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RESEARCH ARTICLE

Tillage, residue, nitrogen and herbicides effects on weeds and greengram productivity and profitability in conservation agriculture-based maize-wheat-greengram system

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ABSTRACT

Conservation agriculture (CA) based intensification of maize (*Zea mays* L.)-wheat (*Triticum aestivum* L. emend Fiori and Paol) system through inclusion of greengram (*Vigna radiata* L. Wilczek) during summer may improve productivity and promote sustainability. However, weeds are the major biotic constraint that limit productivity of short-duration greengram severely, if not controlled timely. Therefore, a field experiment was conducted during 2018-19 and 2019-20 to evaluate the residual effects of nitrogen (N) applied to the preceding crops, and the concurrent effects of tillage, residue and herbicide on weeds and greengram productivity and profitability under a maize-wheat-greengram cropping system. Four main plot treatments comprised of three zero-till (ZT) flat-bed with retention of residues (R) of greengram (in maize), maize (in wheat) and wheat (in greengram) and 50, 75 and 100% N of the recommended 150 and 120 kg N/ha applied to maize and wheat, respectively (~ZT+R+50N, ZT+R+75N, ZT+R+100N), and a conventional tillage (CT) with incorporation of these three crops residue and 100% of the recommended N to the preceding crops (~CT+R+100N). The sub-plot treatments were: ready-mix Na-acifluorfen (16.5%) + clodinafop-propargyl (8%) at 245 (165+80) g/ha applied post-emergence (PoE), pendimethalin at 1000 g/ha pre-emergence (PE) followed by (*fb*) imazethapyr at 75 g/ha PoE, pendimethalin at 1000 g/ha PE *fb* spot hand weeding (HW) at 25 days after sowing (DAS), and unweeded control (UWC). Results indicated that ZT with residue retention (ZT+R), irrespective of previous season N applications led to significant reduction in weed interference compared to CT+R+100N and gave better greengram plant growth, rhizobial symbiosis, yields and profitability over CT+R+100N. Among weed management treatments, sequential application of pendimethalin *fb* imazethapyr was comparable with ready-mix Na-acifluorfen + clodinafop-propargyl, but led to better weed suppression, and higher greengram growth, yields and net income. Thus, summer greengram in a CA based maize-wheat system with appropriate weed control employing herbicides may be a promising strategy for sustainable crop intensification in north-western Indo-Gangetic Plains of India.

Keywords: Conservation agriculture, Crop residues, Greengram, Herbicides, Weeds, Zero-tillage

INTRODUCTION

The cereal-centric cropping systems dominate in the Indo-Gangetic Plains (IGP), which is most significant food producing belt of India. Rice-wheat and maize-wheat are two most important cropping systems in the IGP, and largely contribute to total food grain production. However, the sustainability of these cereal-based systems is under question due to several soil, water, nutrients, weeds, and environment related problems. Further, continuous monoculture of cereal-cereal rotations has led to yield plateaus. Therefore, cropping system intensification through inclusion of legumes in the prevailing cereal-cereal rotations is widely recommended to be a sustainable approach for improving system productivity (Ladha *et al.* 2003, Jat *et al.* 2018). In IGP, the fields remain fallow for almost 70-80 days from harvest of *Rabi* (winter) crops to sowing of the succeeding *Kharif* (rainy) crops. Greengram, being a short-duration crop and having wider adaptability across varied agroclimatic situations can be grown during this period with 1-2 irrigations (Hazra *et al.* 2019). Its inclusion in conservation agriculture (CA) based cereal-cereal rotation can drive sustainable intensification of agricultural production system of the IGP (Gathala *et al.* 2013). It is a good source of dietary protein for majority of vegetarian Indian people. Additional income, N fixation, and improvement in soil health are other benefits accruing from its cultivation may improve cereals system sustainability.

However, greengram often fails to achieve acceptable seed yield primarily due to severe weed interference, low soil fertility (Ezung *et al.* 2020) and overall poor management. Weeds compete with

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greengram for resources more vigorously, reducing yield. Poor competitiveness of greengram against weeds is mainly due to initial slow growth, leading to recurrent flushes of weeds after every rainfall and/or irrigation (Singh and Singh 2020). Moreover, short duration nature (~60-65 days) of greengram allows little scope for crop recovery from the initial setback due to weeds in later stages of growth (Maji *et al.* 2020). Relatively weed-free period of 20-30 days after emergence is critical for greengram (Singh *et al.* 1991, Singh and Singh 2020). Weeds may cause yield losses to the tune of 30-85%, depending on the intensity and spectrum of weeds, soils, and environmental conditions (Singh *et al.* 2015, Kaur *et al.* 2016).

Effective weed management is, therefore, key for sustainable greengram production. Herbicides offer timely, effective, economical and practical weed control, therefore, assumed to be most important weed management tool. In the absence of tillage, the success of CA largely depends on herbicides (Sharma and Singh 2014). Minimum/zero tillage, surface residue retention may alter the efficacy of the applied herbicides. Therefore, crop stubbles should be managed properly, and the timing, rate and method of herbicide application need to be optimized in CA systems for higher herbicide efficacy. The use of herbicides mixture (pre-mix or tank-mix) or sequential application of herbicides along with tillage and residue management leads to integrated weed management, which assumes a great importance for better weed management in summer greengram. Moreover, the location-specificity of herbicides action depending on climate, soils, and weeds calls for enough studies across locations. Therefore, this study was undertaken to evaluate the carryover effects of N applied to preceding crops, and concurrent effects of tillage, residue, and herbicides on weeds, crop productivity and profitability in summer greengram in a maize-wheat-greengram rotation.

MATERIALS AND METHODS

Field experiments were carried out at the ICAR–Indian Agricultural Research Institute (IARI), New Delhi (28°38` N, 77°10` E and 228.6 m above mean sea level) during the summer seasons of 2019 and 2020. The site falls under Trans-Gangetic Plains zone of Indian IGP with sub-tropical and semi-arid climate. Rainfall received during greengram growing seasons were 76.6 and 97.3 mm in 2019 and 2020, respectively. Soil (Inceptisol) was sandy loam in texture with mean pH 7.5 and electrical conductivity 0.31 dS/m.

Four main-plot treatments, involving tillage, crop residue and previous N application, and four sub-plot treatments involving weed management treatments were laid out in a split plot design with three replications. The experiment was part of a long-term CA system initiated in 2008. The main plot treatments were fixed for all three crops, *i.e.*, maize, wheat, and greengram, but the sub-plot weed management treatments were different for these crops based on the selectivity of herbicides. The main plot treatments comprised of three zero-till (ZT) flat-bed with retention of residue (R) of greengram (in maize), maize (in wheat) and wheat (in greengram) and 50, 75 and 100% of the recommended N dose applied to maize and wheat (~ZT+R+50N, ZT+R+75N, ZT+R+100N), and a conventional tillage (CT) with incorporation of three crops residue and 100% of the recommended N to the preceding crops (~CT+R+100N). The sub-plot treatments were: application of ready-mix Na-acifluorfen (16.5%) + clodinafop-propargyl (8%) at 245 (165+80) g/ha post-emergence (PoE), pendimethalin at 1000 g/ha pre-emergence (PE) followed by (*fb*) imazethapyr at 75 g/ha PoE, pendimethalin at 1000 g/ha PE *fb* spot hand weeding (HW) at 25 days after sowing (DAS), and unweeded control (UWC). Around 40% residue of maize and wheat and entire residue (100%) of greengram were retained on the surface (in case of ZT) or incorporated into soil (in case of CT). Recommended dose of N for maize and wheat was 150 and 120 kg N/ha, respectively. Unweeded control (UWC) was a natural uninhibited weed infestation, adopted for comparing the efficacy of weed control/ herbicides treatments (Das 2001). The PE and PoE herbicides were applied at 1 and 25 DAS, respectively using a knapsack sprayer fitted with a flat fan nozzle and 400 litters water/ha. Main and sub-plots were 25.5 × 3.0 m and 6.0 × 3.0 m, respectively. The CT plots were ploughed by a tractor-drawn disc plough and wheat residue was incorporated using a rotavator followed by planking.

Greengram variety '*SML 668*' was sown using a Happy Seeder at a row-space of 20 × 5 cm and 20 kg/ha seed rate. A common 18 kg N/ha through diammonium phosphate (DAP; 100 kg/ha) was applied as basal to counter N immobilization resulting from the addition (retention/ incorporation) of fresh wheat residue along with phosphorus (20 kg P/ha). An area of 50 cm (along the rows) × 40 cm (across the rows), which included 2 rows of greengram was randomly selected from two places in each plot outside the net plot area, leaving the border rows. Weed species were collected from those areas, counted, and categorized into grassy, broad-leaved, and sedge weeds, which were summed up to total weed population. The collected weeds were first sun-dried and kept in a hot-air oven at 70 °C until constant dry weight. Weed control efficiency (WCE) and weed control index (WCI) that reflect per cent reduction in weed density and dry weight across the treatments over control treatments, respectively were calculated using the following equations (Das 2001 2008).

$$WCE\ (\%) = [(WP_C - WP_T)/WP_C] \times 100$$

$$WCI\ (\%) = [(WDW_C - WDW_T)/WDW_C] \times 100$$

where, WP_C and WP_T are the weed population (number/m^2) in control and treatment plots, and WDW_C and WDW_T are the weed dry weight (g/m^2) in control and treatment plots, respectively.

Five green plants were randomly selected from each plot (outside of net plot area) for recording observations on root nodulation and plant growth parameters. Leaf chlorophyll content in terms of SPAD value of four fully expanded uppermost leaves was estimated using a SPAD chlorophyll meter (SPAD-502 Minolta Camera Co., Ltd., Japan). Greengram was harvested when 80-90% of pods were mature from net plot area, threshed manually after sun drying, and seed yields recorded. Yield components were recorded from five randomly selected plants at harvest. The 1000-seed weight of greengram was recorded from sub-samples of harvested seeds of each plot and weighed separately. Seed moisture content was determined for each seed sample, and seed yields and 1000-seed weight were adjusted to 12% moisture (w/w). The prevailing market prices of all inputs/operations applied to a treatment were used to estimate the total cost of cultivation of that treatment. The minimum support price (MSP) of greengram seeds declared by the Government of India during 2018 and 2019, and the local market price of greengram stover were considered for calculating the gross returns. The difference between gross returns and total cost of cultivation constituted the net returns. The ratio of net returns to cost of cultivation indicated the net benefit: cost. Data were analyzed using the analysis of variance (ANOVA) technique by adopting the general linear model (GLM) procedure for split plot design in SAS 9.3 software (SAS Institute Inc., Cary, NC, USA). As wide variation existed, data on weed density and dry weight were subjected to square-root [$(x + 0.5)^{1/2}$] transformation prior to the ANOVA in order to improve the homogeneity of variance (Das 1999). Pairwise comparisons of treatment means were made using Fisher's least significant difference (LSD) (Fisher 1960; Gomez and Gomez 1984) at 5% level of significance.

RESULTS AND DISCUSSION

Weed growth and its control in greengram

The dominant weed species in summer greengram were *Trianthema portulacastrum* L., *Commelina benghalensis* L., and *Digera arvensis* Forsk. (broad-leaved weeds); *Digitaria sanguinalis* (L.) Scop. and *Dactyloctenium aegyptium* (L.) Willd. (grassy weeds); and *Cyperus rotundus* L. (sedge). Among them, broad-leaved weeds (BLW) were dominant, posing higher interference than grasses and sedges (**Tables 1** and **2**). There were differences in density and biomass of BLW, grasses and sedges at 40 DAS owing to tillage, residue, N and weed management. Among tillage, residue and N management practices, CT+R+100N was least effective in suppressing weed growth with significantly higher density and biomass of BLW, grasses, sedges and total composite weeds compared to ZT+R+100N, ZT+R+75N, and ZT+R+50N, which showed similar efficacy on these weeds. On average, CA-based treatments (ZT+R+100N, ZT+R+75N, and ZT+R+50N) appeared to be superior to CT treatments, while reducing population and biomass of composite weeds by 42.7-49.7 and 41.5-46.1% over CT+R+100N, respectively (**Table 1** and **2**). Higher interference of weeds in CT plots might be attributed to the inversion of soil through repeated tillage operations, which redistributed weed seeds lying below the soil surface throughout the soil profile and stimulate germination (Chauhan and Johnson 2009). Moreover, surface residue cover in ZT-based treatments could reduce or delay weed emergence by intercepting solar radiation reaching the ground surface, and by creating a physical barrier to germination and emergence of weeds, altogether leading to significantly lower weed interference in ZT plots (Nichols *et al.* 2015, Baghel *et al.* 2020). The UWC unweeded control treatment resulted in significantly higher population and biomass of BLW, grasses and sedges than the remaining treatments at 40 DAS, leading to substantially higher total weed interference. The weed control treatments significantly reduced weed population and biomass by 58.0-61.8% (WCE) and 73.9-77.1% (WCI), respectively compared to the UWC. Among the weed management treatments, sequential applications of pendimethalin PE *fb* imazethapyr PoE resulted in highest WCE and WCI due to significant reduction in density and biomass of BLW, grasses, and sedges as well as total composite weeds compared to UWC, respectively (**Table 1** and **2**). However, pendimethalin *fb* HW or Na-acifluorfen + clodinafop (ready-mix) were comparable with it in this regard. Although all weed control treatments had similar efficacy against weeds, the post-emergent control of weeds (either by herbicides or by hand weeding) following the application of PE pendimethalin had an edge over single application of post-emergence herbicides. This could be due to the fact that, pendimethalin PE controlled initial flushes of weeds, and later-emerging weeds were effectively controlled by either broad-spectrum imazethapyr or hand weeding. Later, greengram through quick canopy formation covered the ground surface (low light penetration) and smothered late-emerging weeds and reduced weed interference. As there is no vertical mixing of soil under ZT, the below-ground weed seeds do not appear on soil surface and remain dormant. Further, in continued ZT with surface residue retention, surface-lain seeds get disposed of through predation or through microbial decomposition (Govaerts *et al*. 2007, Yang *et al*. 2013, Nichols *et al*. 2015), and weed seedbanks gradually get exhausted, if new recruit of weed seeds is prevented. This called for control of existing weed species effectively for long-term sustainable weed management. Thus, combining ZT with surface residue retention, and appropriate

Table 1. Weed density in greengram across tillage, residue, and herbicides treatments (mean of two years)

Treatment	Weed density (number/m^2) at 40 DAS*				WCE (%)
	BLW	Grass	Sedge	Total	
Tillage, residue and N management					
ZT+R+50N	8.1 (69.6)	4.3 (17.8)	2.1 (3.9)	9.4 (91.3)	42.7
ZT+R+75N	7.9 (64.2)	4.0 (16.2)	2.1 (3.8)	9.1 (84.3)	46.8
ZT+R+100N	7.7 (62.2)	4.0 (15.4)	1.9 (3.4)	8.9 (81.0)	49.7
CT+R+100N	10.5 (125.8)	7.5 (67.1)	3.5 (12.3)	13.4 (205.3)	-
LSD (p=0.05)	0.86	0.40	0.48	0.84	-
Weed management					
Na-acifluorfen + clodinafop 245 g/ha	7.4 (55.3)	4.4 (19.4)	2.3 (5.3)	8.9 (80.0)	58.0
Pendimethalin 1000 g/ha *fb* imazethapyr 75 g/ha	7.1 (49.8)	4.2 (17.9)	2.1 (4.2)	8.4 (71.8)	61.8
Pendimethalin 1000 g/ha *fb* HW	7.2 (52.1)	4.6 (21.3)	2.2 (4.7)	8.8 (78.1)	58.9
Unweeded control	12.5 (164.7)	6.6 (57.8)	3.0 (9.4)	14.6 (232.0)	-
LSD (p=0.05)	0.49	0.47	0.34	0.55	-

ZT: zero tillage, R: residue, N: nitrogen, CT: conventional tillage, HW: spot hand weeding, BLW: broad-leaved weeds, WCE: weed control efficiency, *original/ observed values (in parentheses) were subjected to square-root transformation [$\sqrt{x+0.5}$]

Table 2. Weed dry biomass in greengram across tillage, residue, and herbicides treatments (mean of two years)

Treatment	Weed dry weight (g/m^2) at 40 DAS*				WCI (%)
	BLW	Grass	Sedge	Total	
Tillage, residue and N management					
ZT+R+50N	3.5 (13.3)	2.1 (3.9)	1.2 (1.0)	4.1 (18.2)	41.5
ZT+R+75N	3.4 (12.0)	2.0 (3.8)	1.2 (0.9)	4.0 (16.6)	46.1
ZT+R+100N	3.3 (11.7)	2.0 (3.7)	1.1 (0.9)	3.9 (16.3)	46.0
CT+R+100N	4.5 (26.9)	3.9 (20.1)	2.0 (4.5)	6.2 (51.4)	-
LSD (p=0.05)	0.25	0.23	0.15	0.23	-
Weed management					
Na-acifluorfen + clodinafop 245 g/ha	2.9 (8.0)	2.0 (3.6)	1.1 (0.8)	3.6 (12.3)	73.9
Pendimethalin 1000 g/ha *fb* imazethapyr 75 g/ha	2.8 (7.1)	1.9 (3.2)	1.1 (0.7)	3.4 (11.0)	77.1
Pendimethalin 1000 g/ha *fb* HW	2.8 (7.4)	2.2 (4.5)	1.1 (0.7)	3.6 (12.6)	74.8
Unweeded control	6.3 (41.4)	3.9 (20.2)	2.2 (5.1)	7.7 (66.6)	-
LSD (p=0.05)	0.24	0.23	0.12	0.27	-

ZT: zero tillage, R: residue, N: nitrogen, CT: conventional tillage, HW: spot hand weeding, BLW: broad-leaved weeds, WCI: weed control index, *original/observed values (in parentheses) were subjected to square-root transformation [$\sqrt{x+0.5}$]

Table 3. Greengram crop growth parameters at 45 DAS across tillage, residue, and herbicides treatments

Treatment	Plant height (cm)		DMA (g/m^2)		LAI	
	2019	2020	2019	2020	2019	2020
Tillage, residue and N management						
ZT+R+50N	34.3	36.1	208.2	220.4	3.14	3.29
ZT+R+75N	35.2	37.0	217.3	227.0	3.23	3.33
ZT+R+100N	35.6	37.0	219.4	232.0	3.27	3.41
CT+R+100N	30.9	32.5	192.1	202.7	2.90	3.00
LSD (p=0.05)	3.01	2.61	14.82	15.64	0.18	0.22
Weed management						
Na-acifluorfen + clodinafop 245 g/ha	34.8	36.1	230.0	241.2	3.39	3.57
Pendimethalin 1000 g/ha *fb* imazethapyr 75 g/ha	35.7	37.3	234.9	250.8	3.49	3.61
Pendimethalin 1000 g/ha *fb* HW	35.0	37.0	232.4	243.9	3.42	3.59
Unweeded control	30.4	32.1	139.8	146.2	2.24	2.26
LSD (p=0.05)	2.68	2.61	15.80	15.57	0.18	0.13

ZT: zero tillage, R: residue, N: nitrogen, CT: conventional tillage, HW: spot hand weeding, DMA: dry matter accumulation, LAI: leaf area index herbicidal weed control led to considerably lower weed interference in summer greengram.

Crop growth, nodulation, and leaf chlorophyll content

Crop growth parameters, nodulation, and chlorophyll content in greengram differed significantly amongst the tillage, residue, N and weed management practices. The CA-based ZT+R+100N, being at par with ZT+R+75N and ZT+R+50N led to significantly higher plant height, dry matter accumulation, leaf area index (LAI), nodule number and dry weight, and chlorophyll content compared to the CT+R+100N at 45 DAS. The CA-based ZT+R systems resulted in 13.4 and 12.9%, 11.9 and 11.7%, and 10.8 and 11.4% higher plant height, dry matter accumulation, and LAI in summer greengram in 2019 and 2020, respectively compared to CT (**Table 3**). Considerably lower weed interference in ZT+R systems allowed the crop to gain an advantage over weeds, which resulted in better crop growth compared to CT system. Among the weed control practices, pendimethalin *fb* imazethapyr being at par with Na-acifluorfen + clodinafop and pendimethalin fb HW led to significantly greater plant height (14.6-15.7%), dry matter (66.3-67.8%), and LAI (53.3-58.8%) at 45 DAS due to greater weed suppression by these treatments compared to UWC in both the years (**Table 3**). Greengram nodulation (nodule count and dry weight of effective nodules) at 45 DAS was significantly higher in CA-based ZT+R systems compared to CT-based greengram, the highest being in ZT+R+100N (**Table 4**). The ZT-based systems accounted for 26.6-33.5% and 34.4-42.5% higher number of effective nodules and nodules dry weight, respectively compared to CT. Better soil health and lower weed interference for available resources in ZT-based systems played a role. Severe weed competition in UWC plots affected overall growth of greengram and led to least effective nodulation. The extent of reduction in count and dry weight of nodules in UWC treatments ranged from 43.5 to 45.1% and 51.4 to 55.1%, respectively over the weed control practices during both years of study. Among weed control practices, the highest count and dry weight of nodules were recorded with pendimethalin fb imazethapyr, which was at par with pendimethalin fb HW and Na-acifluorfen + clodinafop (**Table 4**). Application of herbicides (pre-plant incorporation, PE or PoE) has been found to reduce nodulation in greengram, particularly with PE herbicides (Kaur *et al.* 2010, Singh *et al.* 2015, Maji *et al.* 2020). Zaidi *et al.* (2005) observed considerable negative effect of metribuzin on nitrogenase activity in a greengram-rhizobial symbiosis. However, in this study, negative effect of PE herbicide (pendimethalin) on nodule functioning in greengram was not observed or initial setback, if any, was recovered at the later stages; whereas, PoE application of herbicides also showed no inhibition of nodulation as evident from higher nodulation in these treatments. This could be attributed to application of herbicides at proper rate (up to the recommended dose) and time, which might have avoided inhibitory effects on greengram-rhizobial symbiosis (Komal *et al.* 2015, Kumar *et al.* 2016, 2017, Mishra *et al.* 2017, Singh *et al.* 2017). Similar to nodulation, ZT-based systems had significantly higher SPAD values (chlorophyll content) compared to CT system. Similarly, all the weed control treatments recorded significantly higher SPAD values (chlorophyll content) compared to UWC (**Table 4**). As chlorophyll content is directly correlated with plant N status, higher SPAD values suggested better availability and uptake of N by greengram. This could be due to better crop and root growth, soil fertility, and nodulation in greengram under ZT systems, and lower weed competition.

Table 4. Greengram root nodules and leaf chlorophyll content (SPAD value) at 45 DAS across tillage, residue, and herbicides treatments

Treatment	Effective nodules/plant		Nodule dry weight (mg/plant)		Chlorophyll content (SPAD value)
	2019	2020	2019	2020	
Tillage, residue and N management					
ZT+R+50N	26.2	28.0	76.53	80.26	39.48
ZT+R+75N	27.0	28.3	79.57	82.19	40.03
ZT+R+100N	27.7	28.8	83.00	84.18	40.15
CT+R+100N	20.2	22.4	55.94	61.16	36.37
LSD (p=0.05)	3.04	3.69	8.20	11.37	2.62
Weed management					
Na-acifluorfen + clodinafop 245 g/ha	27.3	28.9	82.19	86.64	39.43
Pendimethalin 1000 g/ha *fb* imazethapyr 75 g/ha	29.2	31.6	86.60	90.97	40.00
Pendimethalin 1000 g/ha *fb* HW	28.5	30.3	85.16	90.08	39.67
Unweeded control	16.0	16.6	41.09	40.09	36.93
LSD (p=0.05)	2.97	2.74	6.39	6.80	1.74

ZT: zero tillage, R: residue, N: nitrogen, CT: conventional tillage, HW: spot hand weeding

Yield attributes and yields

Tillage, residue, N and weed management practices caused significant variations in yield attributes and yields of greengram during both years of experimentation (**Table 5**). Number of pods per plant didn't differ across the tillage and residue management practices. However, on average, ZT-based systems recorded 4.5-4.6% higher number of pods/plant compared to CT+R+100N. Number of seeds per pod was significantly higher under ZT+R+100N compared to CT+R+100N, and remained at par with ZT+R+75N and ZT+R+50N. On average, ZT-based systems, resulted in 11.2-11.6% higher number of seeds per pod in greengram compared to CT+R+100N. The tillage, residue and N management practices led to similar 1000-seed weight of greengram. Relative improvements in yield attributing traits in greengram led to significantly higher seed yields under ZT+R+100N, which was at par with ZT+R+75N and ZT+R+50N compared to CT+R+100N during both the years (**Table 5**). The ZT-based systems accounted for 14.1-16.9 and 14.8-21.3% increase in seed yields of greengram in 2019 and 2020, respectivel compared to CT+R+100N. The harvest index was similar across all the tillage, residue and N treatments. The yield traits, *viz*. number of pods/plant and number of seeds/pod were significantly lower in UWC plots in both the years (**Table 5**). The extent of reduction in number of pods/ plant and number of seeds/pod in UWC treatments ranged from 16.9 to 18.4% and 13.5 to 13.8%, respectively over the weed control practices. Among the weed control treatments, pendimethalin *fb* imazethapyr led to highest number of pods/plant and number of seeds/pod, comparable with pendimethalin fb HW and Na-acifluorfen + clodinafop. The 1000-seed weight was not significantly influenced by weed control treatments. The extent of yield reduction in control plots due to severe crop-weed competition was substantially higher, with average yield penalty ranged from 17.2 to 18.8% compared to treatment plots where weed control was adopted. On contrary, weed control treatments remained at par with each other and led to significantly higher seed yields compared to control, with the highest yields obtained with pendimethalin fb imazethapyr treatment in both the years (**Table 5**). With adoption of weed control practices, seed yields of greengram increased to the tune of 17.4-23.2 and 20.3-25.4% compared to UWC in 2019 and 2020 respectively. The weed control treatments resulted in significant improvements in harvest index compared to control treatment. Crop yield is largely influenced by the source-sink characteristics of plants, and translocation of the photosynthates from source to sink. Weed interference and crop yield are negatively correlated, implying that crop yield decreases with increasing weed interference and *vice-versa* (Sen *et al*. 2020, 2021). Higher crop-weed competition for light, water and nutrients adversely affected plant growth, symbiosis, and yield traits (sink formation), and translocation of photosynthates, which ultimately influenced crop yield as observed in control plots. Thus, comparatively lower weed interference in ZT-based systems and greater suppression of density and biomass of weeds (BLW, grasses, sedges and total) facilitated by efficient weed control led to higher yields of greengram compared to that in CT system. Moreover, better soil physical, chemical and biological properties in CA-based ZT + R systems (Bhattacharyya *et al*. 2018, Das *et al*. 2018, Hazra *et al*. 2019, Modak *et al*. 2019, Nath *et al*. 2019, Borase *et al*. 2020, Mondal *et al*. 2020) might have a positive impact on crop growth with greater photosynthetic rate, higher N_2 fixation through better nodule efficiency, larger sinks, and higher translocation of photosynthates to sinks, and it was reflected in yield attributes and yields in greengram (Nath *et al*. 2016). Further, improved soil water balance by means of reducing evaporation through retention of crop residues on soil surface under ZT systems also might have positively impacted crop growth and yields, particularly during hot-dry summer months.

Table 5. Greengram yield attributes and seed yield across tillage, residue, and herbicides treatments

Treatment	No. of pods/plant		No. of seeds/pod		1000-seed weight (g)		Seed yield (t/ha)		Harvest index (%)	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
Tillage, residue and N management										
ZT+R+50N	19.55	18.34	8.21	7.97	40.25	38.62	0.81	0.70	23.8	22.1
ZT+R+75N	19.74	18.54	8.63	8.39	40.31	39.65	0.82	0.72	24.0	22.5
ZT+R+100N	19.81	18.43	8.95	8.71	40.16	40.32	0.83	0.74	24.1	22.4
CT+R+100N	18.85	17.63	7.73	7.49	40.24	39.05	0.71	0.61	22.9	20.7
LSD (p=0.05)	NS	NS	0.79	0.79	NS	NS	0.08	0.07	NS	NS
Weed management										
Na-acifluorfen + clodinafop 245 g/ha	20.07	18.94	8.43	8.19	40.03	39.20	0.81	0.71	25.0	22.4
Pendimethalin 1000 g/ha *fb* imazethapyr 75 g/ha	20.36	19.12	8.83	8.58	40.63	40.09	0.85	0.74	24.6	22.8
Pendimethalin 1000 g/ha *fb* HW	20.23	18.86	8.65	8.40	40.07	40.24	0.84	0.73	25.3	22.5
Unweeded control	17.29	16.02	7.61	7.37	40.24	38.12	0.69	0.59	20.0	20.0
LSD (p=0.05)	1.58	1.60	0.66	0.66	NS	NS	0.05	0.06	1.89	1.55

ZT: zero tillage, R: residue, N: nitrogen, CT: conventional tillage, HW: spot hand weeding

Table 6. Profitability of greengram cultivation across tillage, residue, and herbicides treatments

Treatment	Net returns (×10^3 ₹/ha)		Net benefit: cost	
	2019	2020	2019	2020
Tillage, residue and N management				
ZT+R+50N	28.03	20.04	0.88	0.60
ZT+R+75N	28.64	20.85	0.90	0.63
ZT+R+100N	29.49	22.67	0.93	0.69
CT+R+100N	17.66	9.90	0.50	0.28
LSD (p=0.05)	5.50	4.94	0.17	0.15
Weed management				
Na-acifluorfen + clodinafop 245 g/ha	28.11	21.13	0.90	0.65
Pendimethalin 1000 g/ha *fb* imazethapyr 75 g/ha	29.08	21.24	0.88	0.62
Pendimethalin 1000 g/ha *fb* HW	24.73	16.42	0.68	0.43
Unweeded control	21.88	14.68	0.76	0.49
LSD (p=0.05)	3.67	4.08	0.11	0.12

ZT: zero tillage, R: residue, N: nitrogen, CT: conventional tillage, HW: spot hand weeding

Economics

The profitability in terms of net returns and net benefit: cost differed across treatments (**Table 6**). Higher yields under the ZT systems resulted in significantly higher net returns and net benefit: cost than those under CT, the highest being in ZT+R+100N which was statistically at par with ZT+R+75N and ZT+R+50N during both years. The CA-based ZT systems, on average, led to 62.6 and 114.0% higher net returns, while the net benefit: cost increased by 80.7 and 128.6% over CT+R+100N in 2019 and 2020, respectively. Lower net returns and net benefit: cost in CT system could be due to higher cost incurred in land preparation and residue incorporation coupled with lower yields. Among the weed control practices, pendimethalin *fb* imazethapyr, being statistically at par with Na-acifluorfen + clodinafop resulted in significantly higher net returns than the remaining treatments, with 32.9 and 44.7% increase compared to UWC in 2019 and 2020 respectively. Similarly, Na-acifluorfen + clodinafop and pendimethalin *fb* imazethapyr were comparable in terms of net benefit: cost. Lower yields under control plots ultimately resulted in lowest net returns, while net benefit: cost was lowest under pendimethalin *fb* HW. Despite having sizeable amount of yield, substantially lower profitability was observed under pendimethalin *fb* HW, which was statistically at par with UWC. It was due to higher cost involved in manual weeding. It, thus, indicated the importance of selecting a weed control option, *i.e.*, herbicides that results in a compounding effect on profitability by providing low-cost (cost-effective) weed control.

This study showed that CA-based systems, *i.e.*, ZT with residue retention had substantially lower density and dry weight of weeds, and led to considerable improvements in plant growth, symbiosis, productivity and profitability in greengram. Considerable yield reduction was observed when weeds were left unchecked, indicating the need of adopting a suitable cost-efficient weed control strategy in summer greengram. Sequential application of pendimethalin (1000 g/ha) as pre-emergence followed by imazethapyr (75 g/ha) as post-emergence led to better weed suppression that ultimately reflected in higher yields and net income. In situations where application of pre-emergence herbicides becomes difficult due to inappropriate soil and weather conditions, post-emergent control of weeds through a broad-spectrum herbicide appears to be beneficial towards improving yields and profitability. However, continuous use of herbicides may hasten weed shift and development of herbicide-resistant weed biotypes. Therefore, combining ZT with surface residue retention, and supplementing it with appropriate herbicidal weed control may be adopted as a multi-pronged integrated approach of managing weeds in CA-based greengram for long-term sustainability under maize-wheat-greengram cropping system in north-western IGP of India.

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