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RESEARCH

Conservation Agricultural Practices Influencing the Seasonal Weed Dynamic and Productivity of Wheat in the Trans Indo-Gangetic Plains of India

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Abstract

The study aimed to investigate the impact of various tillage and weed control practices on weed dynamics in wheat crop at ICAR-IARI, New Delhi, India, with a focus on the significance of various tillage and weed control techniques in conservation agriculture. The experiment hypothesized that implementation of conservation agricultural practices positively influenced the seasonal weed dynamics and productivity of wheat crop. Keeping in this regard, the experiment was conducted in split plot design with main plot designated for tillage; conventional tillage with residue at 3.5 t ha^{-1} (CT+R @ 3.5 t ha^{-1}); conventional-tillage without residue (CT–R); zero-tillage with residue at 3.5 t ha^{-1} (ZT+R @ 3.5 t ha^{-1}); and zero-tillage with residue at 5.0 t ha^{-1} (ZT+R @ 5 t ha^{-1}) whereas the subplot treatments included the weed management practices; weedy check, mesosulfuron + iodosulfuron at 0.4 kg ha^{-1} as post-emergence (POE), pendimethalin at 1.0 kg ha^{-1} as pre-emergence (PE) followed by mesosulfuron + iodosulfuron at 0.4 kg ha^{-1} as POE, and pendimethalin at 1.0 kg ha^{-1} as PE. Experimental findings revealed that the density of broad and narrow-leaved weeds (BLWs, NLWs) was higher in the ZT+R @ 3.5 t ha^{-1} plots during 2013. With the progress of the study rather with the progress of the crop towards maturity and seasons of the crop, the density of total weeds and weed dry weight increased, ultimately reaching higher levels with CT–R by the end of the fourth year (2016). Notably, in ZT+R @ 5 t ha^{-1} plots, total weed density decreased by 25.26% compared to CT–R (48 m^{-2}), with a concurrent reduction in weed dry weight by 7.94% for ZT+R @ 3.5 t ha^{-1} and 11.53% for ZT+R @ 5 t ha^{-1}, compared to CT–R (62.74 g m^{-2}). Although CT–R initially yielded higher in the first year (4.40 t ha^{-1}), ZT+R@ 5 t ha^{-1} exhibited a 13.4% increase in yield by the fourth year, stabilizing at 46.58% higher than the weedy check (3.37 t ha^{-1}) in terms of wheat yield. In terms of weed control, the combination of pendimethalin at 1.0 kg ha^{-1} as PE followed by mesosulfuron + iodosulfuron at 0.4 kg ha^{-1} as POE consistently recorded the lowest weed density (27.48 m^{-2}) and weed dry weight (46.76 g m^{-2}) over the years. Among these broad-leaved weeds, *Chenopodium album* (3 m^{-2}) and *Convolvulus arvensis* (8.0 m^{-2}) were effectively managed with POE, while among narrow-leaved weeds such as *Phalaris minor* (6 m^{-2}) and *Avena fatua* (5 m^{-2}) were successfully controlled with PE followed by POE.

Keywords P. minor · Post-emergence herbicides · Weeds, residue retention · Sustainability · Weed management

Introduction

In India, wheat (*Triticum aestivum* L. emend Fiori & Paol) is the second most important food grain crop after rice contributing 30% to the nation's food grain production. It covers an area of 30.5 million ha with a production of 106 million tons having a constant annual yield of 3.5 t ha^{-1} during the past decade, which is very low compared to China (5 t ha^{-1}) and the USA (7–8 t ha^{-1}) (FAO 2023). The low wheat productivity is ascribed to very less organic carbon content in soil (0.2–0.3%), imbalanced nutrient application, inefficient weed management and the vagaries of climate change (Kassam et al. 2009). However, introduction of hybrids as well as high yielding varieties of wheat, heavy demands of agricultural inputs and weed infestation may create a serious problem of wheat particularly in Trans-

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Indo-Gangetic Plain Zone of India (Chauhan et al. 2017; Sharma et al. 2023). In addition, intensive tillage is the main reason for the drastic depletion in soil fertility, usually done by Indian farmers for wheat cultivation which requires lots of energy, fuel, time and money (Hobbs et al. 2007). Moreover, weeds are known to be major constraints of wheat in both conventional tillage and zero tillage that might cause serious yield loss and quality deterioration of wheat (Sharma et al. 2023). However, due to continuous growing of wheat-based cropping system, South Asian people faced lot of challenges like diminishing soil health, herbicide resistant against weed, ground water depletion, growing climatic variability, environmental pollution and changing socio-economic status of the people (Alhammad et al. 2023).

Nutritional security predictions reflected that by 2030 and 2050, per capita wheat consumption will increase to 74 kg and 94 kg year^{-1} compared to the current level (60.4 kg year^{-1}) (FAO 2023). Therefore, there is a need to adopt improved agronomic management practices, which can sustain wheat productivity in the long run under the ever-changing climate scenario. In such cases, conservation agriculture (CA) based practices may enhance crop yield (10–20%), soil organic carbon (5–12%), reduce greenhouse gas emissions (GHGs) and soil erosion (Gathala et al. 2013). Basically, CA has three principles *viz.* 1) minimum/no soil disturbance; 2) crop cover or mulch and 3) crop diversification to achieve improved soil health and sustainability in the system (Hobbs 2001). The major bottleneck in the adoption of CA practices is high weed infestation by the dint of residue retention. Hence, the management of weeds by chemical means or herbicides seemed to be a viable technology. Previous research indicated that the pre-emergence (PE) application of herbicides is not very effective due to the retention of crop residue on the soil surface (Chauhan et al. 2012). Therefore, the application of the post–emergence (POE) herbicide could be an effective method for weed control and could play a pivotal role in higher residue retention in wheat. In wheat grown with conventional tillage (CT) or farmer's practice, the use of sulfosulfuron, clodinafop, mesosulfuron and iodosulfuron as POE have been found effective in increasing the crop yield (12–30%) (Malik and Singh 1993). In general, the sole application of iodosulfuron, was not very effective for wheat crops infested with a good number of NLWs as it is a BLWs killer (Chhokar et al. 2008). However, it was observed that tank–mix (combination of two compatible herbicides) application of iodosulfuron with mesosulfuron enhances herbicidal efficacy. Evidently, few studies indicated weed flora shift under CA-based systems towards perennial weeds such as *Cynodon dactylon* (Pers.) and *Cyperus rotundus* (L.) (Bajwa 2014; Balyan and Malik 2000). Although, Chokkar *et al.* (2007) reported that ZT reduces the weed density of *Phalaris minor* (Retz.) in wheat but the infestation of BLWs such as *Rumex dentatus* (L.) was increased compared to CT. In the contrary, few studies favoured high infestation of NLWs over BLWs in CA (Singh et al. 2023). In India, most of the studies on weed dynamics are confined to the CT system (Sepat et al. 2017). Further, studies on changes in weed floristic composition with time under tillage options in wheat are limited. In view of less literature and information available on the interactive effects of tillage practices and the use of a combination of pre and post-emergence application of herbicides on crop productivity and profitability of wheat crops with varying loads of residues in CA, an experiment was planned and executed (2013–2016) to validate the hypothesis i.e. a combination of PE/POE (compatible herbicides) could reduce the densities of NLWs and BLWs under various residue loads of residue in ZT and increase the wheat productivity and resource use efficiency.

Material and Methods

Site Description

Field experiments were conducted consecutively during the years 2013 to 2016 at the experimental farm, ICAR-Indian Agricultural Research Institute (28^0 40^0 N, 77^{0}12 E, altitude 228 MSL), New Delhi, India. The site is categorized under the "Trans Indo-Gangetic Plains" agro–climatic zone, with sub–tropical and semi–arid climate, having warm summers and cold winters reflecting annual maximum and minimum temperatures of 40.5 °C and 6.5 °C, respectively. The mean annual rainfall was reported as 670 mm and approximately 70–80% confined in July to September months. During wheat seasons (November to April) amount of rainfall received was 17 mm, 68 mm, 34 mm, and 184 mm during the years 2013, 2014, 2015 and 2016, respectively. Mean maximum and minimum temperatures of 32 °C and 6 °C were recorded during the wheat growing period. The soil of the experimental site was sandy–loam in texture (0–30 cm) and classified as Typic Haplustept with pH of 7.72, OC (0.34%) (Walkley and Black 1934), available N (174 kg ha^{-1}) (Subbiah and Asija 1956), P (11.8 kg ha^{-1}) (Olsen et al. 1954), and K (284 kg ha^{-1}) (Hanway and Heidel 1952).

Treatment Details

The experiment was executed with four tillage practices *viz.* conventional-tillage with residue incorporation @ 3.5 t ha^{-1} (CT+R 3.5@ t ha^{-1}), CT without residue incorporation (CT–R), zero-tillage with residue retention @3.5 t ha^{-1} (ZT+R@ 3.5 t ha^{-1}) and ZT with residue retention @ 5 t ha^{-1} (ZT+R 5@ t ha^{-1}) in the main plots. Four

Table 1 Descriptions of treatment combinations applied to wheat crop experiment

Treatment combination details		Treatments (short form)	Treatment details
Main plots	Sub-plots		
CT+R @ 3.5 t ha^{-1}	Conventional tillage (CT) with residue incorporation @ 3.5 t ha^{-1} with weedy check	M1	CT+R @ 3.5 t ha^{-1} – WC
	CT with residue incorporation @ 3.5 t ha^{-1} with POE	M2	CT+R @ 3.5 t ha^{-1} + POE
	CT with residue incorporation @ 3.5 t ha^{-1} with PE *fb* POE	M3	CT+R @ 3.5 t ha^{-1} + PE *fb* POE
	CT with residue incorporation @ 3.5 t ha^{-1} with PE	M4	CT+R @ 3.5 t ha^{-1} + PE
CT–R @ 3.5 t ha^{-1}	CT without residue incorporation with weedy check	M5	CT–R–WC
	CT without residue incorporation with POE	M6	CT–R+POE
	CT without residue incorporation with PE *fb* POE	M7	CT–R+PE *fb* POE
	CT without residue incorporation with PE	M8	CT–R+PE
ZT+R @ 3.5 t ha^{-1}	Zero tillage (ZT) with residue retention @ 3.5 t ha^{-1} with weedy check	M9	ZT+R @ 3.5 t ha^{-1} – WC
	ZT with residue retention @ 3.5 t ha^{-1} with POE	M10	ZT+R @ 3.5 t ha^{-1} + POE
	ZT with residue retention @ 3.5 t ha^{-1} with PE *fb* POE	M11	ZT+R @ 3.5 t ha^{-1} + PE *fb* POE
	ZT with residue retention @ 3.5 t ha^{-1} with PE	M12	ZT+R @ 3.5 t ha^{-1} + PE
ZT+R @ 5 t ha^{-1}	ZT with residue retention @ 5 t ha^{-1} with Weedy check	M13	ZT+R @ 5 t ha^{-1} – WC
	ZT with residue retention @ 5 t ha^{-1} with POE	M14	ZT+@ 5tha^{-1} + POE
	ZT with residue retention @ 5 t ha^{-1} with PE *fb* POE	M15	ZT+R @ 5 t ha^{-1} + PE *fb* POE
	ZT with residue retention @5 t ha^{-1} with PE	M16	ZT+R @ 5 t ha^{-1} + PE

weed control options as unweeded check (UWC), mesosulfuron + iodosulfuron @ 0.4 kg ha^{-1} as POE; pendimethalin @ 1.0 kg ha^{-1} as PE *fb* mesosulfuron + iodosulfuron @ 0.4 kg ha^{-1} as POE and pendimethalin @ 1.0 kg ha^{-1} as PE in subplots and experiment was laid in split–plot design with three replications (Table 1).

The treatments consisted of CT plots with ploughed (4 times) and cultivated (twice) followed by planking (once) under the experiment. In the case of ZT, the soil was not cultivated/tilled during the period under study and residue loads of maize @ 3.5 and 5 t ha^{-1} were retained in the ZT experimental site before the sowing of wheat crop. In weed control treatments, pendimethalin 30%EC (trade name: Stomp BASF) @ 1.0 kg ha^{-1} was applied 1–2 DAS and POE application of mesosulfuron + iodosulfuron 75 WP (trade name: Atlantis BAYER) @ 0.4 kg ha^{-1} was applied at 25 DAS. Application of herbicide was done manually with a hand-operated knapsack sprayer using a flat fan nozzle.

Crop Management

Crop residue of maize @ 3.5 and 5 t ha^{-1} was retained in ZT, while in CT, residue @ 3.5 t ha^{-1} were incorporated while ploughing as per treatments before wheat sowing. Wheat variety *viz.*, HD 2894 quoting high yield potential ($\geq$ 6 t ha^{-1}) was sown using a seed rate of 100 kg ha^{-1}. A multi–row crop planter was used for wheat sowing by keeping a row-to-row spacing at 22.5 cm in both planting systems. The state recommended dose of N, P and K @ of 120, 26, and 33 kg ha^{-1} was applied through urea, single super phosphate (SSP) and *muriate* of potash (MOP), respectively. Half a dose of N and full doses of P and K were applied at the time of sowing, while the remaining half dose of N was applied in two equal splits after the first and second irrigation. A total of 6 irrigations were applied at critical crop growth stages of the crop as crown root initiation (21 DAS), late tillering (42 DAS), late jointing (60 DAS), flowering (80 DAS), milking (95 DAS) and soft dough (115 DAS) stages. In each year, wheat was sown during the third week of November and harvested manually in the second week of April.

Data Collection

Every year, weed data was collected at 55 DAS by placing quadrat measuring (1.0 m × 1.0 m dimensions) randomly at four places in each plot. Individual weed species viz. *Chenopodium album* L. and *Convolvulus arvensis* in BLWs and *Phalaris minor* Retz. and *Avena fatua* L. in NLWs were collected from the sampled area and thereafter oven-dried at 55 °C for 72 h for weeds dry weight. A fixed site was maintained over the four years consisting of gross and net plot sizes of 8.2 × 3.8 m and 7.2 × 2.4 m respectively, for estimation of yield and weed parameters. Grain and straw yields were recorded at a moisture content of 12.5% and 16%, respectively.

Statistical Analysis

Data on weeds observation and wheat grain yield were subjected to ANOVA using a Statistical Analysis System (SAS 9.3 version). The treatment mean separation was done by using Fishers LSD at 5% significance level, when *F* tests indicated that significant differences existed in the treatments ($p \leq 0.05$). Further, GGE biplot analysis (Yan et al. 2000 and Yan and Kang 2003) was performed using a package of the R software. GGE biplots enable G × E interactions to observe the mean yield stability, ranking different tillage and herbicide treatments on their efficiency and identify those which perform optimally.

Results

Effects of Tillage, Incorporated Residue and Weed Management (WM) Options On Weed and Performance of Wheat.

At 55 DAS, the density and dry weight of weeds showed significant variations influenced by several factors, including the year, tillage practices, and WM options (Table 2). Notably, the interaction between the year and tillage methods yielded significant results ($p \leq 0.05$) for all the observed weed parameters, suggesting that the impact of tillage methods varied from year to year, except for total weed density and dry weight, which exhibited consistent effects across the years. Similarly, the interaction between the year and WM options also displayed significance, except for weed dry weight and the density of NLWs. Moreover, the interaction between tillage methods and WM exerted an influence on all the weed parameters. However, the year × tillage × WM interaction did not yield significant effects on the weed parameters.

In the context of wheat yield, interactions between the year and tillage methods, year × WM methods, were found to be significant. This implies that wheat yield was influenced by both tillage practices and WM options, with variations observed across different years. This dynamic relationship underscores the importance of considering the cumulative effects of treatments in successive cropping cycles. Additionally, the effects of tillage methods combined with WM methods were particularly significant concerning specific weed species such as *C. arvensis, C. album, P. minor*, and *A. fatua*. This underscores the importance of tailoring herbicide selection to suit the specific tillage practices being employed, emphasizing the need for an adaptive approach based on varying tillage practices.

Effect of Tillage and Weed Management Options On Weed Density and Weed Dry Weight

In BLWs, *C. album, C. arvensis, Melilotus albus* (Medik.), *Fumaria indica* (Hausskn.) and *Euphorbia hirta* (L.), while *P. minor* and *A. fatua* were the prominent NLWs during the study period. There was a significant ($P \leq 0.05$) influence

Table 2 Analysis of variance (F probability values) showing the significance of treatments on weed density, weed dry weight and yield over 4 years

Source of variation	DF	Weed density (no m^{-2})			Weed dry weight (g m^{-2})	Yield (t ha^{-1})		Individual weed spp. (no m^{-2})			
		Broad-leaved	Narrow-leaved	Total		Grain	Straw	*C. arvensis*	*C. album*	*P. minor*	*A. fatua*
Replication	2	1.98	0.03	35.08**	94.76**	3.00	6.99	0.03	1.01	0.14	32.27*
Year (Y)	3	9.72*	31.21**	0.25	0.11	35.08**	94.76**	6.23*	5.68**	8.92	0.85
E (a)	6	1.15	0.87	33.82	22.05	0.25	0.11	0.92	3.73	0.97	0.18
Tillage	3	51.49**	48.83**	4.45**	1.76 ns	33.82**	22.05**	57.14*	3.83 ns	6.35**	42.01*
Y × Tillage	9	6.37**	35.46**	2.32	2.75	4.45**	1.76 ns	5.09**	4.23**	8.11*	3.45**
E (b)	24	0.87	1.46	426.3	296.4	2.32	2.75	0.88	2.82	1.25	0.48
WM	3	637.4**	413.0**	2.97**	1.95*	426.3**	296.4**	336.28	701.7	82.92	106.3
Tillage × WM	9	2.54*	4.80**	2.19**	4.71**	2.97**	1.95*	3.90	4.05	1.26 ns	2.81
Y × WM	9	15.5**	1.03 ns	1.96 ns	2.49**	2.19**	4.71**	18.2**	23.4*	16.7**	32.5*
Y × Tillage × WM	27	0.59 ns	0.91 ns	0.67 ns	2.04 ns	1.96 ns	2.49**	0.43 ns	0.56 ns	0.89 ns	0.92
E (c)	96	–	–	–	–	–	–	–	–	–	–

WM weed management

*Significant at $p \leq 0.05$, **Significant at $p \leq 0.01$

on the densities of BLWs, NLWs and total weed density of tillage and WM (Table 3).

In CT–R, the highest BLWs were recorded (30 m^{-2}), while ZT+R @ 5 t ha^{-1} had the lowest value (23 m^{-2}). However, the lower density of NLWs was observed in CT+R @ 3.5 t ha^{-1} (14 m^{-2}) and ZT+R @ 5 t ha^{-1} (16 m^{-2}). The lowest total weed density was found with ZT+R @ 5 t ha^{-1} (36 m^{-2}) followed by CT+R @ 3.5 t ha^{-1} (40 m^{-2}). The treatment ZT+R @ 5 t ha^{-1} significantly reduced the total weed density by 33.8% compared to CT–R (48 m^{-2}). WM options significantly reduced the density of BLWs (73.36%), NLWs (40.58%) and in totality (67.46%) compared to weedy check (58, 24 and 89 m^{-2}, respectively). Sole application of POE herbicides was effective in controlling the BLWs (11 m^{-2}), NLWs (13 m^{-2}) and total weeds density (24 m^{-2}) followed by a combination of PE and POE application (13, 14 and 27 m^{-2}, respectively). Sole application of PE herbicides recorded the highest total weed density among the various WM options (35 m^{-2}).

The impact of different tillage methods and WM practices on the density of NLWs and total weeds exhibited significant differences (Fig. 1a). The treatment involving ZT combined with the application of 3 and 5 t ha^{-1} of residue with POE herbicides recorded the lowest density of BLWs (8 m^{2} and 9 m^{-2}, respectively). The adoption of ZT, combined with residue along with PE and POE herbicides, resulted in a notable reduction of BLWs density by 42.22% compared to CT-R along with PE and POE herbicides (17 m^{-2}). The highest density of NLWs was observed with CT–R + WC followed by ZT+R @ 3.5 t ha^{-1} + WC and ZT+R @ 5 t ha^{-1} + WC. Interestingly, in fields with residue cover under ZT, there was less NLWs infestation, underscoring the significance of ZT in contrast to CT practices. When it came to NLWs, CT combined with residue and POE or PE, and ZT combined with 5 t ha^{-1} of residues and POE all exhibited comparable values.

The total weed density was notably lower in combinations involving ZT and residues, such as ZT+R+POE (62 m^{-2}), ZT+R @ 5 tha^{-1}+PE fb POE (70 m^{-2}), and CT+R+POE (71 m^{-2}). On the other hand, CT–R+WC exhibited a considerably higher total weed density at 275 m^{-2}, while the lowest density was observed in ZT+R @ 5 t ha^{-1} + WC (242 m^{-2}).

Tillage practices significantly decreased the weeds' dry weight over the years (Table 3). The highest weed dry weight was observed in CT–R, while the lowest was recorded with ZT+R @ 5 t ha^{-1}. A decline of 11.53% was noticed by ZT+R @ 5 t ha^{-1} compared to CT–R (62.74 g).

Weed dry weight was reduced (66.27%) with WM practices over to weedy check (83.62 g). POE recorded low weeds dry weight followed by PE *fb* POE. Weeds dry weight significantly reduced with interactions of tillage and WM practices (Fig. 1b). ZT+R+POE registered lower

Table 3 Effect of tillage and weed management options on weed parameters and yield of wheat over 4 years

Treatments	Weed density (no. m^{-2})			Straw yield (t ha^{-1})	Weed dry weight (g m^{-2})	Individual weed spp. (no. m^{-2})			
	Broad-leaved	Narrow-leaved	Total			*C. arvensis*	*C. album*	*P. minor*	*A. fatua*
Tillage practices									
CT+R 3.5 t ha^{-1}	26b	14c	40c	5.18c	58.50bc	10c	11a	8a	6bc
CT–R	30a	18a	49a	4.98d	62.74a	14a	12a	8a	8a
ZT+R 3.5 t ha^{-1}	26b	19a	44b	5.39b	57.76bc	12b	11a	8a	7ab
ZT+R 5 t ha^{-1}	22c	16b	36d	5.82a	55.50c	10c	9a	6b	7ab
Weed management options									
Weedy check	58a	24a	89a	4.37d	83.62a	18a	30a	10a	11a
POE	11d	13c	24d	5.93a	43.51d	8d	3cd	6c	5b
PE *fb* POE	13c	14bc	28c	5.73b	46.76c	9c	4c	6c	5b
PE	22b	15b	35b	5.34c	60.61b	10b	7b	7b	6b

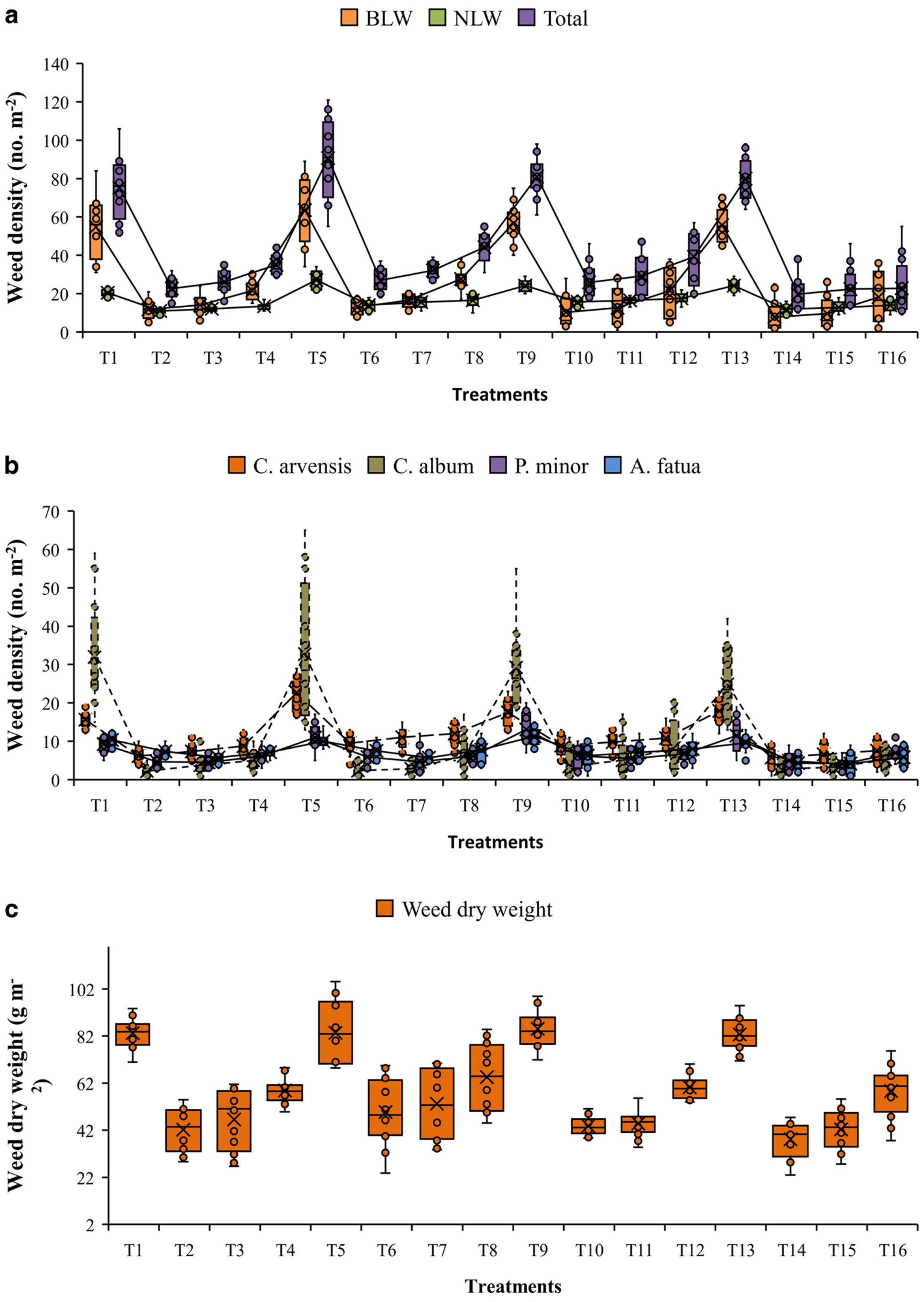

Fig. 1 Interactive effects of tillage and weed management practices on weeds: **a** weed density, **b** density of individual weeds and **c** weed dry weight (4 years of pooled data). Treatments details in Table 1

weeds dry weight (38.23 g), which remain comparable with ZT+R+PE *fb* POE (42.34 g) and CT+R+POE (42.26 g).

Individual weed spp. *viz., C. arvensis, P. minor* and *A. fatua* were recorded at lower frequency with ZT+R @ 5 t ha^{-1} and ZT+R @ 3.5 t ha^{-1} than CT+R @ 3.5 t ha^{-1} (Table 3). CT–R increased the infestation of individual weeds by 5.39–14.77% as compared to ZT+R @ 3.5 t ha^{-1}. Different WM options significantly reduced the density of individual weed spp. by 37.92–85.87% compared to weedy check (10–30 m^{-2}). POE and sequential application of PE *fb* POE herbicides recorded at par density of *C. arvensis* (7–9 m^{-2}), *C. album* (3–4 m^{-2}), *P. minor* (6 m^{-2}) and *A. fatua* (5–6 m^{-2}).

Temporal analysis for *C. arvensis, C. album, P. minor* and *A. fatua* indicated a significant interaction between tillage and WM options (Fig. 1c). ZT+R 5 t ha^{-1}+POE (6 m^{-2}) reduced *C. arvensis and C. album* infestation by 74.63% compared to CT–R+WC (23 m^{-2}). Empirically, ZT+R @ 5 t ha^{-1}+POE and ZT+R @ 5 t ha^{-1} + PE *fb* POE were highly effective in controlling *A. fatua* and *P. minor.*

Table 4 Year × tillage and year × weed management interaction for wheat grain yield (t ha^{-1}) across years ($n = 4$) and replications ($n = 3$)

Parameters	Tillage					Weed management options				
Year	CT+R 3.5 t ha^{-1}	CT–R	ZT+R 3.5 t ha^{-1}	ZT+R 5 t ha^{-1}	Mean	Weedy check	POE	PE *fb* POE	PE	Mean
2013	4.21	4.40	4.02	4.28	4.23	3.06	4.79	4.67	4.38	4.23
2014	4.35	4.71	4.44	4.86	4.59	3.68	5.10	4.97	4.61	4.59
2015	3.90	4.66	4.00	4.85	4.35	3.48	4.88	4.72	4.33	4.35
2016	4.00	4.22	4.11	4.99	4.33	3.27	4.97	4.77	4.31	4.33
Mean	4.12	4.50	4.14	4.75	–	3.37	4.94	4.78	4.41	–
LSD$_{0.05}$	Year				0.08	Year				0.08
	Tillage				0.13	Tillage				0.13
	WM				0.08	WM				0.08
	Year × Tillage				0.23	Year × Tillage				0.23
	Year × WM				0.15	Year × WM				0.15

Yield of Wheat

The weedy check in ZT produced the lowest grain (3.37 t ha^{-1}) and straw yield (4.37 t ha^{-1}), which increased significantly ($p \leq 0.05$) with the adoption of WM practices by 29.51% and 39.96%, respectively (Table 4). Among WM practices, PE recorded lower grain (4.41 t ha^{-1}) and straw (5.34 t ha^{-1}) yield. Alternately, POE recorded a higher yield of grain and straw (4.94 and 5.93 t ha^{-1}) followed by PE *fb* POE (4.78 and 5.73 t ha^{-1}).

In the case of PE with CT–R the grain yield declined by 8.49% as compared to CT–R+PE *fb* POE (4.6 t ha^{-1}) and by 25.47% with ZT+R @ 5 t ha^{-1} + PE *fb* POE (5.32 t ha^{-1}). A high straw yield was observed with ZT+R+POE (6.43 t ha^{-1}) and ZT+R+PE *fb* POE (6.27 t ha^{-1}) treatments (Fig. 2). An increase of 10.29% was observed in ZT+R@ 5 t ha^{-1}+POE compared to CT–R+PE *fb* POE (5.83 t ha^{-1}). The wheat grain yield exhibited significant variations across different years, primarily influenced by tillage and WM practices. The highest mean grain yield was observed in 2016, whereas the lowest yield occurred in 2013, reflecting the strong influence of environmental factors on grain production. Among the various tillage practices, ZT combined with the application of 5 t ha^{-1} of residues yielded the highest grain and straw output, with values of 4.75 and 5.82 t ha^{-1}, respectively. The adoption of ZT, particularly with 5 t ha^{-1} of residues, led to a significant increase in grain yield by 14.73% compared to without residue cover CT–R, which yielded 4.14 t ha^{-1}. Similarly, there was a gain of 16.86% in straw yield with ZT+R @ 5 t ha^{-1} compared to CT–R (4.98 t ha^{-1}). The presence of weeds significantly reduced grain (3.37 t ha^{-1}) and straw (4.37 t ha^{-1}) yield in the ZT-weedy check. However, the adoption of WM practices substantially increased both grain and straw yields by 29.51% and 39.96%, respectively. Among the WM practices, POE recorded lower grain (4.41 t ha^{-1}) and straw (5.34 t ha^{-1}) yields. In contrast, POE resulted in higher grain and straw yields (4.94 and 5.93 t ha^{-1}, respectively), followed by the combination of PE and POE (4.78 and 5.73 t ha^{-1}). The significant interaction of tillage and WM revealed that ZT+R @ 5 t ha^{-1}+POE or ZT+R@ 5 t ha^{-1}+PE *fb* POE recorded higher grain yield followed by ZT+R–POE (Fig. 2). Compared to CT–R combined with PE fb POE (4.60 t ha^{-1}), ZT+R @ 5 t ha^{-1} +

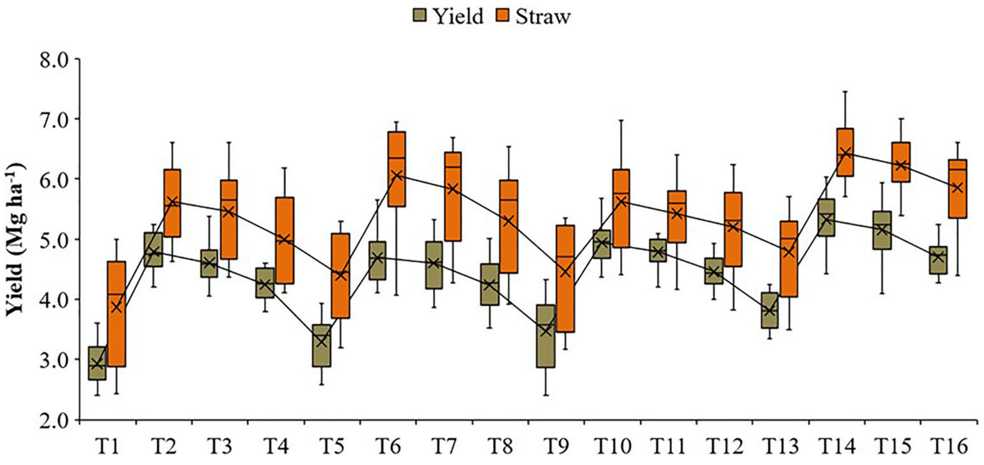

Fig. 2 Interactive effects of tillage and weed management on wheat yield (t ha^{-1}) (pooled data of four years). For treatment details see Table 1

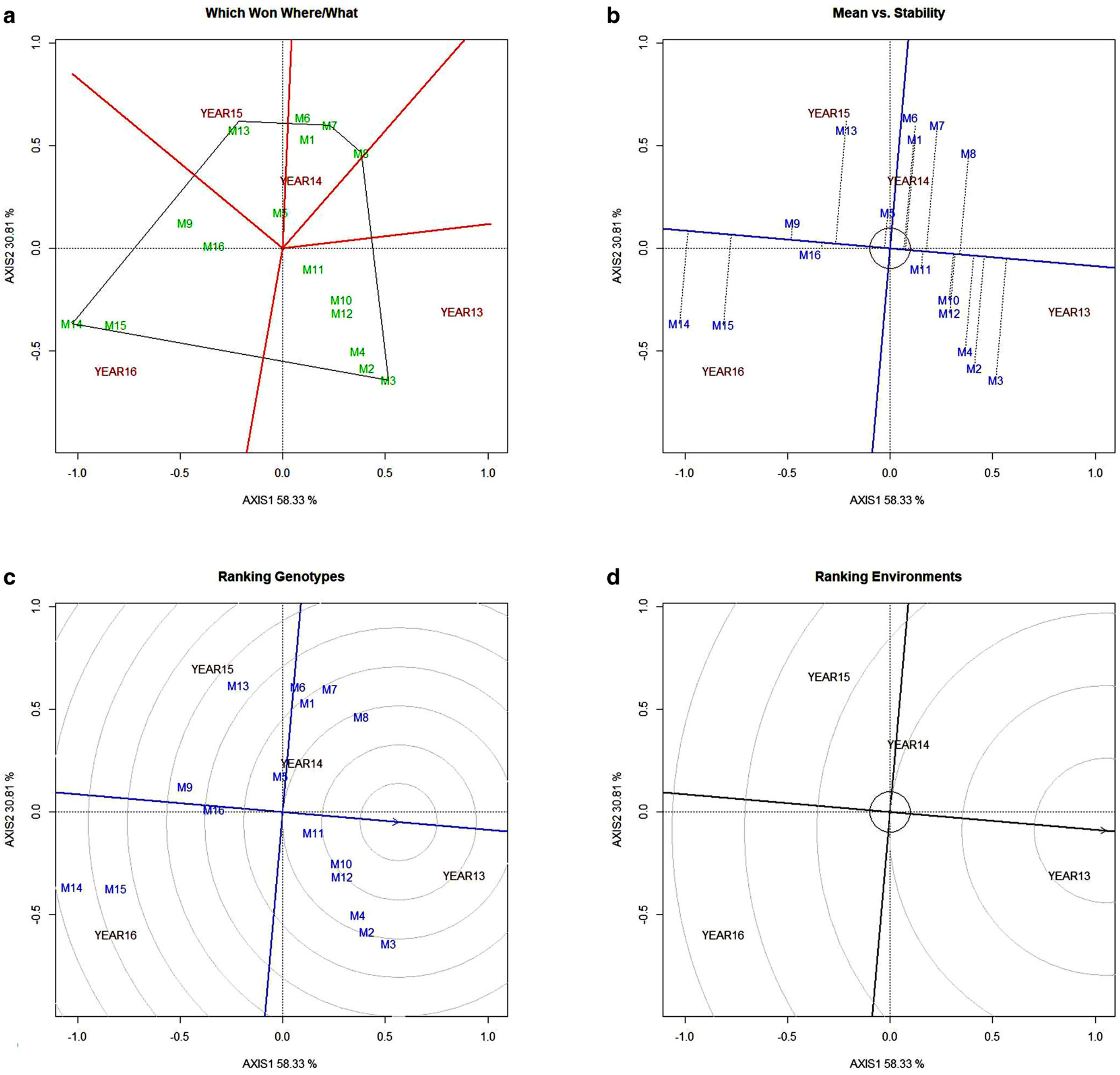

Fig. 3 GGE biplot analysis of yield trend of wheat under various tillage and weed control practices. **a** Polygon view (Which Won Where/What), **b** Mean vs stability, **c** Ranking treatments and **d** Ranking Environments(years)

POE led to a significant 15.65% increase in grain yield. Sole PE was found to be less effective, resulting in lower wheat grain yields, whether used with ZT+R @ 5 t ha^{-1} + PE (4.70 t ha^{-1}) or CT–R+PE (4.24 t ha^{-1}). In the case of PE with CT–R, there was an 8.49% decline in grain yield compared to CT–R combined with PE followed by POE (4.60 t ha^{-1}) and a substantial 25.47% reduction compared to ZT+R @ 5 t ha^{-1}+PE followed by POE (5.32 t ha^{-1}). Notably, high straw yields were observed with ZT+R+POE (6.43 t ha^{-1}) and ZT+R+PE followed by POE (6.27 t ha^{-1}), with a 10.29% increase observed in ZT+R @ 5 t ha^{-1}+POE compared to CT–R combined with PE followed by POE (5.83 t ha^{-1}).

GGE Biplot Analysis

GGE Biplot Analysis for Wheat Yield

The 'which won where/what' polygon (Fig. 3a) indicated the performance of winning management practices in one or more environments (treatments × year interactions). The total variation explained by PC1 (58.33%) and PC2 (30.81%)

was 89.1%, which indicates the significance of implied treatments on wheat yield.

The red lines in the biplot divide the polygon into different sectors and the treatment in every sector represents the best treatment for the sector. Treatments M14, M15, and M16 fall in the same sector coupled with the year 2016 which indicates that these treatments performed broadly similarly. So, treatments M14 and M15 performed best concerning wheat yield. On the other hand, M2, M3, M4, and M10, were identical with wheat performance and remained as the least performer environment.

The mean *vs.* stability GGE polygon is useful to identify the most stable treatment across the various treatments. The direction of the arrow-head of the average environment coordinate (AEC) (blue lines) indicated the average quantity of a particular treatment (Fig. 3b). The Length of projection from AEC (dotted black line) is negatively related to the treatment stability. Here, M16 followed by M9 and M11 were the most stable in terms of grain yield as the absolute length of projection from AEC is low for these treatments. It is noticed that M14 had the highest values followed by M15 and M16 while M8, M7, M1 and M6 performed poorly for the grain yield.

Ranking treatment of polygon indicated the performance of different treatments in terms of their efficiency of producing higher yields (Fig. 3c). An optimal treatment is one located farthest to the center of the concentric rings and is likely to perform well in all tested environments. In terms of the economic grain yield, M14 and M10 were the most and least optimal, respectively. The ranking environment biplot positions the different years in terms of their yielding ability levels (Fig. 3d). An optimal year is one located farthest to the center of the concentric rings. Based on this, the year 2016 and year 2013 were the most and least optimal, respectively, in terms of the yield of wheat.

GGE for Weed Density and Weed Dry Weight

The polygons developed for NLWs, BLWs, total weed density and weed dry weight have deeper insights on year × tillage × WM interactions (Fig. 4). For BLWs, the percentage of total variation explained by PC1 was 86.8% and PC2 was 10.4% (Fig. 4a). For NLWs, the percentage of total variation explained by PC1 was 91.6% and PC2 was 5.9% (Fig. 4b). As far as total weed density is concerned, the percentage of total variation explained by PC1 was 87.4%, and PC2 was 9.3% (Fig. 4c). From weed dry weight point of view, polygons explained 87.4% of the variation, with PC1 68.7% and PC2 18.6% (Fig. 4d). Treatment M16, M14, and M15 were grouped best performers for all the parameters of weed studies in 2015. On the other hand, M8 and M10 were categorized as least performers.

GGE for Individual Weed Species

The biplot polygons showed the performance of individual weed spp. *viz., C. album, C. arvensis, P. minor* and *A. fatua* concerning tillage × WM × environments interactions (Fig. 5). The percentage of total variation explained by PC1 was 90.3% and PC2 was 7.66% of *C. album* (Fig. 5a). For *C. arvensis*, the percentage of total variation explained by PC1 was 92.14% and PC2 was 5.89% (Fig. 5b) and M4, M7, M5 and M8 formed one mega-environment with year 2015 and year 2016 and performed best. While M14 and M15 with the year 2014 categorized as the second-best sector for *C. album*.

In the case of *P. minor*, the percentage of total variation explained by PC1 was 68.0% and PC2 was 27.74% (Figs. 5c and 6). Treatments M9, M10, M11, M14 and M15 were concentrated jointly in the winner mega-environment. For *A. fatua*, the biplot polygons explained 92.81% of the variation, with PC1 56.21% and PC2 36.60% (Fig. 5d). Treatments M9, M14, and M15 were lying jointly with the environment year 2015 in the lead mega-environment. On the other hand, M8 and M10 were categorized as least performers.

Sunfrost Visualization of Seasonal Weeds Dynamics in Response to Grain and Straw Yields Under CA-based Management Practices

Sunfrost visualization of seasonal weeds dynamics in response to grain and straw yields under CA-based management practices have been presented in Fig. 6. The first outermost circle shows total weeds populations, weeds biomass, and densities of BLWs and NLWs, the second middle circle indicates the wheat grain yield and the innermost circle is indicating the adopted CA practices. The colour intensity of Fig. 6 depends on gradient straw yield.

Discussion

Effective weed management is a critical component of CA, as it plays a pivotal role in achieving higher yields (Sharma et al. 2023). In our study, we observed that the total weed density was initially higher with ZT combined with the application of 3.5 and 5.0 t ha^{-1} of residues during the early years of the experiment. However, this weed density gradually declined after the stabilization of ZT system with effective weed control measures and showed a significant impact by the end of the fourth year, in 2016. Tillage practices have a notable impact on both the horizontal and vertical distribution of weed seeds in the soil, as documented by various researchers (Bajwa 2014). In ZT, for instance, approximately half of the weed seeds produced tend to be

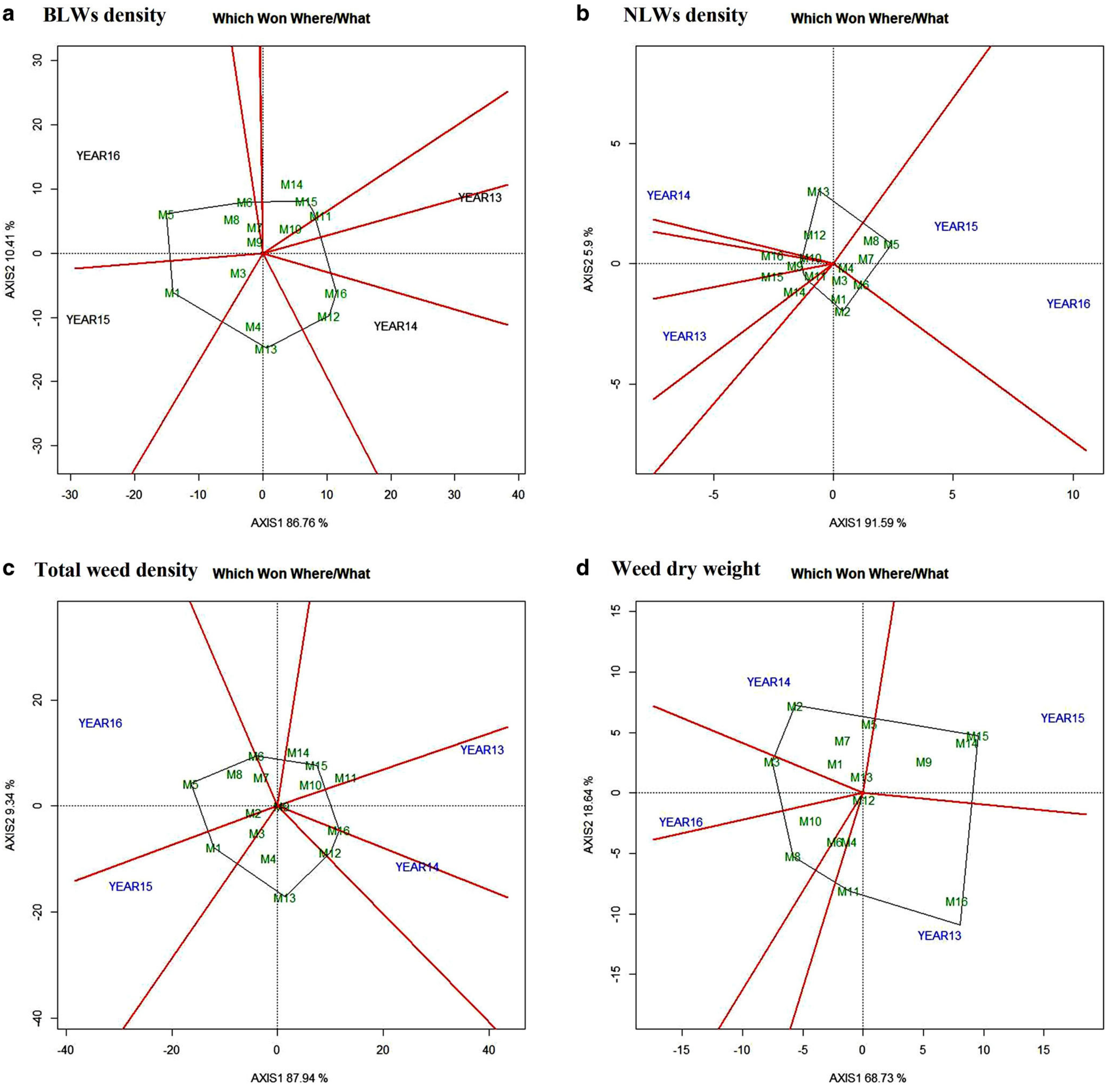

Fig. 4 GGE biplot analysis of trends of weeds under various tillage and weed control practices; **a** polygon view (Which Won Where/What) of BLWs density, **b** polygon view of NLWs density, **c** polygon view of total weed density and **d** polygon view of weed dry weight

concentrated within the top 0–5 cm of soil depth (Lutman et al. 2002). Moreover, favourable soil moisture and temperature conditions, combined with organic matter residue loads of 3.5 and 5 t ha^{-1}, created an environment conducive to the germination of weeds, particularly during the initial years (Chhokar et al. 1999). For effective management of diverse weed flora, we employed PE and POE herbicides. These herbicides played a crucial role in inhibiting the initial germination of weed seeds, desiccating, and eliminating emergent weeds, thereby reducing the overall weed severity with tillage systems (Dass et al. 2016).

In the year 2013, the density of BLWs was notably low in CT–R treatment. However, this density gradually increased over the experimental period. As observed, reduced BLWs density in CT–R can be attributed to the rigorous and continuous ploughing, which effectively curbed weed flora through uprooting, disturbance, and deep mechanical burial within the soil (Chhokar et al. 2007; Farooq and Nawaz 2014). The seeds of these buried weeds, as a result

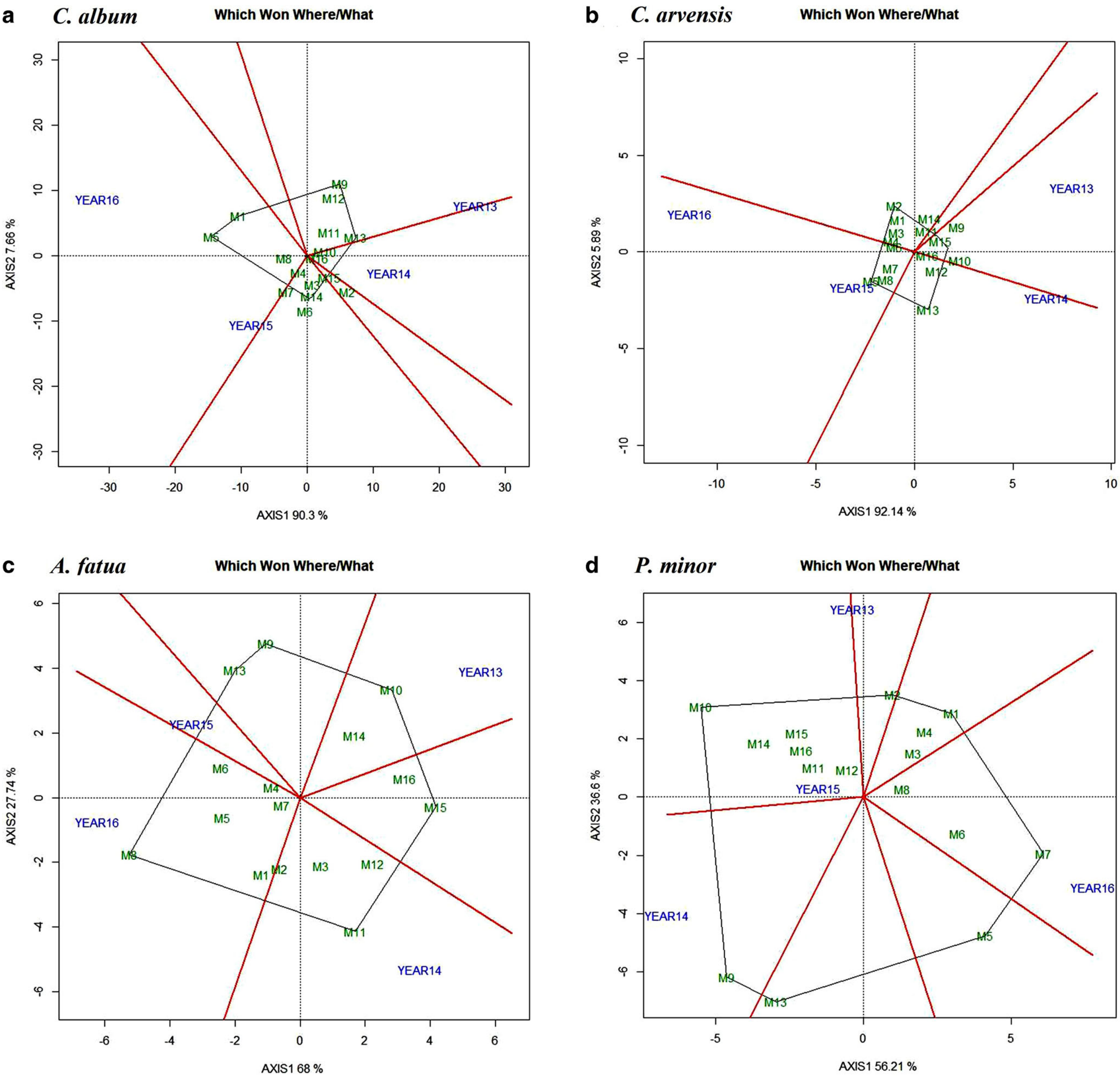

Fig. 5 GGE biplot analysis of trends of individual weeds under various tillage and weed control practices. **a** polygon view (Which Won Where/What) of *C. album*, **b** polygon view of *C. arvensis*, **c** polygon view of *A. fatua* and **d** polygon view of *P. minor*

of ploughing, became uniformly mixed with the soil and distributed throughout the ploughed depth zone (0–30 cm), which accumulated over the years (Clement et al. 1996). Consequently, by the year 2016, CT–R exhibited a higher density of BLWs, NLWs, and total weeds owing to weed seeds multiplications, resurfaced, and germinated from the deeper layers of the soil.

In the case of CT+R @ 3.5 t ha^{-1}, during the initial year (2013), the incorporation of crop residue inhibited the germination of NLWs. Conversely, in CT–R, seeds of NLWs demonstrated better adaptability to frequent soil tillage, so weed density continually increased by 2016 (Lutman et al. 2002). The application of PE or POE herbicides, effectively managed NLWs, BLWs, and total weed density with the presence of higher residue loads (ZT+R @ 5 t ha^{-1}). In this context, selecting a broad-spectrum selective herbicide, such as mesosulfuron + iodosulfuron, can be a suitable alternative under high-residue-retention ZT systems. However, in ZT+R @ 3.5 t ha^{-1}, the proper adoption of PE followed by POE is necessary for effective weed control.

In CT, whether with residue incorporation or without, the sequential application of herbicides is recommended

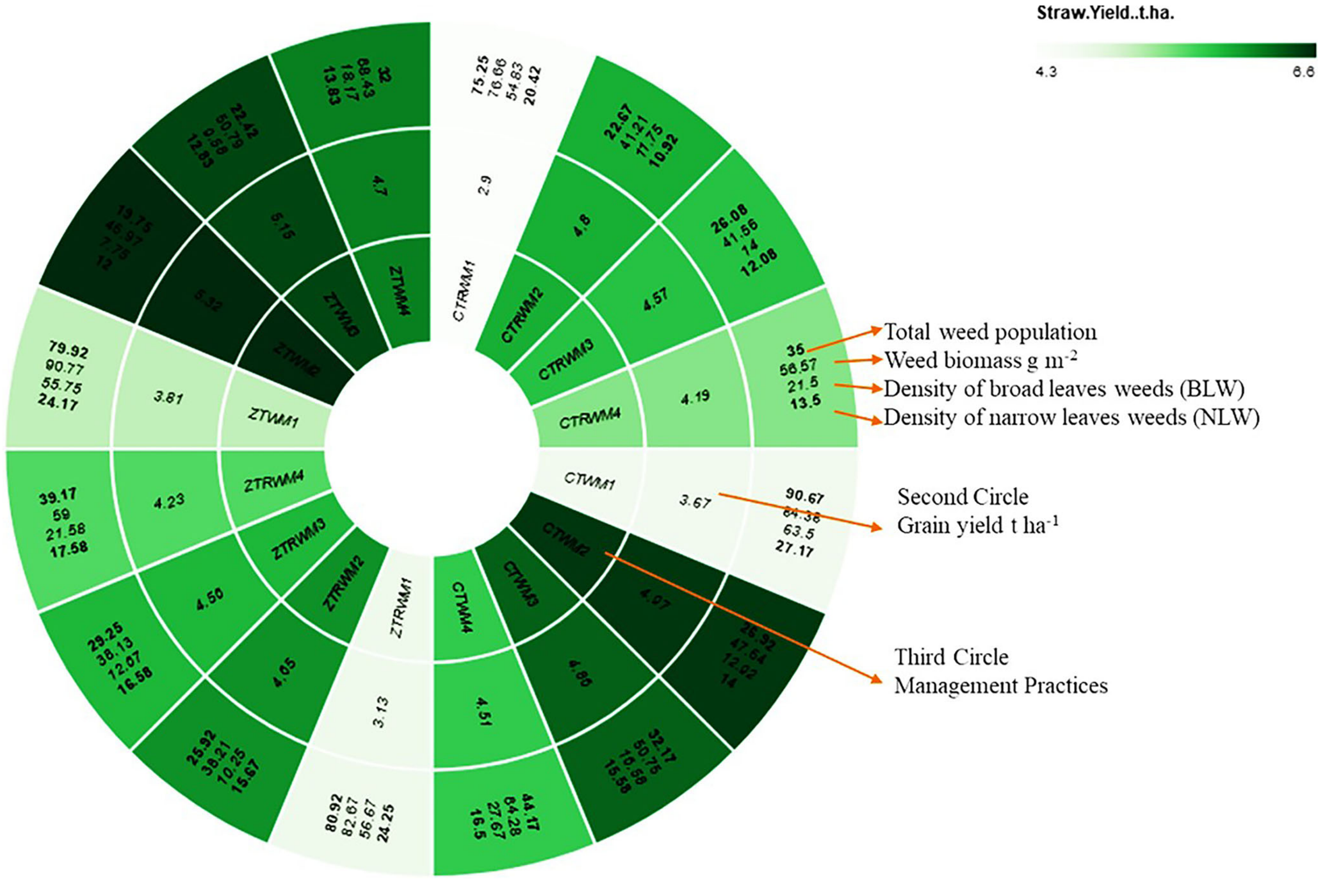

Fig. 6 Sunfrost visualization of seasonal weeds dynamics in wheat crop under CA based management practices Note: *First outer most circle* is showing total weeds populations, weeds biomass, densities of BLWs and NLWs; *Second middle circle* is indicating the wheat grain yield; the *innermost circle* is indicating the adopted CA practices (colour intensity depends on gradient straw yield)

based on this study. Nevertheless, it is essential to be cautious, as such practices may lead to herbicide resistance in the long run. On a different note, the sole application of pendimethalin PE was found to be ineffective in ZT due to the presence of retained crop residues, hindering the herbicide molecule's contact with the soil and its ability to activate the proper mode of action. In contrast, the use of mesosulfuron + idosulfuron was selective against a broad range of BLWs and NLWs flora in ZT+R @ 3.5 or 5 t ha^{-1}, compared to sole PE (Balyan and Malik 2000), as it functions through the appearance of visible chlorotic patches and shoot necrosis.

Initially, variable floristic compositions of weeds *viz. C. arvensis* and *C. album* (in BLWs) and *A. fatua* and *P. minor* (in NLWs) were high in ZT+R @ 3.5 t ha^{-1} which reversed after 4 years. In CA, the retention of crop residue on the soil surface is one of the pillars which aid in moisture and soil conservation (Sepat et al. 2015; Alhammad et al. 2023) and also suppress weed germination (Gupta and Seth 2007).

Regarding BLWs, ZT demonstrated a comparable performance to CT. However, the presence of a substantial amount of residue in ZT inhibited the germination and emergence of NLWs by limiting the available light for growth. Pale shoots of weeds were subsequently suppressed by herbicide action. It's noteworthy that in the weedy check with CT, both total and NLWs exhibited an increasing trend over the years. In contrast, ZT+R effectively reduced NLW and total weed infestations, even in the weedy check. This highlights the effectiveness of ZT in controlling troublesome annual NLWs like *P. minor* and *A. fatua*, as well as total weed density.

In wheat cultivation, the slow decomposition of maize residues, attributed to low temperatures from October to January, coupled with the presence of maize residue at 3.5 tons per hectare, acted as effective mulch. This mulch layer effectively prevented direct sunlight from reaching the soil, inhibiting initial weed germination and growth. By 2016, the accumulation of a substantial residue amount with low weed infestation favoured higher wheat yields in the ZT+R @ 5 t ha^{-1} treatment, particularly when combined with either POE herbicides (mesosulfuron + iodosulfuron) or PE herbicides (pendimethalin) followed by POE herbicides. However, it is important to note that heavy reliance on herbicides in zero-tillage systems can lead to the development of resistance in weed populations and shifts in weed flora. Therefore, in India, it becomes imperative to incorporate ecological approaches alongside chemical weed management practices to ensure sustainable wheat production.

Conclusions

This comprehensive four-year study underscores the effectiveness of employing PE and POE herbicides as a viable strategy for weed control within the ZT system in wheat. In ZT, there was a gradual reduction in the density of BLWs and total weed populations. However, it is noteworthy that the density of NLWs continued to increase towards the end of the study period. In ZT systems with a high residue load (ranging from 3.5 to 5 t ha^{-1}), the use of POE proved highly effective in curbing NLWs and reducing the overall weed density. In ZT+R, the application of both PE and POE herbicides emerged as effective methods for unlocking the full yield potential of wheat, particularly in the Indo-Gangetic Plains of India. However, to ensure long-term sustainability and address potential issues of weed resistance, it is essential to explore herbicide rotation strategies and assess their efficacy in managing weeds within the ZT system. This proactive approach is crucial to combat potential challenges posed by evolving weed populations and resistance in the future.

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Availability of data and materials Data used in the article will be available after request to the corresponding author.

Conflict of interest S. Sepat, A. Kumar, R. Kaur, H. Singh, B. Phogat, D. Kumar, R. Sadhukhan, S.L. Meena, S.R. Choudhary, A. Gaber and A. Hossain declare that they have no competing interests.

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