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Weed management in direct-seeded rice under a long-term conservation agriculture-based rice (*Oryza sativa*)-wheat (*Triticum aestivum*) system

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ABSTRACT

Weeds that occur in repeated flushes pose major challenges to direct-seeded rice (DSR). Zero till (ZT) DSR with crop residue influences weed interference considerably and can be substitutive to resource-intensive puddled transplanted rice (PTR). Field experiments were conducted at ICAR-Indian Agricultural Research Institute during 2018–19 involving conservation agriculture (CA)-based DSRs and weed control/herbicides treatments to appraise weed interference and productivity under an eight-year old CA-based rice-wheat system (RWS). All DSRs encountered more weeds than PTR. A double ZT system without residue [~ZTDSR-ZT wheat (ZTW); C1] had highest density and dry weight of grassy weeds, but a triple ZT system without residue [~ZTDSR-ZTW-ZT mungbean (ZTMB); C4] had highest density and dry weight of broad-leaved and sedge weeds. However, a triple ZT system with three crops residue [~ZTDSR + mungbean residue-ZTW + rice residue-ZTMB + wheat residue; C5)] could reduce weed interference significantly and led to 9.3% and 21.8% higher rice yield than C1 and C4, respectively. The application of pyrazosulfuron-ethyl 0.025 kg/ha pre-emergence followed by (*fb*) cyhalofop-butyl 0.100 kg/ha at 20 days after sowing (DAS), *fb* bispyribac-Na 0.025 kg/ha at 25 DAS (W4) led to significant reduction in grassy, broad-leaved and sedge weeds densities by 92.5, 96.6 and 67.7%, respectively. The triple ZT system with rice, wheat and mungbean residues (C5) combined with application of pyrazosulfuron-ethyl *fb* cyhalofop-butyl *fb* bispyribac-Na (W4) gave almost similar rice yield with PTR (C6). This may be recommended for adoption in Indo-Gangetic Plains (IGP) of India and in similar agro-ecologies of the tropics/sub-tropics.

Keywords: Bispyribac-Na, Crop residue, Cyhalofop-butyl, Pendimethalin, Pyrazosulfuron-ethyl, *Sesbania* brown manuring, Weeds

The low input-/resource-use efficiency, lowering of water table, energy and labour crisis, multi-nutrient deficiency, greenhouse gases emission, weed shift and resistance are challenges experienced in the puddled transplanted rice (PTR)–conventional till wheat (CTW) system (Hobbs and Gupta 2003, Raj *et al*. 2017). The PTR is less resource-efficient (Das *et al*. 2020b) and puddling affects soil structure and reduces sub-surface permeability (Mondal *et al*. 2019). Direct-seeded rice (DSR) could be a potential alternative to PTR. The zero till DSR (ZTDSR)–ZT wheat (~ZTW) system with residue has several advantages over transplanting (Raj *et al*. 2017), but weeds are major constraint in DSR (Rao *et al*. 2007, Baghel *et al*. 2020, Sen *et al*. 2021). Weeds cause heavy yield losses in DSR depending on management practices across locations (Chauhan and Opena 2012, Raj *et al*. 2016a). Conservation Agriculture (CA) can influence weed interference in DSR, for example, the ZTDSR can alter seeds dispersal across soil depths and influence weeds dominance and diversity. Residue retention, brown manuring, crop intensification with legume may also impact weeds growth (Das *et al*. 2020a). Besides, continuous adoption of ZTDSR-ZTW system could lead to a shift in weed flora towards annual grassy weeds [*Dactyloctenium aegyptium* (L.) Wild., *Dinebra retroflexa* (Vahl) Panz., *Leptochloa chinensis* (L.) Nees] and perennial sedges [*Cyperus esculentus* (L.), *Cyperus rotundus* (L.)] which were hardly controlled by recommended herbicides. In this study, newer combinations of herbicides such as the sequential applications of pre-emergence pyrazosulfuron-ethyl (as substitute of pendimethalin) followed by (~*fb*) post-emergence cyhalofop-butyl and bispyribac-Na have been attempted to manage weed better and delay in weed shift. The hypothesis was that the combined use of CA and weed control practices might lead to better weed management and higher yield in DSR. Therefore, this experiment was

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conducted under CA-based rice-wheat cropping system with an objective to evaluate CA and weed management practices on weed dynamics and productivity of rice.

MATERIALS AND METHODS

Field experiments were conducted at the ICAR-Indian Agricultural Research Institute, New Delhi (28°38'38″ N and 77°09'08″ E; 228 m amsl) in the 9th (~2018) and 10th (~2019) year of a long-term CA-based rice–wheat system. Soil (order Inceptisol, typic Haplustept) was clayey loam in texture. Semi-arid climate with dry hot summer and cold winter prevails in this region. Annual rainfall is 709 mm of which 80% is received during July–September. There were six main plot treatments (CA & CT): zero-till (ZT) direct-seeded rice (ZTDSR)-zero-till wheat (ZTW) (C1), ZTDSR + wheat residue (WR)-ZTW + rice residue (RR) (C2), ZTDSR + WR + brown manuring (BM)-ZTW + RR (C3), ZTDSR-ZTW-ZT mungbean (ZTMB) (C4), ZTDSR + mungbean residue (MBR)-ZTW + RR-ZTMB + WR (C5), puddled transplanted rice (PTR)-conventional till wheat (CTW) (C6), and four weed control sub-plot treatments: un-weeded control (W1), pendimethalin at 1.5 kg/ha applied at 1 day after sowing (DAS) or 3 days after transplanting (DAT) as pre-emergence (PE) followed by (*fb*) post-emergence (PoE) bispyribac-Na at 0.025 kg/ha applied at 25 DAS/DAT (W2), pyrazosulfuron-ethyl at 0.025 kg/ha as PE *fb* tank-mixture of cyhalofop-butyl at 0.100 kg/ha + bispyribac-Na at 0.025 kg/ha at 25 DAS (PoE) (W3), and pyrazosulfuron-ethyl at 0.025 kg/ha as PE *fb* cyhalofop-butyl at 0.100 kg/ha at 20 DAS *fb* bispyribac-Na at 0.025 kg/ha at 25 DAS (PoE) (W4). The experiment was laid out in a split-plot design with three replications. The main plots and sub-plots were 48.7 m × 4.0 m and 3.6 m × 4.0 m, respectively. Un-weeded control (W1) was natural weed infestation adopted for comparing the efficacy of weed control treatments (Das 2001).

In C2 treatment, the 40% residues of wheat (WR) in ZTDSR, and of rice (RR) in ZTW were retained. In C3, addition to ZTDSR + WR-ZTW + RR, *Sesbania bispinosa* was grown as a co-culture with ZTDSR for brown manuring. Its seeds (20 kg/ha) were broadcasted manually while sowing ZTDSR in rows and were allowed to grow with rice for about 25 days. Herbicide 2,4-D at 0.5 kg/ha was sprayed at 25 DAS, which resulted in killing of *Sesbania* plants. Whereas, in C5 a 100% residue of mungbean as anchored residue, were left in ZTDSR after picking of mature pods, 40% rice residue was retained for ZTW and 40% wheat residue was retained for ZT mungbean. For ZTDSR, rice hybrid Arize 6129 Gold (Bayer CropScience) was sown using a Turbo Happy Seeder with 30 kg seed/ha at 20 cm × 5–7 cm spacing and 2.0–2.5 cm depths of soil. In PTR, the transplanting was done manually at 20 cm × 10 cm spacing with 25 days old seedlings. Recommended doses of 150 kg N, 26.2 kg P and 33 kg K/ha were applied to both DSR and PTR. A non-selective herbicide such as glyphosate at 1.5 kg/ha was applied after a crop harvest and before sowing of next season crop to kill leftover weeds in all CA based treatments (C1–C5). Two central rows of rice (~0.40 m width) up to a length of 0.5 m were selected randomly from two locations in each plot and weeds were collected, counted species-wise and categorized into grassy, broad-leaved and sedge weeds. After recording density of weeds, same weeds samples were first sun-dried for 2 days and then kept in an oven at 70 ± 5°C for 48 hours for estimating dry weights. Weed control efficiency (WCE) and weed control index (WCI) were calculated following the Eq. 1 and Eq. 2 (Das and Das 2018).

$$\text{WCE} = (\text{WDc} - \text{WDt})/\text{WDc} \times 100 \qquad (1)$$

where WDc, the weed density (number/m^2) in control plot; WDt, the weed density (number/m^2) in treated plots.

$$\text{WCI} = (\text{WDMc} - \text{WDMt})/\text{WDMc} \times 100 \qquad (2)$$

where WDMc, the weed dry biomass (g/m^2) in control plot; WDMt, the weed dry biomass (g/m^2) in treated plots.

Twenty rice panicles were randomly collected from each treatment and spikelets in 20 panicles were counted and expressed as spikelets per panicle. They were categorized into filled (grain with endosperm) and un-filled (without endosperm) spikelets. Spikelet fertility was calculated following Eq. 3.

$$\text{Spikelet fertility (\%)} = (\text{Number of filled spikelets/total number of spikelets}) \times 100 \qquad (3)$$

A net plot area comprising of 16 rows of rice up to a length of 2.8 m (~3.2 m × 2.8 m) was harvested for estimation of rice grain and straw yields. The grain yield was recorded at 12% moisture. Harvest index (HI) was calculated by following Eq. 4.

$$\text{HI (\%)} = [\text{Grain yield/total biomass (grains + straw) yield}] \times 100 \qquad (4)$$

Data on weed density and dry weight were transformed through square-root method $\sqrt{(x+0.5)}$ before analysis of variance (ANOVA) (Das 1999). The ANOVA of weed and rice data was done in a split-plot design using PROC GLM in SAS 9.3 (SAS Institute, Cary, NC). A least significant difference (LSD) test was carried out to appraise the significance of treatment means at P≤0.05. Principal component analysis (PCA) was performed to find out linear correlations between CA (C) and weed management (W) combinations and weed species distribution. The PCA biplots gave the type and degree of association of weeds with treatment combinations through a vector diagram. The vectors represent weeds parameters and the direction of a vector indicates type of association between weeds variables and C × W. The strength of association is proportional to the vector length. Weeds variables were selected based on the eigen values of each PC and the scores of different weeds parameters within each PC.

RESULTS AND DISCUSSION

Weed flora diversity and interference: The experimental field under natural infestation of weeds in the un-weeded control had 14 weeds comprising of 6 grassy [*Echinochloa colona* (L.) Link, *Echinochloa crus-galli* (L.) Beauv, *Dactyloctenium aegyptium* (L.) Willd., *Dinebra retroflexa* (Vahl) Panz., *Leptochloa chinensis* (L.) Nees, *Eleusine indica* (L.) Gaertn.], 4 broad-leaved [*Eclipta alba* (L.), *Phyllanthus niruri* (L.), *Alternenthera philoxeroides* (Mart.) Griseb, *Trianthema portulacastrum* (L.)] and 4 sedge [*Cyperus esculentus* (L.), *Cyperus rotundus* (L.), *Cyperus difformis* (L.)., *Cyperus iria* (L.)] weeds. The density and dry weight (Table 1) of grassy, broad-leaved, sedge and total weeds were significantly influenced by conservation agriculture (CA) and weed management treatments. All DSRs treatments had higher infestations of these categories of weeds compared to PTR. The C1 (~ZTDSR-ZTW) had highest density and dry weight of grassy weeds; C4 (~ZTDSR-ZTW-ZTMB) had significantly higher density and dry weight of broad-leaved, sedge, and total weed than other CA/CT treatments except C1, which had similar total weed dry weight with C4. However, the mungbean inclusive triple ZT system with three crop residues (~ZTDSR + MBR-ZTW + RR-ZTMB + WR; C5) resulted in lowest density and dry weight of grassy weeds and total weed. Long-term adoption of ZT, crop residue retention and crop rotation greatly influenced the density, dry weight, and diversity of weeds species (grassy, broad-leaved and sedge weeds) (Nichols *et al*. 2015, Baghel *et al*. 2020, Das *et al*. 2020b). Higher grassy weeds in double ZT system without residue (C1) resulted from higher weed seed accumulation on the soil surface (0–5 cm) and their profuse germination triggered by sunlight (Chauhan and Opena 2012), helping emergence of grassy weeds and subsequent building up of their seed bank near soil surface (Mishra and Singh 2012). This indicated that only ZT was not enough but ZT with residue retention was necessary to control weeds. Crops residue provides physical barriers to sunlight, reducing weed germination substantially, besides releasing allelo-chemicals into soil. Growing mungbean during summer without residue provided favourable micro-climate, adequate moisture, and lower soil temperature through irrigation that could help germination and preponderance of few broad-leaved and perennial sedge weeds. On the contrary, the mungbean inclusive triple ZT system with three crops residues (C5) led to lowest density and dry weight of grassy weeds and

Table 1 Effect of conservation agriculture and weed control practices on weed density (no./m^2) and dry weight (g/m^2) (mean of two years)

Treatment	Densities/populations (no./m^2)‡					Dry weight (g/m^2)‡				
	Grassy weeds	Broad-leaved weeds	Sedge weeds	Total weeds	WCE (%)	Grassy weeds	Broad-leaved weeds	Sedge weeds	Total weeds	WCI (%)
Conservation agriculture practice ¥										
C1: ZTDSR-ZTW	8.4^{a}† (85)	2.8^{b}† (10)	6.6^{c}† (45)	11.1^{b}† (140)	40.4	9.3^{a}† (112)	1.8^{c}† (4)	4.0^{c}† (17)	10.4^{a}† (132)	33.3
C2: ZTDSR + WR-ZTW + RR	7.4^{b} (66)	2.8^{b} (10)	6.0^{d} (37)	10.1^{c} (113)	51.9	8.2^{b} (86)	1.9^{c} (4)	3.7^{d} (14)	9.2^{b} (103)	48.0
C3: ZTDSR + WR + BM-ZTW + RR	6.7^{c} (54)	1.7^{d} (4)	5.4^{e} (30)	8.9^{d} (87)	63.0	7.5^{c} (72)	1.2^{d} (1)	3.4^{e} (12)	8.4^{c} (84)	57.6
C4: ZTDSR-ZTW-ZTMB	5.4^{d} (33)	4.9^{a} (31)	12.0^{a} (152)	14.1^{a} (215)	8.5	5.9^{d} (41)	3.5^{a} (16)	6.9^{a} (50)	9.9^{a} (107)	46.0
C5: ZTDSR + MBR-ZTW + RR-ZTMB + WR	4.5^{e} (23)	2.8^{b} (10)	8.2^{b} (70)	9.8^{c} (103)	56.2	4.8^{e} (27)	2.3^{b} (7)	4.8^{b} (24)	7.3^{d} (58)	70.7
C6: PTR-CTW	3.5^{f} (16)	2.3^{c} (7)	4.9^{f} (27)	6.5^{e} (50)	78.7	4.7^{e} (29)	1.4^{d} (2)	3.4^{e} (12)	5.9^{e} (43)	78.3
Weed control practice										
W1: Unweeded control (UWC)	9.9^{a} (107)	5.1^{a} (29)	9.4^{a} (99)	15.0^{a} (235)	0.0	11.9^{a} (153)	3.0^{a} (10)	5.6^{a} (35)	13.7^{a} (198)	0.0
W2: Pendimethalin *fb* bispyribac	4.7^{c} (23)	1.8^{c} (3)	6.2^{c} (43)	8.1^{c} (69)	70.6	5.0^{c} (26)	1.3^{b} (1)	3.8^{c} (16)	6.5^{c} (43)	78.3
W3: Pyrazosulfuron *fb* cyhalofop + bispyribac	6.5^{b} (45)	3.7^{b} (15)	7.8^{b} (67)	11.0^{b} (127)	46.0	7.3^{b} (57)	2.9^{a} (11)	4.7^{b} (24)	9.4^{b} (91)	54.0
W4: Pyrazosulfuron *fb* cyhalofop *fb* bispyribac	2.8^{d} (8)	1.0^{d} (1)	5.4^{d} (32)	6.1^{d} (41)	82.6	2.8^{d} (8)	1.0^{c} (1)	3.3^{d} (12)	4.4^{d} (20)	89.9

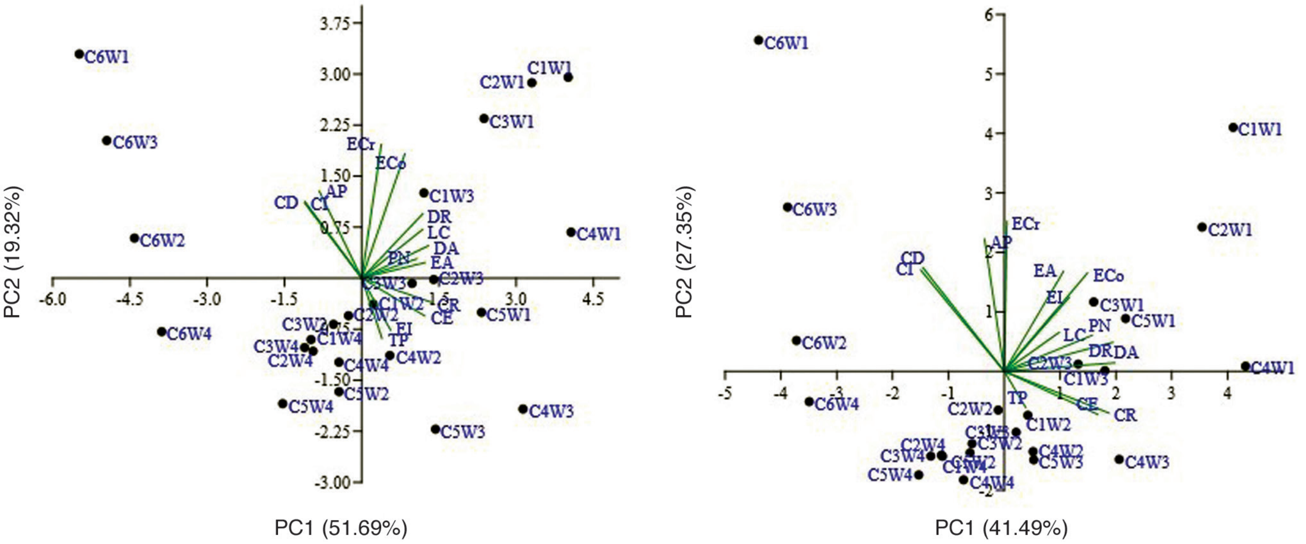
¥ All treatments are described in Materials and Methods; ‡Transformed data through square-root $(x+0.5)^{1/2}$ method before analysis of variance (ANOVA); †Within a column, means followed by the same letter are not significantly different at $P \leq 0.05$ using LSD test. Values in the parentheses are original/observed density of the respective categories of weeds.

total weed. The combined effect of ZT and crop residue retention played roles.

Weed control treatments consisting of sequential applications of pre-emergence (PE) and post-emergence (POE) herbicides led to significant reduction in density and dry weight of grassy, broad-leaved, sedge, and total weeds (Table 1). The most effective was the application of pyrazosulfuron (PE) *fb* cyhalofop (early PoE) *fb* bispyribac (PoE) (W4), which brought about significant reduction in densities by 92.5, 96.6 and 67.7% and dry weight by 94.8, 90.0 and 65.7% of grassy, broad-leaved and sedge weeds, respectively compared to un-weeded control (W1). The W4, W2 and W3 treatments led to 82.6, 70.6 and 46.0% weed control efficiency (WCE), and 89.9, 78.3, and 54.0% weed control index (WCI), respectively in rice. Repeated flushes of germination of weeds in DSRs advocate adoption of repeated weed control measures. Only pre-emergence (PE) application of single herbicide could not control weeds (Baghel *et al*. 2020). Raj *et al*. (2016a) found that the application of pendimethalin *fb* bispyribac was very effective for weed control in PTR. In contrast, Baghel *et al*. (2020) reported that this combination was not much effective against late-emerging grassy weeds and perennial sedge *C. rotundus*, and recommended one hand weeding at 35 DAS after application of these herbicides for better weed control in DSR. Pyrazosulfuron controlled early weed interference right from weed germination. Bispyribac-Na was less effective against new grassy weeds *D. retroflexa*, *L. chinensis* and *D. aegyptium*. The sequential application of cyhalofop-butyl controlled *D. retroflexa*, *L. chinensis* effectively and *D. aegyptium* moderately.

The effects of CA and weed control practices on weed species distribution was reflected in PCA (Fig 1a and 1b). The PC1 and PC2 contributed to ~71 and ~69% of total variability in 2018 and 2019, respectively. Weed species, namely, *L. chinensis* (LC), *D. aegyptium* (DA), *D. retroflexa* (DR), *E. alba* (EA), *P. niruri* (PN), *C. rotundus* (CR) and *C. esculentus* (CE) had higher loading value for PC1, and *A. philoxeroides* (AP), *E. alba* (EA), *E. crusgalli* (ECr) and *E. colona* (ECo) for PC2 in 2018 and 2019. It revealed that weed species were distinctly located on PCA coordinates. The direction of vector indicated that the treatment combinations of C1W1, C2W1, C3W3 and C4W1 had closer association with weeds ECo, DR, LC, DA, EA and PN, and C6W1 and C6W3 with weeds CD and CI.

Rice yield attributes, yield and harvest index: The CA and weed control/herbicides treatments significantly influenced rice yield attributes (Table 2). The PTR-CTW (C6) resulted in significantly higher values of filled grains per panicle and spikelets fertility than CA-based DSRs. Among CA-based DSRs, the C5 had higher filled grains and spikelets fertility, and lesser unfilled grains. Due to this treatment, filled grains per panicle increased by 8.0, 15.6, 16.5 and 14.7% compared to C1, C2, C3, and C4, respectively. The sequential application of pyrazosulfuron *fb* cyhalofop *fb* bispyribac (W4) led to significantly higher filled grains per panicle and spikelets fertility than W1 and W3 and was comparable with W2. This gave ~55%, 12% and 5% higher filled grains than W1, W3 and W2, respectively. Grain and straw yields and harvest index of rice were significantly influenced by CA and weed control/herbicides (Table 2). The C6 (~PTR-CTW) system led to significantly higher grain yields than all DSRs. Among DSR treatments, the C5 gave 9.3, 20.1, 22.0 and 21.8% higher grain yield (Table 2) than



Bi-plot (axes PC1 and PC2: 71.01%)

Bi-plot (axes PC1 and PC2: 68.84%)

Fig 1 PCA bi-plot (PC1 vs PC2) of weed species across conservation agriculture practices and weed management practices in 2018 (a) and 2019 (b).

Treatments (C1–C6 and W1–W4) are given in Materials and Methods. Eco, *Echinochloa colona*; ECr, *Echinochloa crusgalli;* DA, *Dactyloctenium aegyptium;* DR, *Dinebra retroflexa;* LC, *Leptochloa chinensis;* EI, *Eleusine indica;* EA, *Eclipta alba;* PN, *Phyllanthus niruri;* AP, *Alternenthera philoxeroides;* TP, *Trianthema portulacastrum*; CE, *Cyperus esculentus*; CR, *Cyperus rotundus*; CD, *Cyperus difformis*; CI, *Cyperus iria.*

Table 2 Effect of conservation agriculture and weed control practices on filled and un-filled grains, spikelet fertility, yield (grain and straw) and harvest index (HI) of rice (mean of two years)

Treatment	Filled grains (no./panicle)	Unfilled grains (no./panicle)	Spikelet fertility (%)	Grain yield (t/ha)	Straw yield (t/ha)	HI (%)
Conservation agriculture practice ¥						
C1: ZTDSR-ZTW	$137^{bc\dagger}$	29^{a}	81.2^{c}	$5.47^{c\dagger}$	7.62^{c}	41.0^{ab}
C2: ZTDSR + WR – ZTW + RR	128^{c}	30^{a}	80.8^{c}	4.98^{d}	7.00^{d}	40.7^{b}
C3: ZTDSR + WR + BM – ZTW + RR	127^{c}	31^{a}	79.9^{c}	4.90^{d}	6.76^{d}	41.7^{ab}
C4: ZTDSR-ZTW-ZTMB	129^{c}	30^{a}	80.2^{c}	4.91^{d}	6.85^{d}	41.3^{ab}
C5: ZTDSR + MBR-ZTW + RR-ZTMB + WR	148^{b}	24^{b}	85.5^{b}	5.98^{b}	8.35^{b}	41.6^{ab}
C6: PTR-CTW	161^{a}	19^{c}	89.7^{a}	6.77^{a}	9.37^{a}	41.8^{a}
Weed control practice						
W1: Unweeded control (UWC)	102^{c}	32^{a}	75.2^{c}	2.57^{d}	3.92^{d}	39.0^{c}
W2: Pendimethalin *fb* bispyribac	151^{a}	25^{bc}	85.5^{a}	6.53^{b}	8.96^{b}	42.2^{a}
W3: Pyrazosulfuron *fb* cyhalofop + bispyribac	142^{b}	28^{b}	83.6^{b}	5.88^{c}	8.24^{c}	41.7^{b}
W4: Pyrazosulfuron *fb* cyhalofop *fb* bispyribac	159^{a}	24^{c}	87.1^{a}	7.03^{a}	9.51^{a}	42.6^{a}

¥ All treatments are described in Materials and Methods; †Within a column, means followed by the same letters are not significantly different at P≤0.05 using LSD test.

C1, C2, C3 and C4, respectively, and was most superior. But, the C6 (~CT) system gave 13.2% higher grain yield than even C5. In C6 (~PTR-CTW) system, significantly lower weed interference resulted in higher yield variables, grain and straw yields. However, among DSRs, the C5 comprising of triple ZT system with three crops residue was most superior. Lower weed interference played roles. Crop residue is the principal source of carbon, which regulates the efficiencies of fertilizer, water, and other inputs used in crops. Similar happened to this study being eight-year old CA-based rice-wheat system, the effect of ZT, crop residue and crop culture was clearly visible on yield attributes and yield of rice under the C5 treatment. Among weed control treatments, W4 (pyrazosulfuron *fb* cyhalofop *fb* bispyribac) led to ~173.5%, 19.6% and 7.7% higher grain yield (Table 2) than W1, W3 and W2, respectively.

In this study a CA-based triple zero-till (ZT) system, involving ZT direct-seeded rice with mungbean residue - ZT wheat with rice residue - ZT mungbean with wheat residue constituted a set of integrated weed management modules/ options in DSR. It gave slightly lower grain yield than puddled transplanted rice. Similarly, weed management through the application of pyrazosulfuron *fb* cyhalofop *fb* bispyribac-Na led to higher yield in ZT direct-seeded rice and made it more productive. Therefore, it may be concluded that the zero-till based triple cropping system (rice-wheat-mungbean) with residue retention combined with the application of pyrazosulfuron *fb* cyhalofop *fb* bispyribac-Na may be recommended for production of direct-seeded rice in the North-western Indo-Gangetic Plains of India, which, could be a possible alternative to puddled transplanted rice as well.

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