2020
Tillage and residue management (T)												
ZTR *fb* ZTM	3.06^{bc} (9.27)	3.00^{bc} (8.85)	2.47^{bc} (5.93)	2.38^{bc} (5.47)	2.60^{abc} (6.47)	2.50^{bc} (6.00)	2.65^{bc} (6.67)	2.37^{b} (6.20)	2.83^{bc} (7.67)	2.63^{bc} (6.60)	7.51^{c} (57.53)	7.21^{c} (53.11)
PBDSR + R *fb* PBDSM + R	2.80^{c} (7.80)	2.78^{c} (7.60)	2.24^{bc} (4.73)	2.11^{c} (4.20)	2.47^{bc} (5.87)	2.34^{bc} (5.40)	2.51^{c} (5.93)	2.30^{b} (5.07)	2.68^{bc} (6.87)	2.50^{c} (5.93)	6.99^{d} (49.93)	6.67^{d} (45.53)
PBDSR-R *fb* PBDSM-R	3.27^{ab} (10.47)	3.23^{ab} (10.13)	2.51^{b} (6.13)	2.45^{ab} (5.80)	2.79^{ab} (7.47)	2.69^{ab} (7.00)	2.88^{ab} (7.87)	2.64^{a} (6.93)	2.93^{ab} (8.33)	2.77^{b} (7.40)	7.98^{b} (64.67)	7.70^{b} (60.27)
CTR *fb* CTM	3.55^{a} (12.33)	3.45^{a} (11.60)	2.85^{a} (7.87)	2.76^{a} (7.33)	2.91^{a} (8.13)	2.88^{a} (8.00)	2.94^{a} (8.27)	2.85^{a} (8.00)	3.21^{a} (10.13)	3.05^{a} (9.07)	8.54^{a} (73.93)	8.29^{a} (69.73)
Organic weed management (W)												
Unweeded control	4.07^{a} (16.17)	3.93^{a} (15.00)	3.27^{a} (10.25)	3.19^{a} (9.75)	3.30^{a} (10.50)	3.29^{a} (10.42)	3.04^{a} (9.25)	2.82^{a} (9.00)	3.52^{a} (12.08)	3.37^{a} (11.00)	9.75^{a} (94.83)	9.44^{a} (88.92)
Vermicompost mulch	3.29^{b} (10.42)	3.25^{b} (10.17)	2.74^{b} (7.08)	2.63^{b} (6.50)	2.85^{b} (7.67)	2.75^{b} (7.17)	2.85^{ab} (8.25)	2.62^{b} (7.17)	3.18^{b} (9.58)	2.91^{b} (8.00)	8.23^{b} (67.50)	7.96^{b} (63.17)
P- enriched Vermicompost mulch	3.08^{b} (9.17)	3.06^{b} (9.00)	2.48^{c} (5.83)	2.42^{c} (5.50)	2.73^{b} (7.00)	2.62^{b} (6.42)	2.74^{bc} (7.64)	2.51^{bc} (6.58)	3.09^{b} (8.00)	2.70^{bc} (6.83)	7.72^{c} (59.42)	7.47^{c} (55.75)
Live mulch	2.71^{c} (7.17)	2.68^{c} (6.92)	2.15^{d} (4.25)	2.01^{d} (3.67)	2.42^{c} (5.42)	2.29^{c} (5.08)	2.62^{cd} (7.00)	2.47^{bc} (5.25)	2.87^{c} (7.83)	2.52^{c} (5.92)	6.90^{d} (47.75)	6.61^{d} (43.75)
Weed-free	2.70^{c} (6.92)	2.65^{c} (6.64)	1.96^{d} (3.42)	1.87^{d} (3.08)	2.18^{d} (4.33)	2.08^{c} (3.92)	2.47^{d} (6.25)	2.27^{d} (4.75)	2.77^{c} (7.25)	2.20^{d} (4.50)	6.19^{e} (38.08)	5.86^{e} (34.23)
LSD (T)	0.35	0.25	0.28	0.31	0.32	0.35	0.26	0.22	0.32	0.24	0.25	0.40
LSD (W)	0.28	0.23	0.25	0.18	0.19	0.29	0.20	0.18	0.21	0.22	0.23	0.20
LSD (T × W)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Prior to analysis, the original values presented in parentheses were subjected to square root transformation. Treatment means followed by the unlike lower-case letters are significantly diverse at $p \leq 0.05$ levels of significance as per Duncan's multiple range test. NS: Non-Significant.

R *fb* PBDSM-R across the years of study respectively in maize (Table 6).

Among organic weed management strategies in rice, the minimum weed biomass was found with weed-free treatment. Among the rest of the treatments, live mulch recorded 31.3 and 36.5 % lower weed biomass than unweeded treatment in rice during both years respectively (Table 6). Similarly, in maize, live mulch recorded the lowest weed biomass, which was 19.0 and 23.3 % lower weed biomass as compared to the average of vermicompost mulch and P-enriched vermicompost mulch treatment during 2019–20 and 2020–21 respectively.

Weed control index (WCI) varied significantly with tillage and organic weed management practices in rice-maize rotation. During both the years in rice, the PBDSR-R *fb* PBDSM-R showed lower WCI than PBDSR + R *fb* PBDSM + R treatment (Table 6). A similar trend was witnessed in maize during 2019–20 and 2020–21 respectively. Among various weed management practices, weed-free recorded maximum WCI in rice-maize rotations. However, in maize live mulch showed higher WCI in comparison to vermicompost mulch treatment during both the years. Whereas, interaction effect between tillage practices and organic weed management practices across the years for weed biomass and WCI of rice and maize was non-significant.

3.3. Crop yield

3.3.1. Rice

Tillage, residue, and weed management had a substantial influence on yield of rice over the two-year experimental period. The maximum grain yield was achieved in PBDSR + R *fb* PBDSM + R (pooled data of two years) that was 8.6 and 21.7 % higher relative to ZTR *fb* ZTM and CTR *fb* CTM respectively (Fig. 2). The weed-free treatment showed highest grain yield among weed management strategies and was statistically similar with live mulch. Furthermore, the live mulch had 9.8 and 6.8 % greater grain yield than vermicompost mulch and P-enriched vermicompost mulch respectively. The pooled data of two years showed that unweeded control had 47.7, 49.1, 52.3 and 53.7 % lower grain yield than vermicompost mulch, P-enriched vermicompost mulch, live mulch, and weed-free treatment respectively. There was no significant difference in the interaction between tillage and organic weed management strategies.

3.3.2. Maize

Yield of maize was affected by tillage and organic weed management strategies within the years of the study. Among tillage and residue management practices, the pooled data of two years showed that CTR *fb* CTM reported lower grain yield (14.6 %) than PBDSR + R *fb* PBDSM + R which showed the highest grain yield (9.36 t ha^{-1}). Also, ZTR *fb* ZTM resulted in higher grain yield (11.7 %) than CTR *fb* CTM (Fig. 2). The lowest grain yield was found with unweeded control and maximum in weed-free treatment. The weed-free treatment recorded 93.7 % higher grain yield than the unweeded control but was found statistically similar to P-enriched vermicompost mulch and live mulch. The interaction between tillage and organic weed management practices was non-significant.

4. Discussion

4.1. Weed dynamics

We tested the influence of various tillage, residue management, and weed control strategies on the weed dynamics in rice-maize rotations. In India, hand weeding is the most common practice specifically where family labour is used. Nevertheless, such a practice is becoming uneconomical due to the hike in labour prices. This calls for alternative practices of controlling weeds such as the use of

Table 6
Weed biomass at 30 DAS and weed control index (WCI) in rice-maize rotation as influenced by tillage and residue management practices and organic weed management in rice-maize rotation.

Treatments	Rice				Maize			
	Weed biomass (g m^{-2})		WCI (%)		Weed biomass (g m^{-2})		WCI (%)	
	2019	2020	2019	2020	2019–20	2020–21	2019–20	2020–21
Tillage and residue management								
ZTR *fb* ZTM	3.08^{c} (9.38)	2.91^{c} (8.47)	48.84	52.71	2.72^{c} (14.13)	2.61^{c} (6.86)	47.11	49.97
PBDSR + R *fb* PBDSM + R	2.88^{d} (8.20)	2.70^{d} (7.27)	49.62	54.52	2.54^{d} (6.37)	2.43^{d} (5.87)	46.22	50.63
PBDSR-R *fb* PBDSM-R	3.27^{b} (10.61)	3.09^{b} (9.56)	45.37	51.23	2.87^{b} (3.20)	2.77^{b} (7.71)	44.98	48.56
CTR *fb* CTM	3.55^{a} (12.58)	3.45^{a} (11.95)	48.42	52.04	3.06^{a} (9.32)	2.96^{a} (8.80)	42.80	45.20
Organic weed management								
Unweeded control	4.12^{a} (16.55)	4.05^{a} (16.06)	0.00	0.00	3.82^{a} (14.23)	3.82^{a} (14.16)	0.00	0.00
Vermicompost mulch	3.50^{b} (11.84)	3.40^{b} (11.03)	28.35	30.65	3.04^{b} (8.78)	2.95^{b} (8.24)	38.34	41.99
P- enriched Vermicompost mulch	3.33^{c} (10.64)	3.21^{c} (9.70)	35.75	38.53	2.86^{c} (7.72)	2.79^{c} (7.36)	45.89	48.36
Live mulch	2.83^{d} (7.55)	2.57^{d} (6.17)	54.53	61.62	2.39^{d} (5.25)	2.20^{d} (4.38)	63.45	69.41
Weed-free	2.20^{e} (4.39)	1.94^{e} (3.09)	73.60	79.71	1.88^{e} (3.05)	1.70^{e} (2.40)	78.73	83.19
LSD (T)	0.12	0.10	–	–	0.08	0.12	–	–
LSD (W)	0.09	0.08	–	–	0.08	0.06	–	–
LSD (T × W)	NS	NS	–	–	NS	NS	–	–

Treatment means followed by the unlike lower-case letters are significantly diverse at $p \leq 0.05$ levels of significance as per Duncan's multiple range test. NS: Non-Significant.

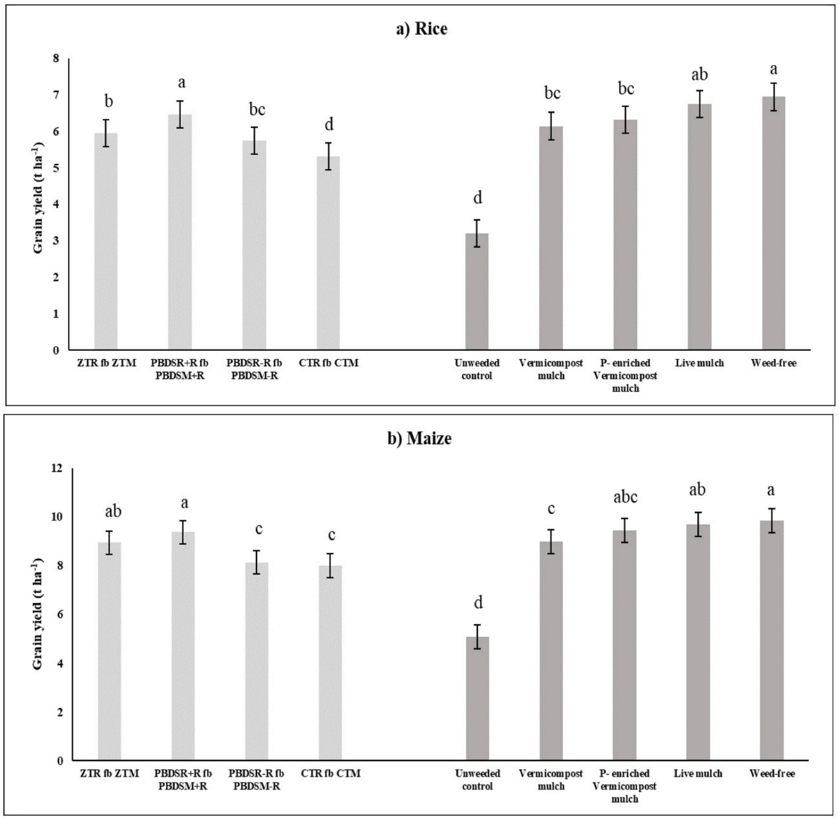

Fig. 2. Grain yield (combined data of 2 years) of rice (a) and maize (b) as affected by tillage, residue, and organic weed management practices. Treatment means followed by the unlike lower-case letters are significantly diverse at $p \leq 0.05$ levels of significance as per Duncan's multiple range test.

herbicides, which in the long run causes soil degradation and environmental pollution. In our experiments, different organic weed management strategies were tested, among them *Sesbania* and *Pisum* as live mulch was able to provide a long-lasting soil cover within a short period [3]. Moreover, live mulch recorded less weed density among all organic weed management treatments. Similarly, Singh et al. [45] reported 20–33 % lower grassy weed density and 76–83 % lower broadleaf weed density with live mulch practice in rice. Furthermore, Ezung et al. [13] also observed that cowpea live mulching greatly decreased the density and dry weight of the weeds. Moreover, in rice-maize rotations, due to the dominance of broad-leaved weeds given that there was wider spacing in winter maize which restored the soil seed bank with these weeds.

The reduction in weed density under PBDSR + R *fb* PBDSM + R relative to CTR *fb* CTM might be due to the minimal soil disturbance and the mulching of soil surface with crop residues. In PB, retention of crop residues act as physical barrier over bare soil and subdued the weed seed germination. The direct interception of sunlight at the upper soil surface is normally limited when the soil is covered with crop residues which leads to release of phytotoxins from straw decomposition overwhelm weed development [5,36]. Furthermore, the optimal use of organic and live mulches might inhibit weed growth by obstructing light and liberating chemicals that are allelopathic [31,42]. Subsequently, the weed seeds lying on the soil surface dried out got attacked by fungi, and/or were subjected to predation by bacteria and insects [41]. In contrast to our findings, Brown and Gallandt [4] found a negative connection between mulch coverage and weed emergence due to less light stimulation. According to Chauhan et al. [6], species of perennial weeds were more challenging to manage in no-tillage system. The primary reason of this was the presence of shaded weed seeds on the soil surface, which increased weed pressure and emergence [4,21]. Thus, for weeds that need light to germinate, mulch has a greater effect on weed control [10].

The PBDSR + R *fb* PBDSM + R system recorded significantly higher WCI over the CTR *fb* CTM system (Table 6). Tillage operations in the CTR *fb* CTM system affected the vertical dispersal of weed seed centered on the type and frequency of tillage implement used. Under the CT system, there was extensive soil pulverization, which resulted in the burying of weed seeds in deep soil layers. Such seeds could not be exposed to sunlight and hence ended up not germinating. Ultimately, this led to the germination of peculiar seeds in the field at the expense of the planted ones, which remained in the soil. Such results led to a uniformity in germination tratis. On the contrary, ZTR *fb* ZTM, PBDSR + R *fb* PBDSM + R, and PBDSR-R *fb* PBDSM-R systems provided an equal opportunity for all weed seeds to emerge due to unbiased seed deposition of weeds on the soil surface. In a study conducted in South Asia, it was reported that wheat residues (i.e. 5 t ha^{-1}) decreased the emergence of sedge species, broadleaf, and grass in the range by 22–70 %, 65–67 %, and 73–76 %, respectively, relative to no residue control in ZT-DSR. In addition, Alhammad et al. [2] reported that CT (T)–ZT–ZT had the lowermost weed biomass over the three years under the rice-wheat-greengram system. Principal component bi-plot analysis of the second year also confirmed the unique disparity in weed community conformation among CTR *fb* CTM and PBDSR + R *fb* PBDSM + R systems (Fig. 3), as they are distantly located in the ordinates. In ZT and PB systems, tillage was only confined to the sowing operations, therefore for most of the species, the weed seeds remained on the soil surface [9,12]. The present study also suggested that the adoption of different tillage, residue, and weed management may encourage or suppress the emergence of weeds, given that the germination of a few weeds is affected by hitherto germinated weeds, due to inter-specific competition. The preponderance of *Chenopodium album*, *Cyperus* spp., *Amaranthus viridis*, *Alternanthera* spp. was confirmed by the principal component bi-plot study, which gives a direction for future weed management strategies (Fig. 3). The application of different types of mulch releases allelochemicals that hinder the growth and development of weeds, resulting in fewer weed seed emergence [1,22]. Hence, our hypothesis that weed biomass and density are lower in the PBDSR + R *fb* PBDSM + R system than in the CTR *fb* CTM system holds, and hence accepted.

4.2. Yield

The data obtained from the current study showed the paybacks of shifting from flats to permanent bed systems coupled with residue retention. This can be due to the low weed density during the initial crop growth stage (i.e., 30 DAS) in these treatments. According to our results, higher rice yields were observed in PBDSR + R *fb* PBDSM + R and ZT *fb* ZTM compared to CTR *fb* CTM, consistent with previous findings in rice-wheat systems [11,14,30]. In contrast to our findings in silt loam soils, Yadav et al. [50] established similar findings for DSR and CTR in silt loam and clay loam soils, respectively. Under two cropping systems, inconsistent results may be accredited to reduced percolation losses of nutrients and water, improved weed control, quick seedling establishment, and enhanced nutrient accessibility as a result of puddling under CTR conditions [19].

Moreover, the capricious rainfall pattern in the study area may equally contribute to the inconsistencies in yields observed between treatments [44,50]. Moreover, residue-retained permanent beds resulted in considerably increased grain production. The pooled yield of the two years showed that the maize grain yield in PBDSR + R *fb* PBDSM + R and ZTR *fb* ZTM was significantly higher than in CTR *fb* CTM. According to Jat et al. [24], maize production was greater with no-tillage (NT) than with CT. Additionally, the maize yield was greater by 6–82 % in the CA-based PBM + R rice-maize system compared to PBM-R and CTM [25]. Moreover, Ghosh et al. [16] reported that approximately 75 % loss of grain yield in cereal-based cropping systems is due to abundant weed flora in the Indian subcontinent under ZT ecology.

Amongst the weed management options, unweeded treatment recorded the minimum grain yield during both years. 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 of the CA-based tillage residue retained treatments and mulching on the weed population that eventually aided in an upsurge in grain yield of the crop under study [23]. The findings of Kumar and Ladha [30] are also in agreement with the concept. However, Chikoye et al. [8] found that weeding using manual labour (three times) was essential to achieve maximum grain yield. The increase in yield in live mulch and P-enriched vermicompost might be due to an upsurge in the photosynthetic area, more translocation of photosynthates towards the sink, dry matter accumulation per plant, and improved yield [26]. Contrary to the general belief that *Sesbania*-rice intercropping can result in rice yield

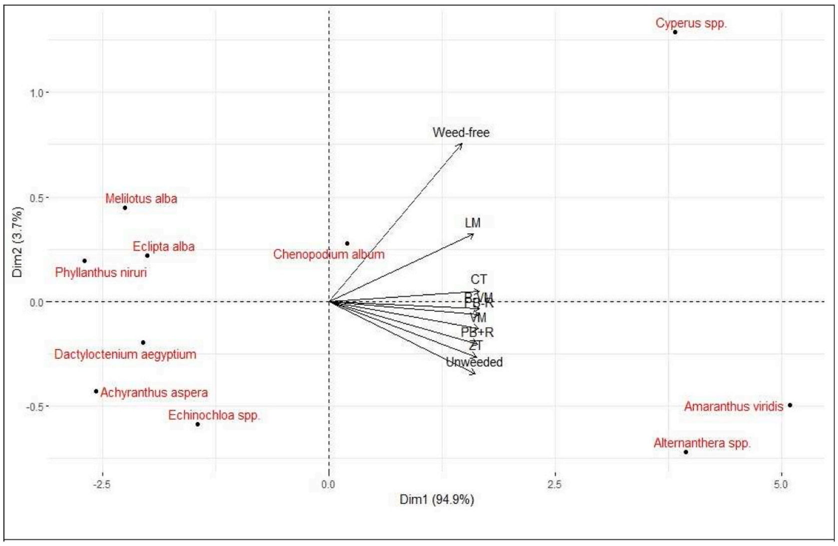

Fig. 3. Principal component (bi-plot) analysis of weed communities at 30 DAS in rice-maize rotation under different tillage, residue, and weed management options in the year 2020–21. CT: CTR fb CTM; PB + R: PBDSR + R fb PBDSM + R; PB-R: PBDSR-R fb PBDSM-R; ZT: ZTR fb ZTM; VM: vermicompost mulch; P-VM: P enriched vermicompost mulch; LM: Live mulch; Details of tillage treatments is given in Table 1.

loss [32], our study exhibited some beneficial payback principally due to weed control.

5. Conclusion

In conclusion, the results showed significant differences in weed abundance and grain yield induced by different weed and tillage management regimes in rice-maize cropping system. Adoption of permanent bed with residue retention improved grain yield, and reduced the weed density. On the other hand, conventional tillage induced an increase in the weed species that were otherwise less in all other treatments. Application of live mulch reduced weed density and biomass up to 110 and 90.6 % increases in grain yield of rice and maize respectively in comparison to unweeded control. The results indicate a shift towards residue retention-based tillage practices, and therefore the adoption of suitable live mulch practices can be the key to weed management and the productivity of rice-maize cropping systems. However, further study can be investigated to assess its influence on different rice-based cropping systems. Moreover, the effect on soil physicochemical properties and microorganisms should be studied in depth for further understand the bonus payback of adopting residue retention and organic weed management on the field crop growing environment for its large-scale adoption.

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Data availability statement

Data will be made available on request to corresponding authors.

CRediT authorship contribution statement

Subhra Sahoo: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mahmoud F. Seleiman:** Writing – review & editing, Visualization, Software, Funding acquisition. **Dhirendra Kumar Roy:** Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Shivani Ranjan:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Sumit Sow:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Raj Kumar Jat:** Writing – review & editing, Visualization, Resources. **Bushra A. Alhammad:** Writing – review & editing, Formal analysis, Funding acquisition. **Harun Gitari:** Writing – review & editing, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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