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Research Paper

Crop-establishment methods and weed management effects on weeds, wheat (*Triticum aestivum*) yield and economics under a conservation agriculture-based rice (*Oryza sativa*)–wheat system

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ABSTRACT

A field experiment was conducted at the ICAR-Indian Agricultural Research Institute during the winter (*rabi)* season of 2018–19 and 2019–20 involving 6 tillage and residue practices, viz. T_1, zero-till (ZT) direct-seeded rice (*Oryza sativa* L.) (ZTDSR)–zero-till wheat [*Triticum aestivum* (L.) emend Fiori & Paol] (ZTW); T_2, ZTDSR + wheat residue (WR)–ZTW + rice residue (RR); T_3, ZTDSR + WR + brown manuring (BM) – ZTW+RR; T_4, ZTDSR–ZTW–ZT mungbean [*Vigna radiata* (L.) R. Wilczek] (ZTMB); T_5, ZTDSR + mungbean residue (MBR) – ZTW + RR – ZTMB+WR; T_6, puddled transplanted rice (PTR)–conventional till wheat (CTW) in main plot; and 4 weed-control treatments, i.e. W_1, un-weeded control; W_2, Total (ready mix of sulfosulfuron + metsulfuron-methyl) 0.040 kg/ha at 30 day after sowing (DAS); W_3, tank-mixture of clodinafop-propargyl 0.060 kg/ha + metsulfuron-methyl 0.004 kg/ha at 30 DAS; W_4, tank-mixture of clodinafop-propargyl 0.060 kg/ha + carfentrazone-ethyl 0.02 kg/ha at 30 DAS in sub-plot under a split-plot design and replicated thrice. Treatment T_6 resulted in significantly higher population and dry weight of littleseed canarygrass (*Phalaris minor* Retz.), yellow sweet clover [*Melilotus indica* (L.) All.] and swine cress [*Coronopus didymus* (L.) Smith] than other treatments, whereas, population and dry weight of common lambsquarter (*Chenopodium album* L.)*,* sour dock (*Rumex dentatus* L.) and annual sowthistle (*Sonchus oleraceus* L.) were significantly higher under T_1 and T_4 treatments. The treatment T_5 registered ~62, 44, 35, 31 and 24% lower population of *P. minor* than T_6, T_1, T_4, T_2 and T_3 treatments, respectively. Similarly, total weed population and total weed dry weight were ~38 and 33% lower under T_5 compared with T_6 treatment respectively. Better wheat growth and lower weed interference under T_5 treatment led to 14.6% higher wheat grain yield under this treatment than T_6. The tank- mix of clodinafop-propargyl + metsulfuron significantly reduced the population and dry weight of all weeds compared to UWC and it led to 88.9% weed-control efficiency (WCE) and 89.4% weed-control index (WCI) in wheat. Therefore, growing of wheat under zero-till triple cropping system with rice, wheat and mungbean residues (T_5) combined with tank-mix application of clodinafop + metsulfuron at 30 DAS may be recommended for better weed management, and higher productivity and profitability from wheat in Indo-Gangetic Plains (IGP) of India and in similar agro-ecologies of the tropics/ sub-tropics.

Key words: Clodinafop-propargyl, Crop residue, Gross returns, Metsulfuron-methyl, *Phalaris minor*, Weed interference, Zero-tillage

Conservation agriculture (CA) is gaining popularity worldwide as a means of ensuring food security and agricultural sustainability under climate change and degrading natural resources base (Das *et al*., 2021; Sharma *et al*., 2021). In order to utilize CA to its fullest potential, system-based CA practices and location-specific appropriate crop rotations must be studied (Das *et al.,* 2018; Kassam *et al.,* 2019). Wheat [*Triticum aestivum* (L.) emend Fiori & Paol] is the second most important cereal crop in India after rice (*Oryza sativa* L.). To make the field loose, friable and well-pulverized for wheat sowing, farmers often execute frequent tillage after rice harvesting. Increased cultivation cost results in lower profitability (Chhokar *et al.,* 2007). A significant amount of greenhouse gases (GHGs) is also released into the environment by increased usage of fuel

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and machinery for repeated tillage. But, now-a-days zero till (ZT) sowing of wheat by using a Turbo Happy Seeder is adopted by farmers, especially in North-western India because of its ability to enable early and timely sowing of wheat after rice under residue-laden conditions, thus, lowering production cost and increasing yield and profitability (Chhokar *et al.,* 2007; Sidhu *et al.,* 2007; Sharma *et al.,* 2012).

As the CA alters soil ecology, the original weed species get replaced by species more suited to new habitat (Chauhan *et al.,* 2006; Nicholas *et al.,* 2015). Tillage and residue management are important factors determining weed species diversity. Chauhan *et al.* (2007) reported that weed establishment was reduced in CA compared to CT. In addition, a notable transition in weed flora of croplands from annual weed species to perennial and problematic weeds area observes (Armengot *et al.,* 2016). Weed-control strategy also varies depending on tillage, residue (kind, amount) and other agro-practices (Raj *et al*., 2020). Additionally, weather, crop species, and soil type and nutrients management may affect the degree and direction of weed species shifts as well as the density of weeds. Tilling the soil brings the dormant weed seeds buried deep in soil back to the soil surface. Seeds stay concentrated on the soil surface and annual species are partially replaced by perennials because there is hardly any soil disturbance while adopting CA. By lowering light availability and altering the properties of soil, residues on the soil surface in CA systems change the conditions (humidity, *p*H and temperature) for germination and the emergence of weed seeds (Holland, 2004). The weed shift poses a serious threat to CA because it has an impact on the competitive relationships between crops and weeds. Also, various tillage intensities affect weed competitiveness, and, in turn, weed management strategies. Therefore, a comprehensive study is required to know how the various CA components combine to cause weed species shifts, which may aid in the development of effective weed-control strategies to maintain a stable and low weed abundance. In CA practice, using herbicides and herbicide mixtures could be an efficient means to reduce weed seeds (Lee and Thierfelder, 2017). Therefore, this study was conducted to evaluate the effect of crop establishment methods and weed management on weed interference, and yield and economics of wheat under a CA-based rice-wheat system.

MATERIALS AND METHODS

A field experiment was conducted at the ICAR-Indian Agricultural Research Institute, New Delhi (28°38'383 N, 77°09'083 E; 228 m above mean sea-level) in the 9^{th} (2018-19) and 10^{th} (2019-20) year of a long-term CA-based rice–wheat system. Soil (order Inceptisols, Typic Haplustept) was clayey loam in texture. There were 6 main plot treatments (tillage and residue management, TRM); T_1, zero-till (ZT) direct-seeded rice (ZTDSR)-zero-till wheat (ZTW); T_2, ZTDSR + wheat residue (WR)– ZTW + rice residue (RR); T_3, ZTDSR + WR + brown manuring (BM) – ZTW + RR; T_4, ZTDSR-ZTW-ZT mungbean (ZTMB); T_5, ZTDSR + mungbean residue (MBR) – ZTW + RR – ZTMB + WR; T_6, puddled transplanted rice (PTR) – conventional till wheat (CTW); and 4 weed control sub-plot treatments, i.e. W_1, unweeded control; W_2, Total (ready mix of sulfosulfuron + metsulfuron-methyl) at 0.040 kg/ha at 30 day after sowing (DAS); W_3, tank-mixture of clodinafop-propargyl at 0.060 kg/ha + metsulfuron-methyl at 0.004 kg/ha at 30 DAS; W_4, tank-mixture of clodinafop-propargyl at 0.060 kg/ha + carfentrazone-ethyl at 0.02 kg/ha at 30 DAS.The experiment was laid out in a split plot design with 3 replications. Un-weeded control had natural weed infestation, and no weed control practice was adopted for it. It was included for comparing the weed-control efficacy of the treatments (Das 2001). A pre-sowing irrigation was applied immediately after rice harvesting for the sowing of wheat. In ZT treatments, wheat was sown by using a turbo happy seeder. Two-time disking and 1 pass cultivator followed by 2 passes of rotavator were done for sowing of wheat under CTW treatment. Wheat was sown at 20 cm row-spacing using 100 kg seed/ha. Recommended doses of 150 kg N, 26.2 kg P and 33 kg K/ha were applied to both ZTW and CTW. The 30% recommended dose of N and full doses of P and K were applied at sowing. Remaining N was applied equally at 25 and 60 DAS.

Two central rows of wheat (~0.40 m width) up to a length of 0.5 m were selected randomly from 2 locations in each plot and weeds were collected, and counted species-wise. After recording the density of weeds, the 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).

$$WCE = [(WDc - WDt)/WDc] \times 100 \quad (1)$$

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

$$WCI = (WDMc - WDMt)/WDMc \times 100 \quad (2)$$

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

A net plot area comprising of 16 rows of wheat up to a length of 3.0 m (~3.2 m × 3.0 m) was harvested for estimating the wheat grain yield. The grain yield was recorded at 14% moisture. Common cost of all the treatments was determined by summing up the prevailing costs of inputs and operations such as seed, fertilizer, irrigation, plant protection (excluding herbicide), harvesting, and threshing. A treatment's cost considered the costs of tillage (ZT/CT/puddling), sowing (DSR/nursery), transplanting, brown manuring, crop residue, herbicide as applicable for the treatment. The common cost-*plus* treatment cost constituted the total cost of a treatment. Minimum support price for wheat grains as declared by the Government of India was used for calculating economics.

Data on weed density and dry weight were transformed through square-root method $[(\times+0.5)^{½}]$ before analysis of variance (ANOVA) to reduce the higher coefficient of variation in original/ observed data (Das, 1999). The ANOVA of weed and wheat 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. Data on weed density and dry weight and grain yield and economics of wheat were subjected to Levene's test for homogeneity of variance, which implied that the error variance of most of the studied parameters of weed and wheat crop were homogeneous. Therefore, data of those parameters were subjected to pooled analysis to find out the effect of year and its interactions with tillage, residue, and weed management practices.

RESULTS AND DISCUSSION

Weed interference

Species-wise population and dry weight and weed control efficiency

The experimental field under natural infestation of weeds in the un-weeded control had 6 weeds comprising of one grassy (*Phalaris minor* Retz.) and 5 broad-leaved [*Chenopodium album* L., *Melilotus indica* (L.) All., *Coronopus didymus* (L.) Smith, *Sonchus oleraceus* L. and *Rumex dentatus* L.] weeds. The population of *P. minor, C. album*, *M. indica*, *S. oleraceus* and dry weight of *P. minor* and *M. indica* did not differ significantly due to growing season (i.e., years), whereas year had significant effect on population of *C. didymus* and *R. dentatus and* dry weight of *C. album*, *S. oleraceus, C. didymus,* and *R. dentatus* (Tables 1, 2). Tillage and residue management and weed control treatments and their interactions significantly influenced the population and dry weight of all the weed species (Tables 1, 2, 3). The PTR-CTW (T_6) led to significantly higher populations and dry weights of *P. minor, M. indica* and *C. didymus* than T_1, T_2, T_3, T_4, T_5 treatments, whereas ZTDSR-ZTW (T_1) and ZTDSR-ZTW-ZTMB (T_4) resulted in significantly higher population and dry weight of *C. album, R. dentatus and S. oleraceus*. The treatment T_5 (ZTDSR+MBR- ZTW+RR - ZTMB+WR) registered the lowest population and dry weight of *P. minor,* whereas T_6 (PTR-CTW) had the highest population and dry weight of this weed. The population of *P. minor* were ~62, 44, 35, 31 and 24% lower in T_5 than T_6, T_1, T_4, T_2 and T_3 treatments, respectively. Similarly dry weight of *P. minor* was reduced by ~63, 46, 33, 29 and 25% in T_5 compared to T_6, T_1, T_4, T_2 and T_3 treatments, respectively. The population and dry weight of *M. indica* and *C. didymus* were significantly lower in T_5 than T_6 and T_1 treatments and remained similar to treatments having zero-tillage combined with retention of crop residue (i.e. T_3 and T_2). The population and dry weight of weed species such as *C. album*, *S. oleraceus,* and *R. dentatus* were lowest in the PTR-CTW than the other TRM practices.

Again, the total weed population and dry weight were lowest due to T_5 treatment than other conservation and conventional agriculture-based treatments. The treatment T_5 was a CA-based triple ZT system with 3 crops residue in the cropping system mode, which played a role towards greater reduction in weed interference in wheat, and this CA practice proved superior to the other TRM and CT treatments. The reduction in total weed population and total weed dry weight due to this treatment was ~38 and 33%, respectively compared to CT (T_6) treatment. Conventional tillage (T_6) and zero-tillage without residue treatments (T_1 and T_6) registered similar population and dry weight of total weeds (Table 3), which again highlighted the weed suppressive ability of crops residue retained on the soil surface. Management practices such as tillage (Singh *et al*., 2012; Baghel *et al*., 2018), nutrients (Raj *et al*., 2020), residue cover, and crop rotation (Nichols *et al*., 2015; Baghel *et al*., 2020; Das et al., 2020) greatly influences weed species population, dry weight and diversity. Singh *et al*. (2012) reported greater emergence of weeds in conventional tilled wheat (CTW), when it was followed after puddled transplanted rice. Franke *et al*. (2006) observed that, the seedling emergence of *P. minor* was reduced in direct sowing compared to conventional till sowing.The lower population and dry weight of *P. minor* under ZT system was mainly owing to minimum soil disturbance supplemented with residue retention, which provided higher mechanical impedance to *P. minor* seeds present in lower soil layers and prevented them from germination (Singh *et al*., 2015).The surface retention of crop residue in CA provides physical barriers to sunlight, and may release allelochemicals after their decomposition, which further strengthen the inhibitory effects on germination of weed seed and early weed growth and development.The ZT and crop residue also encouraged weed seed foraging and predation actions by ants, insects, and birds, and reducing surface-laden seed-bank. In contrast, inversion, turning and mixing of soil by tillage implements bring buried deeper-layer weed seeds to the upper

Table 1. Species-wise weed distribution in wheat under crop establishment methods and weed control practices

Treatment	*Phalaris minor* (no./m²)*†			*Melilotus indica* (no./m²)*			*Chenopodium album* (no./m²)*			*Coronopus didymus* (no./m²)*			*Sonchus oleraceus* (no./m²)*			*Rumex dentatus* (no./m²)*		
	2018–19	2019–20	Pooled	2018–19	2019–20	Pooled	2018–19	2019–20	Pooled	2018–19	2019–20	Pooled	2018–19	2019–20	Pooled	2018–19	2019–20	Pooled
Year (Y)																		
2018–19	-	-	3.8	-	-	1.2	-	-	1.4	-	-	0.9	-	-	1.4	-	-	1.0
2019–20	-	-	4.0	-	-	1.3	-	-	1.5	-	-	1.1	-	-	1.5	-	-	1.2
SEm±	-	-	0.1	-	-	0.03	-	-	0.03	-	-	0.03	-	-	0.1	-	-	0.03
CD (P=0.05)	-	-	NS	-	-	NS	-	-	NS	-	-	0.1	-	-	NS	-	-	0.1
Tillage and residue management (TRM) ¥																		
T_1, ZTDSR-ZTW	4.2	4.4	4.3	1.2	1.3	1.3	1.7	1.9	1.8	1.0	1.2	1.1	1.8	1.9	1.8	1.3	1.8	1.5
T_2, WR+ZTDSR-RR+ZTW	3.7	3.9	3.8	1.2	1.2	1.2	1.4	1.5	1.5	0.9	0.9	0.9	1.1	1.1	1.1	1.0	1.1	1.1
T_3, WR+ZTDSR+BM-RR+ZTW	3.6	3.8	3.7	0.9	1.0	1.0	1.4	1.5	1.4	0.9	0.9	0.9	1.5	1.6	1.5	1.0	1.1	1.1
T_4, ZTDSR-ZTW-ZTMB	3.8	4.1	3.9	1.0	1.2	1.1	1.9	1.9	1.9	1.0	1.0	1.0	1.9	2.2	2.1	1.3	1.5	1.4
T_5, MR+ZTDSR-RR+ZTW-WR+ZTMB	2.9	3.1	3.0	0.8	0.9	0.9	1.1	1.1	1.1	0.8	0.9	0.9	1.1	1.3	1.2	1.0	1.0	1.0
T_6, TPR-CTW	4.7	4.8	4.8	2.1	2.2	2.1	0.7	0.7	0.7	1.3	1.7	1.5	0.7	0.7	0.7	0.7	0.9	0.8
SEm±	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.05	0.1	0.05	0.1	0.1	0.1	0.05	0.1	0.04
CD (P=0.05)	0.4	0.6	0.4	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.1	0.2	0.4	0.2	0.1	0.2	0.1
Weed control (W) ¥																		
W_1, UWC	5.5	6.3	5.9	2.1	2.4	2.2	2.5	2.8	2.6	1.6	1.9	1.8	2.2	2.5	2.3	1.8	2.4	2.1
W_2, Sulf+met (ready mix) (W2)	4.1	4.2	4.1	1.1	1.1	1.1	1.4	1.5	1.5	0.8	0.8	0.8	1.3	1.5	1.4	0.8	0.9	0.9
W_3, Clodin+met (tank mix) (W3)	2.6	2.5	2.5	0.9	0.8	0.8	0.7	0.7	0.7	0.7	0.8	0.7	0.9	0.9	0.9	0.7	0.7	0.7
W_4, Clodin+carfen (tank mix) W4)	3.0	3.1	3.1	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.9	0.8	1.0	1.0	1.0	0.9	0.9	0.9
SEm±	0.1	0.1	0.1	0.1	0.1	0.04	0.1	0.1	0.04	0.0	0.1	0.04	0.1	0.1	0.1	0.1	0.05	0.04
CD (P=0.05)	0.3	0.3	0.2	0.2	0.1	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.2	0.2	0.1	0.2	0.1	0.1
Interaction																		
Y × TRM	-	-	NS	-	-	NS	-	-	NS	-	-	NS	-	-	NS	-	-	NS
TRM ×W	S	S	S	S	S	S	S	S	S	S	S	NS	S	S	NS	S	S	S
Y × W	-	-	S	-	-	S	-	-	S	-	-	S	-	-	S	-	-	S
Y × TRM × W	-	-	NS	-	-	NS	-	-	NS	-	-	NS	-	-	NS	-	-	NS

†Except *Phalaris minor* which is a grassy weed, all other weeds presented above are broad-leaved weeds. *weed data presented here are square-root transformed through $(X+0.2)^{1/2}$.
¥ All treatments are described in Materials and Methods

Table 2. Species-wise weed dry weight in wheat as influenced by crop establishment methods and weed control practices

Treatment	*Phalaris minor* (g/m²)*†			*Melilotus indica* (g/m²)*			*Chenopodium album* (g/m²)*			*Coronopus didymus* (g/m²)*			*Sonchus oleraceous* (g/m²)*			*Rumex dentatus* (g/m²)*		
	2018–19	2019–20	Pooled	2018–19	2019–20	Pooled	2018–19	2019–20	Pooled	2018–19	2019–20	Pooled	2018–19	2019–20	Pooled	2018–19	2019–20	Pooled
Year (Y)																		
2018–19	-	-	6.5	-	-	1.4	-	-	1.9	-	-	1.1	-	-	2.0	-	-	1.8
2019–20	-	-	6.4	-	-	1.5	-	-	2.2	-	-	1.3	-	-	2.2	-	-	2.2
SEm±	-	-	0.1	-	-	0.1	-	-	0.1	-	-	0.03	-	-	0.1	-	-	0.1
CD (P=0.05)	-	-	NS	-	-	NS	-	-	0.2	-	-	0.1	-	-	0.2	-	-	0.3
Tillage and residue management (TRM) ¥																		
T_1, ZTDSR-ZTW	7.1	6.9	7.0	1.5	1.5	1.5	2.6	3.0	2.8	1.1	1.3	1.2	2.9	3.1	3.0	2.6	3.5	3.1
T_2, WR+ZTDSR-RR+ZTW	6.2	6.2	6.2	1.2	1.4	1.3	2.1	2.4	2.2	0.9	1.0	1.0	1.5	1.6	1.5	1.7	1.8	1.7
T_3, WR+ZTDSR+BM-RR+ZTW	6.1	5.9	6.0	1.0	1.1	1.1	2.0	2.2	2.1	0.9	1.0	1.0	2.2	2.4	2.3	1.6	2.1	1.9
T_4, ZTDSR-ZTW-ZTMB	6.4	6.7	6.5	1.2	1.3	1.3	2.7	3.1	2.9	1.0	1.1	1.1	3.1	3.7	3.4	2.5	2.7	2.6
T_5, MR+ZTDSR-RR+ZTW-WR+ZTMB	4.9	4.8	4.8	0.9	0.9	0.9	1.4	1.4	1.4	0.9	0.9	0.9	1.6	1.8	1.7	1.5	1.5	1.5
T_6, TPR-CTW	8.0	7.6	7.8	2.5	2.6	2.5	0.7	0.7	0.7	1.5	2.0	1.7	0.7	0.7	0.7	0.7	1.1	0.9
SEm±	0.3	0.3	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.3	0.2
CD (P=0.05)	0.8	0.9	0.6	0.4	0.5	0.4	0.4	0.4	0.3	0.3	0.2	0.2	0.4	0.8	0.4	0.4	0.8	0.5
Weed control (W) ¥																		
W_1, UWC	9.4	10.7	10.1	2.5	2.9	2.7	3.9	4.5	4.2	1.9	2.4	2.1	3.6	4.1	3.9	4.1	4.3	4.2
W_2, Sulf+met (ready mix) (W2)	6.9	6.3	6.6	1.2	1.2	1.2	2.0	2.4	2.2	0.8	0.9	0.9	1.9	2.3	2.1	1.0	1.1	1.1
W_3, Clodin+met (tank mix) (W3)	4.3	3.8	4.1	0.9	0.8	0.8	0.7	0.7	0.7	0.7	0.8	0.7	1.1	1.1	1.1	0.7	0.8	0.8
W_4, Clodin+carfen (tank mix) W4)	5.1	4.7	4.9	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.9	0.9	1.3	1.4	1.4	1.2	2.3	1.8
SEm±	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.5	0.2
CD (P=0.05)	0.6	0.6	0.4	0.3	0.3	0.2	0.2	0.3	0.2	0.2	0.2	0.1	0.4	0.4	0.3	0.5	1.3	0.7
Interaction																		
Y × TRM	-	-	NS	-	-	NS	-	-	NS	-	-	NS	-	-	NS	-	-	NS
TRM ×W	S	S	S	S	S	S	S	S	S	S	NS	NS	S	S	S	S	NS	NS
Y × W	-	-	S	-	-	NS	-	-	S	-	-	S	-	-	NS	-	-	NS
Y × TRM × W	-	-	NS	-	-	NS	-	-	NS	-	-	NS	-	-	NS	-	-	NS

†Except *Phalaris minor* which is a grassy weed, all other weeds presented above are broad-leaved weeds. *Weed data presented here are square-root transformed through $(X+0.2)^{1/2}$.
¥All treatments are described in Materials and Methods.

soil layers and hasten more germination of weeds in CT practice.

Weed control practices consisting of tank mix and ready-mix application of herbicides as post-emergence (PoE) led to significant reduction in population and dry weight of *P. minor, C. album, M. indica*, *C. didymus*, *S. oleraceus, R. dentatus* and total weeds than un-weeded control (UWC) (Tables 1, 2 and 3). These herbicides proved to be supplementary to TRM/ CA practices adopted in this study towards better management of weeds. The tank-mix of clodinafop-propargyl 0.060 kg/ha + metsulfuron-methyl 0.004 kg/ha at 30 DAS (W_3) significantly reduced the population and dry weight of all the weeds compared to UWC and Total (Ready mix of sulfosulfuron + metsulfuron-methyl) 0.040 kg/ha applied at 30 days after sowing (W_2). The performance of tank-mixture of clodinafop-propargyl 0.060 kg/ha + carfentrazone-ethyl 0.02 kg/ha at 30 DAS (W_4) for reducing weeds population and dry weight was found slightly inferior to former treatment (W_3), but significantly superior to W_2 and W_1. The W_3, W_4 and W_2 treatments led to 88.9, 82.0 and 64.1% weed-control efficiency (WCE) and 89.4, 81.2 and 65.9% weed-control index (WCI), respectively in wheat (Fig. 1).

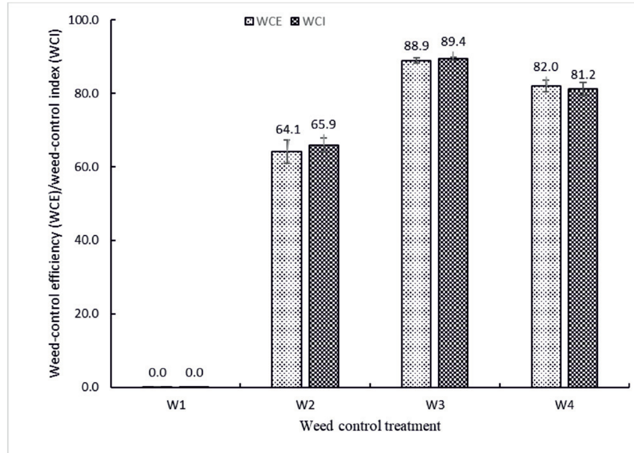

Fig. 1. Weed-control efficiency (WCE) (%) and weed-control index (WCI) (%) of different weed control treatments. Vertical bars are ± standard error. All treatments are described under Materials and Methods.

Repeated application of same herbicides continuously for weed control in wheat may develop resistance in weeds, which advocates herbicide rotation to be followed in crops for better weed management. Chhokar *et al*. (2007) reported that, the tank-mix application of sulfosulfuron+

Table 3. Total population and dry weight of weeds in wheat as influenced by crop establishment methods and weed control practices

Treatment	Total weed population (no./m^2)*			Total weeds dry weight (g/m^2)*		
	2018–19	2019–20	Pooled	2018–19	2019–20	Pooled
Year (Y)						
2018–19	-	-	4.5	-	-	7.5
2019–20	-	-	4.7	-	-	7.8
SEm±	-	-	0.1	-	-	0.1
CD (P=0.05)	-	-	0.1	-	-	NS
Tillage and residue management (TRM) ¥						
T_1, ZTDSR-ZTW	5.1	5.4	5.2	8.7	9.2	9.0
T_2, WR+ZTDSR-RR+ZTW	4.2	4.5	4.3	7.0	7.4	7.2
T_3, WR+ZTDSR+BM-RR+ZTW	4.1	4.3	4.2	7.1	7.4	7.2
T_4, ZTDSR-ZTW-ZTMB	4.8	5.3	5.0	8.2	9.0	8.6
T_5, MR+ZTDSR-RR+ZTW-WR+ZTMB	3.3	3.4	3.3	5.6	5.7	5.6
T_6, TPR-CTW	5.2	5.4	5.3	8.5	8.3	8.4
SEm±	0.1	0.1	0.1	0.2	0.2	0.2
CD (P=0.05)	0.4	0.4	0.3	0.8	0.7	0.5
Weed control (W)¥						
W_1, UWC	7.2	8.3	7.8	12.3	14.0	13.2
W_2, Sulf+met (ready mix) (W2)	4.6	4.7	4.6	7.7	7.5	7.6
W_3, Clodin+met (tank mix) (W3)	2.7	2.6	2.6	4.4	4.1	4.3
W_4, Clodin+carfen (tank mix) W4)	3.3	3.3	3.3	5.6	5.7	5.7
SEm±	0.1	0.1	0.1	0.2	0.2	0.2
CD (P=0.05)	0.3	0.3	0.2	0.6	0.7	0.4
Interaction						
Y × TRM	-	-	NS	-	-	NS
TRM ×W	S	S	S	S	S	S
Y × W	-	-	S	-	-	S
Y × TRM × W	-	-	NS	-	-	NS

*Weed data presented here are square-root transformed through $(X+0.2)^{1/2}$. ¥All treatments are described in Materials and Methods metsulfuron was most effective for weed control in wheat than single application of sulfosulfuron or clodinafop or metsulfuron. This study revealed that the tank mix application of clodinafop-propargyl + metsulfuron-methyl (W_3) was superior to the ready-mix (TOTAL) application and the best option for efficient weed management in wheat. The tank-mix proved more effective than ready-mix, might be the lower dose of metsulfuron in the Ready-mix was responsible.

Wheat yield and economics

Wheat grain yield, gross and net returns were highly influenced by tillage and residue management (TRM) and weed control/ herbicides treatments (Table 4). Grain yield of wheat did not differ significantly due to crop growing season/year, but the gross returns varied significantly owing to crop growing season/year. The tillage and residue management treatment, T_5 (ZTDSR+MBR- ZTW+RR - ZTMB+WR) resulted in 14.6, 10.2, 8.5, 8.4 and 6.6% higher wheat grain yield than T_6, T_2, T_1, T_3 and T_4, respectively, and was most superior. The treatment T_5 resulted in significant reduction in weed growth and interference (Tables 1, 2, 3), which might have facilitated to better growth and higher grain yield of wheat. Besides, 3 crop residues (~8-9 t/ha/year) under T_5 treatment led to build up of soil organic matter (Das *et al*., 2020), recycle nutrients, and improve soil physical environment (Raj *et al*., 2022). Crop residue is the principal source of carbon, which regulates the efficiencies of fertilizer, water, and other inputs used in crops. Similar happened in this study where the effect of long-term ZT, crop residue retention and multiple (three) crop culture under the T_5 treatment was clearly visible on grain yield of wheat. Among the weed control treatments, W_3 (clodinafop + metsulfuron) resulted in significantly higher grain yields of wheat (Table 4). This treatment led to 28.5, 7.7 and 2.9 higher grain yield than W_1, W_2 and W_4, respectively. This W_3 treatment had lowest weed interference due to better broad spectrum weed control. Clodinafop being a grassy weed killer controlled the *P. minor* (the only grassy weed present in wheat) more effectively, and metsulfuron being a broad-leaved weed killer, controlled almost all broad-leaved weeds present in wheat. This led to better growth and yield of wheat in W_3. This tank-mixture treatment would have other added merit too. Effective broad-spectrum control of weeds owing to this treatment would reduce the chances of developing

Table 4. Grain yield and economics of wheat as influenced by crop establishment methods and weed control practices

Treatment	Grain yield (t/ha)			Cost of cultivation (×10³ INR/ha)			Gross returns (×10³ INR/ha)		
	2018–19	2019–20	Pooled	2018–19	2019–20	Pooled	2018–19	2019–20	Pooled
Year (Y)									
2018–19	-	-	5.76	-	-	40.1	-	-	123.9
2019–20	-	-	5.86	-	-	41.3	-	-	131.0
SEm±	-	-	0.06	-	-	-	-	-	1.0
CD (P=0.05)	-	-	NS	-	-	-	-	-	3.1
Tillage and residue management (TRM) ¥									
T_1, ZTDSR-ZTW	5.72	5.84	5.78	39.2	40.3	39.7	123.0	130.5	126.7
T_2, WR+ZTDSR-RR+ZTW	5.65	5.74	5.69	39.2	40.4	39.8	121.5	128.1	124.8
T_3, WR+ZTDSR+BM-RR+ZTW	5.74	5.82	5.78	39.2	40.4	39.8	123.5	130.1	126.8
T_4, ZTDSR-ZTW-ZTMB	5.85	5.92	5.88	39.2	40.3	39.7	125.9	132.3	129.1
T_5, MR+ZTDSR-RR+ZTW-WR+ZTMB	6.21	6.34	6.27	39.2	40.4	39.8	133.3	141.5	137.4
T_6, TPR-CTW	5.42	5.52	5.47	44.9	46.1	45.5	116.3	123.3	119.8
SEm±	0.13	0.12	0.11				2.2	2.1	1.8
CD (P=0.05)	0.40	0.38	0.31				6.9	6.5	5.3
Weed control (W) ¥									
W_1, UWC	4.97	4.87	4.92	38.5	39.5	39.0	107.9	109.8	108.8
W_2, Sulf+met (ready mix) (W2)	5.77	5.97	5.87	40.7	41.9	41.3	124.2	133.1	128.7
W_3, Clodin+met (tank mix) (W3)	6.24	6.40	6.32	41.0	42.2	41.6	133.7	142.6	138.2
W_4, Clodin+carfen (tank mix) W4)	6.07	6.21	6.14	40.5	41.6	41.1	129.9	138.3	134.1
SEm±	0.08	0.09	0.06	-	-	-	1.4	1.5	1.0
CD (P=0.05)	0.24	0.25	0.17	-	-	-	4.0	4.3	2.9
Interaction									
Y × TRM	-	-	NS	-	-	-	-	-	NS
TRM × W	S	S	S	-	-	-	S	S	S
Y × W	-	-	NS	-	-	-	-	-	S
Y × TRM × W	-	-	NS	-	-	-	-	-	NS

¥All treatments are described in Materials and Methods herbicide resistance in weeds and possible shift in weed flora. The cost of production of wheat was higher in TPR-CTW (T_6) than all other TRM treatments (Table 4). Treatment ZTDSR+MR-ZTW+RR-ZTMB+WR (T_5) incurred 12.5% lesser cost of cultivation, but fetched 14.7% higher gross returns over T_6 treatment. Among the weed control treatments, tank mix application of clodinafop-propargyl + metsulfuron-methyl incurred higher cost than UWC and gave significantly higher gross returns than the others. The treatment W_3 registered ~27, ~7 and ~3% higher gross returns than W_1, W_2 and W_4 respectively.

Therefore, it may be concluded that the CA-based zero till triple cropping system (rice-wheat-mungbean) with retention of residue of these 3 crops combined with the application of tank-mixture of clodinafop + metsulfuron would reduce weed interference significantly and give higher wheat productivity and profitability in the North-western Indo-Gangetic Plains of India and in similar agroecologies of the tropics and sub-tropics. This would reduce shift and resistance of weeds as well.

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