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RESEARCH ARTICLE

Influence of tillage and herbicide strategies on weed dynamics and wheat (*Triticum aestivum* L.) performance in saline soils of Northern India

Mohammad Vaheed[1*], Chandra Bhushan[1], Sunil Kumar Verma[1], SB Singh[2], Sudhir Kumar Rajpoot[1], Sidra Qidwai[2] & Sameer Shrivastava[1]

[1]Department of Agronomy, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi 221 005, Uttar Pradesh, India
[2]Department of Agronomy, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya 224 229, Uttar Pradesh, India

*Correspondence email - vaheedias@bhu.ac.in

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Abstract

A field experiment was conducted during the *rabi* season of 2019-20 at the Agronomy Research Farm, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya, to assess the effects of tillage and herbicide combinations on weed dynamics, crop growth and wheat yield under saline soil conditions. The study involved 15 treatment combinations arranged in a split -plot design (SPD) with three replications. The main plots included three tillage operations: T_0-zero tillage (ZT), T_1-minimum tillage (MT) and T_2-conventional tillage (CT). The sub-plots consisted of five weed management treatments: pendimethalin 1.5 kg active ingredient/ha (pre-emergence), pendimethalin 1.0 kg active ingredient/ha (pre-emergence) followed by sulfosulfuron (SFS) at 0.025 kg active ingredient/ha (post-emergence), SFS + metsulfuron-methyl (MSM) at 0.032 kg active ingredient/ha (post-emergence), a weedy check and a weed-free control. The results revealed that ZT significantly reduced weed density and dry weight while enhancing weed control efficiency (WCE) compared to MT and CT. Among the herbicide treatments, the sequential application of pendimethalin (1.0 kg active ingredient/ha) followed by SFS (0.025 kg active ingredient/ha) was the most effective in suppressing weed growth and improving WCE and enhancing crop growth and yield. This treatment was statistically on par with the SFS + MSM application. The combination of ZT with pendimethalin followed by SFS (T_0W_2) recorded the lowest weed infestation and the highest values for plant height, dry matter accumulation, tillers per m row length and grain yield. This was closely followed by the ZT combined with SFS + MSM treatment (T_0W_3), highlighting the synergistic benefits of conservation tillage and sequential herbicide application.

Keywords: herbicide; saline soil; tillage; weed control efficiency; wheat; yield

Introduction

After rice, wheat (*Triticum aestivum* L.) is Indias' second-largest cereal crop and a major contributor to the nations' food security. It constitutes 33.53 % of Indias' total food grain production. Wheat production in India during 2022-23 was 110.55 MT with an area of 31.40 Mha with a productivity of 6.40 t/ha. Over the decades, Indias' wheat production has risen substantially, rising from 6.40 MT in 1949-50 to 110.55 MT in 2022-23. Madhya Pradesh, Punjab and Uttar Pradesh are the three main wheat-producing states; Uttar Pradesh alone accounts for 31.77 % of the nations' wheat production (1).

Despite this impressive progress, wheat production in India faces several challenges, particularly traditional tillage practices and heavy weed infestation (2, 3). These issues are exacerbated by the delayed harvesting of preceding rice crops, which often delays wheat sowing, especially under conventional tillage systems that require intensive land ploughing (4). Late sowing has been shown to significantly reduce yield, by approximately 38 to 78 kg/ha/day when sown after 14th November (5).

Weeds also play a critical role in limiting wheat productivity. Globally, weed competition causes more crop losses than the combined effects of insect pests and disease. In India, severe competition from diverse weed flora can reduce wheat yields by 30-80 % (6). Traditional weed control methods, such as manual weeding, are labour-intensive, time-consuming and expensive. Consequently, herbicide-based weed management has gained popularity because of its lower labour costs and effective weed suppression (7).

CT, particularly ZT and reduced tillage (RT), has emerged as a sustainable solution to overcome these challenges. ZT allows timely sowing of wheat by reducing the need for extensive land preparation. Additionally, it affects weed dynamics and improves yields by conserving water; energy and labour (8, 9), reduces soil degradation, improve nutrient cycle and promote environmental sustainability (10).

However, despite these advantages, the adoption of CT has been hindered by high weed infestation, particularly during the initial years. Small-seeded weed species tend to thrive under reduced tillage systems, necessitating the use of diverse herbicidal strategies (11). The effective use of herbicides during the initial stages of conservation tillage is therefore crucial to minimize the weed-seed bank and ensure long-term sustainability. Therefore, an effort was made to access the effect of herbicides and tillage on dynamics of weeds and wheat yield in saline soil.

Materials and Methods

A field study was conducted during the *rabi* season of 2019-20 at the Agronomy Research Farm of Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya, Uttar Pradesh, India. The geographical coordinates were located at 26°32⊠55⊠⊠N latitude, 81°50⊠14⊠⊠E longitude and at an altitude of 113 m above sea level (Fig. 1). During the experimental period, the maximum recorded temperatures ranged between 14.0 °C and 36.6 °C, while the minimum temperatures ranged from 5.3 °C to 18.7 °C. The total rainfall during the study period was 184.6 mm. The surface-soil layer was silty-loam, with a pH of 8.08 and low organic carbon content

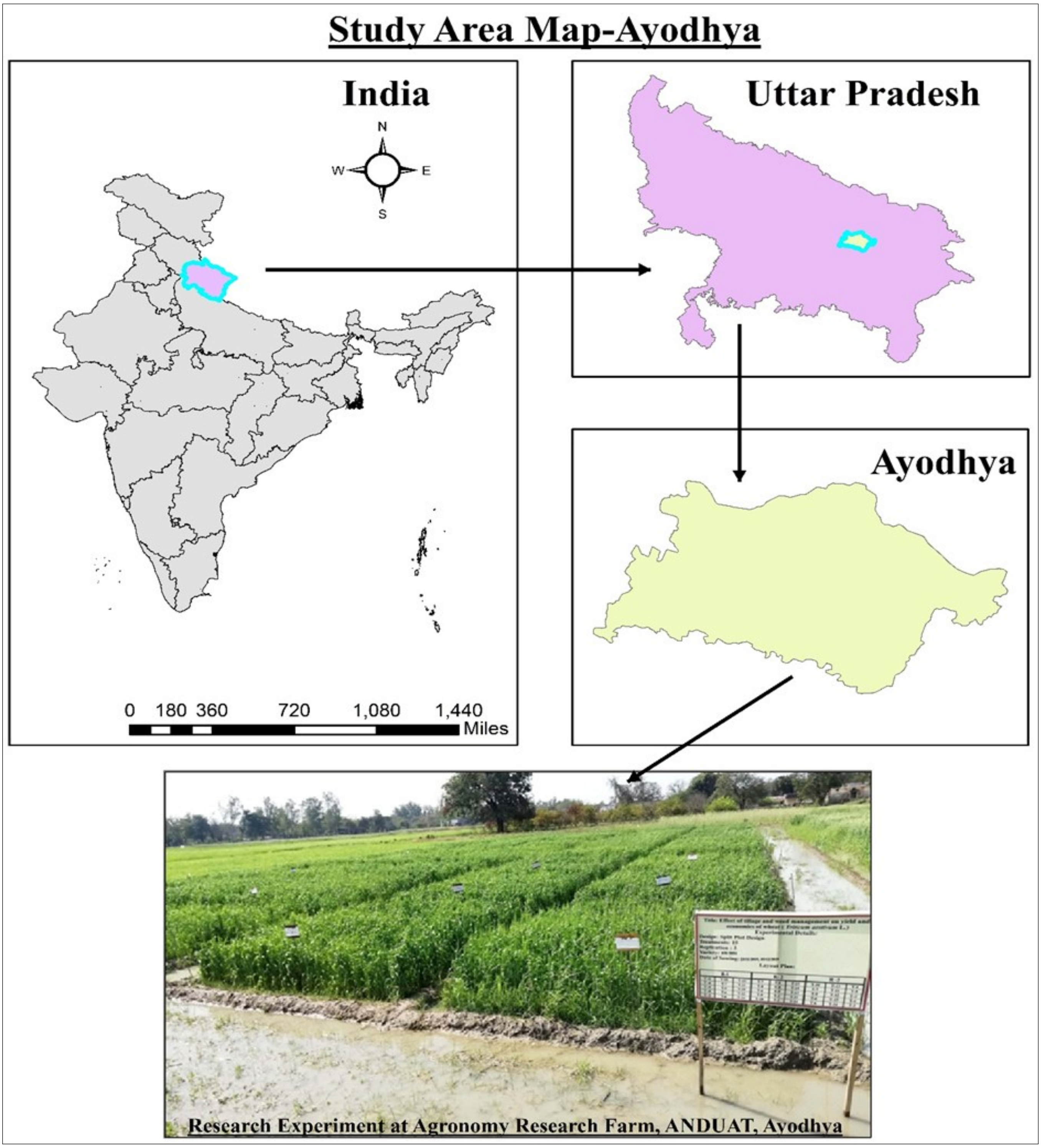

Fig. 1. Location of the experimental site. The figure illustrates the geographical context of the study area, beginning with a map of India, followed by zoomed-in views of Uttar Pradesh and Ayodhya district and concluding with a photograph of the experimental field where the research was conducted.

(0.40 %).

The study comprised fifteen treatment combinations arranged in an SPD with three replications. The main plots included three tillage treatments: T_0: ZT-no ploughing, T_1: MT-two ploughing and T_2: CT-four ploughing with broadcast seeding and in sub-plots were herbicides i.e. W_1: pendimethalin at 1.5 kg active ingredient/ha as a pre-emergence (PE), W_2: pendimethalin at 1.0 kg active ingredient/ha (PE) followed by SFS 0.025 kg active ingredient/ha as post-emergence (PoE), W_3: SFS + MSM at 0.032 kg active ingredient/ha (PoE), W_4: weedy-check and W_5: weed–free (up to 60 days).

In ZT (T_0) plots, glyphosate was sprayed at 1.0 kg active ingredient/ha 10 days prior to sowing to control the persistent weeds. In MT and CT plots, seedbeds were prepared through two and four ploughings respectively. Utilizing a ZT-seed drill to open slits the wheat variety NW-5054 was seeded at the seed rate of 100 kg/ha utilizing various crop establishment techniques with a 20 cm row spacing.

To meet the crops' nutritional needs, the prescribed fertilizer dosage of 120, 60, 40 kg/ha of nitrogen (N), phosphorous (P_2O_5) and potash (K_2O) was applied. Half the dose of N and the full dose of P_2O_5 and K_2O were applied at sowing, while the remaining N was applied in two equal top dressings; once after first irrigation and second at the tillering stage respectively. All other agronomic practices were carried out as per crop requirements to ensure successful crop establishment and growth.

Observations

The relative composition of each group of weeds was determined from weedy plots (weedy checks) by calculating the proportion of the single group of weeds in total number of all groups of weeds multiplied by 100. Weed density (WD) was determined at 30, 60, 90 days after sowing (DAS) and at harvest, using a quadrant of 50 × 50 cm size. Four random samples were collected from each treatment plot. All weeds within the sampled area were collected individually and categorized into 3 major groups: grasses, broad-leaf weeds (BLWs) and sedges. The total density of weeds was then determined.

After collection, individual weed species were washed twice, first with clean water and then with distilled water and air dried for 2-3 hr. These air-dried samples were kept in large brown paper bags and further dried in a hot-air oven at 70 °C till the constant weight was obtained. An electronic balance was used to record the dry weight of individual groups of weeds. The dry weight of the individual group of weeds was summed up to get total weed dry weight (WDW).

The mature crop was harvested from the net-plot area (4 × 3.2 m), excluding a 0.5 m border on all side, in the second week of April 2020. Harvested crops were sun-dried and weighed to get biological yield. After threshing, all grains were cleaned and weighed to determine grain yield and reported at 14 % moisture content. The grain yield was subtracted from biological yield to get straw yield.

The relative composition of weed was further computed based on the proportion of each major weed group to the total weed population. Weed control efficiency (%) at 30, 60 and 90 DAS of crops was determined by using the expression (12).

$$\mathrm{WCE}\ (\%) = \frac{\mathrm{DMC} - \mathrm{DMT}}{\mathrm{DMC}} \times 100$$

Where, WCE is weed control efficiency; DMC is dry weight of weeds (gm^{-2}) for control plot (weedy check) and DMT is dry weight of weeds (gm^{-2}) for the treated plot.

Statistical analysis

All recorded data were average replication-wise and subjected to statistical analysis using analysis of variance (ANOVA) (13) and mean comparisons were based on the least significant difference (LSD) at a 5 % probability level (p<0.05). Data pertaining to $\sqrt{(x+0.5)}$ WD and WDW were first transformed using the square-root-transformation and then analyzed. 'F-test' was used to establish the significance of treatment effects.

Results and Discussion

Relative composition of weeds

The wheat field was affected by *Phalaris minor, Avena ludoviciana Chenopodium album, Anagallis arvensis* and *Cyperus rotundus.* Among the grassy weeds, *P. minor* was the dominant weed followed by *A. ludoviciana*. Of the two dominant broad–leaf weeds, *C. album* showed 21.78 % highest density over *A. arvensis* 16.22 % (Fig. 2). In total, narrow-leaf weeds comprised the largest proportion (39 %) of the overall weeds followed by broad-leaf weeds (38 %) and sedges (23 %) (Fig. 3).

Weed density

Data were analyzed using analysis of variance (ANOVA) and treatment means were compared using the least significant difference (LSD) test at a 5 % significance level. Error bars indicate standard errors based on the error degrees of freedom from ANOVA. Treatment differences were considered significant at $p \leq 0.05$. The density of all weed groups was lowest at 30 DAS, but as the crop progressed towards maturity, the weed density gradually increased, reaching its peak at 60 DAS. All the tillage operations significantly affected WD with ZT resulting in the lowest WD across all groups, followed by MT, while CT exhibited the highest density. The superior performance of ZT in reducing weed infestation and enhancing wheat yield aligns with previous studies (2, 14). Reduced soil disturbance under ZT minimises the upward movement of weed seeds from deeper soil layers, thereby lowering the chances of germination. Conversely, intensive ploughing in CT facilitates weed emergence by exposing buried seeds to favourable environmental conditions (15-17). This mechanistic explanation underscores the sustainability of conservation tillage in saline soil conditions.

Among herbicidal treatment, W_1-W_3 and W_5 had noticeable negative effects on weeds and were shown to have reduced the densities of all weed groups compared to the untreated weedy-check (Fig. 4-6). Application of pendimethalin at 1.5 kg active ingredient/ha followed by SFS at 0.025 kg active ingredient/ha (W_2) significantly reduced WD and it was statistically at par with SFS + MSM at 0.032 kg active ingredient/ha (W_3). The density of grasses, BLWs and sedges was significantly impacted by the interaction between tillage and

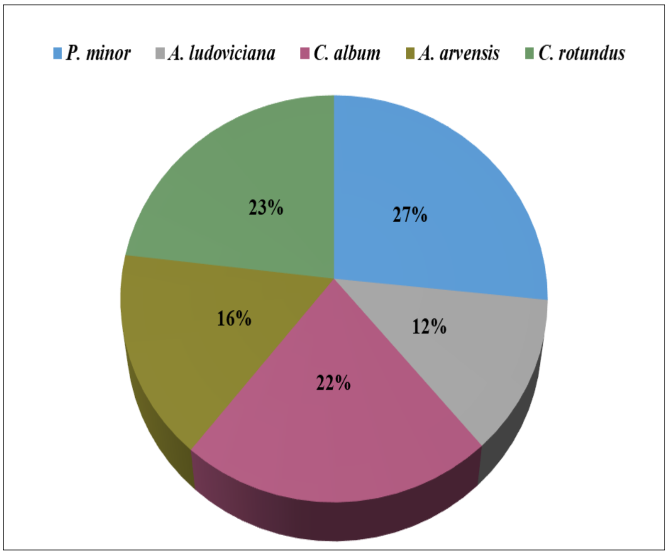

Fig. 2. Relative composition of weed species at 60 days after sow-

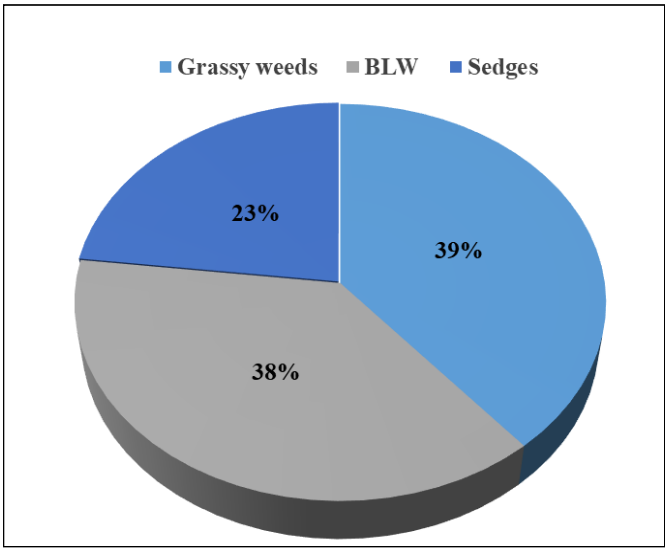

Fig. 3. Relative composition of weed groups at 60 days after sowing.

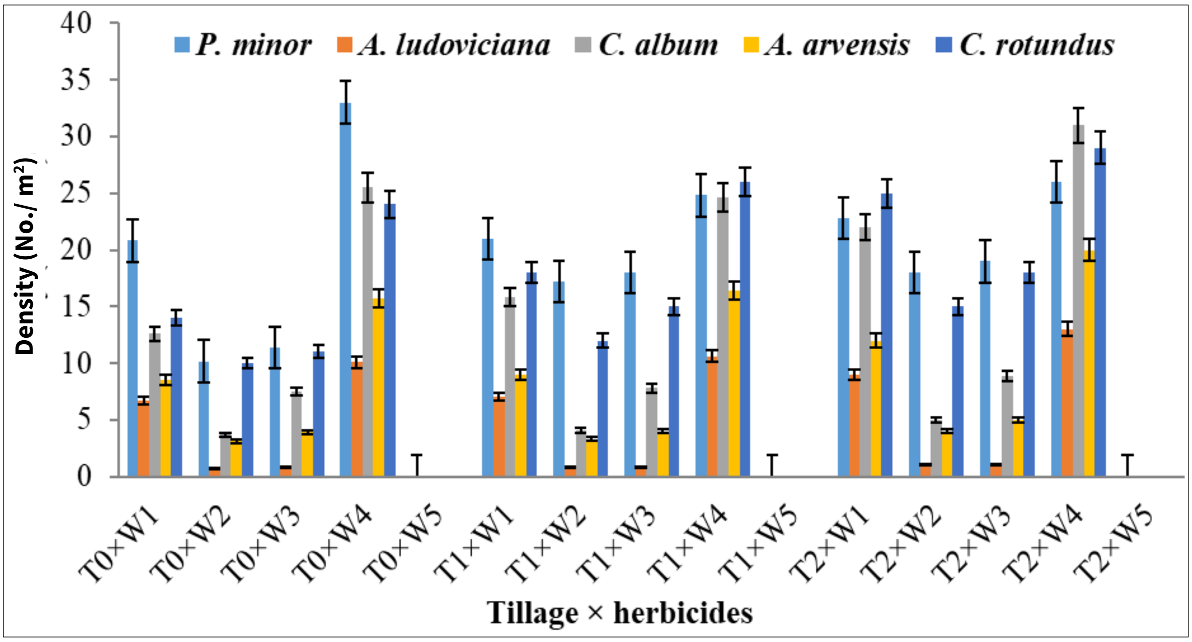

Fig. 4. Interaction effect of tillage and herbicide treatments on weed density (No. m^{-2}) at 30 days after sowing. The figure represents five dominant weed species: *Phalaris minor*, *Avena ludoviciana*, *Chenopodium album*, *Anagallis arvensis* and *Cyperus rotundus*.

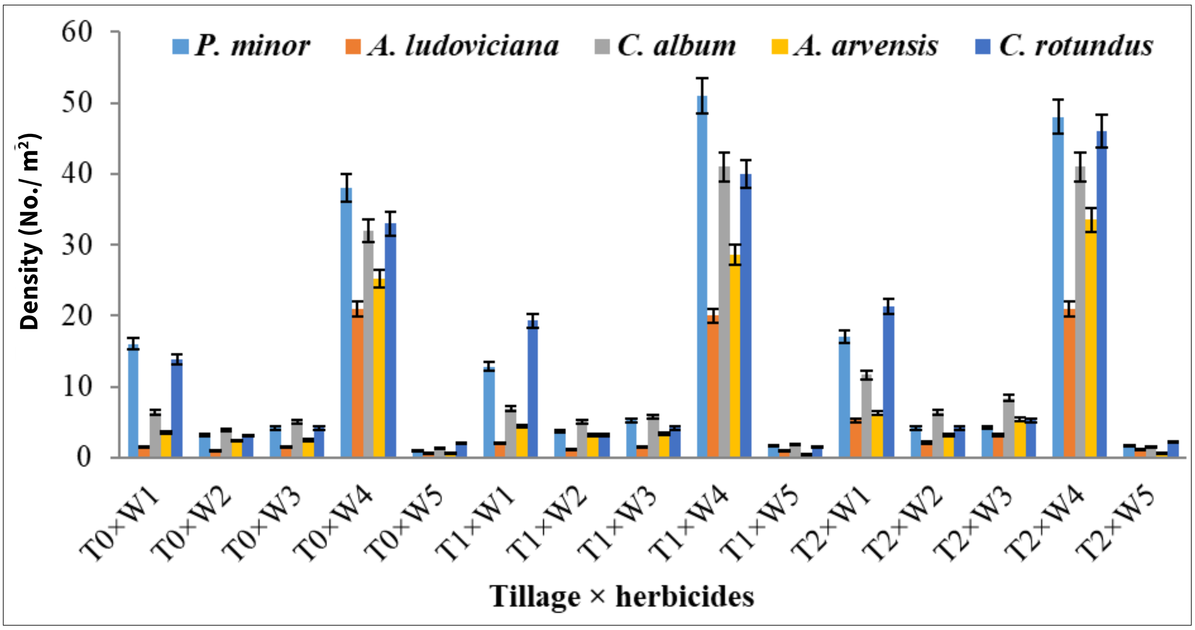

Fig. 5. Interaction effect of tillage and herbicides on density of weeds (No./m^2) at 60 days after sowing. The figure represents five dominant weed species: *Phalaris minor*, *Avena ludoviciana*, *Chenopodium album*, *Anagallis arvensis* and *Cyperus rotundus.*

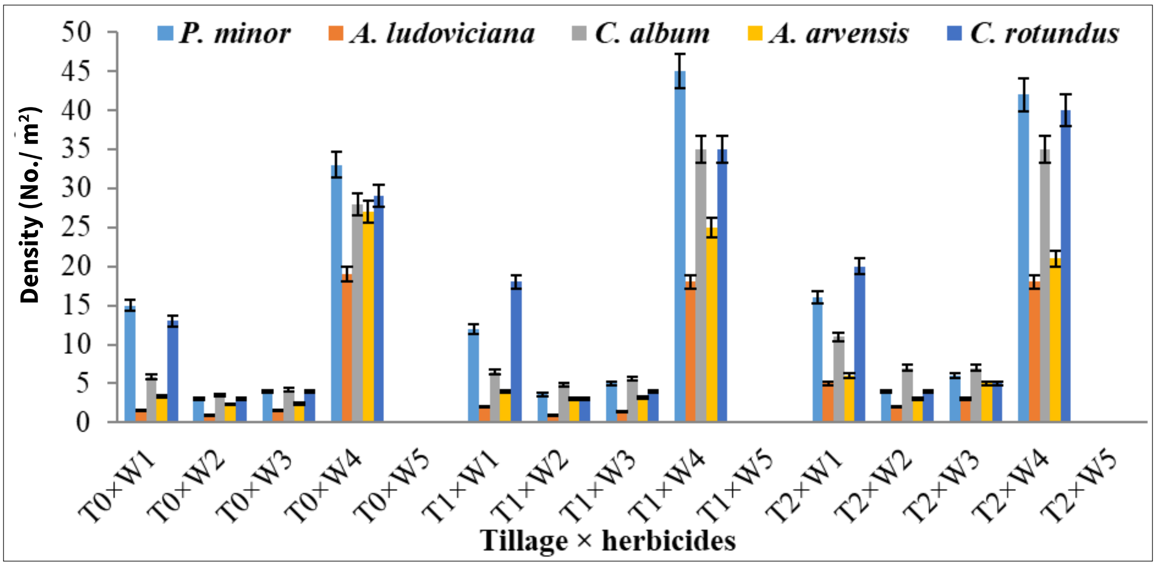

Fig. 6. Interaction effect of tillage and herbicides on density (No./m^2) of weeds at 90 days after sowing.

The figure represents five dominant weed species: *Phalaris minor*, *Avena ludoviciana*, *Chenopodium album*, *Anagallis arvensis* and *Cyperus rotundus*.

herbicidal treatment. The lowest density of all weed groups was recorded under ZT along with the application of pendimethalin at 1.0 kg active ingredient/ha followed by SFS at 0.025 kg active ingredient/ha (T_0W_2), outperforming all other tillage and herbicide treatment combinations (6, 18, 19).

Total weed density, weed dry weight and weed control efficiency

There is a strong correlation observed between WD and WDW, with both being highest in the weedy-check plots. Among the tillage treatment, ZT had the lowest overall WD, WDW and maximum WCE, followed by MT and CT respectively. The enhanced soil structure (i.e. tilth) and the upward movement of weed seeds to the surface layer in conventional tillage likely resulted in a higher weed population, leading to increased weed biomass and reduced WCE in the CT system (2, 8, 20).

Among herbicidal treatments, W_2 was the most effective in reducing both total weed density and dry weight and recorded the highest WCE across treatments (Fig. 7-9). It was due to the lowest weed population and dry weight observed under this treatment. These outcomes are consistent with the other findings (17).

Tillage and herbicides had a significant interaction effect in the T_0W_2 followed by T_0W_3 treatment combinations. However, total WD at 60 DAS was significantly lower (38.10 to 72.16 %); in T_0(ZT) plots treated with (W_2) pendimethalin at 1.0 kg active ingredient/ha followed by SFS at 0.025 kg active ingredient/ha compared to the T_2 plots × (W_1, W_2, W_3) combinations and being at par with T_1 plots (MT). When compared with the weedy check (W_4), the reduction in weedy density under the T_0W_2 combination ranged from 73.71 to 90.39 %.

Furthermore, under W_1 and W_2 treatments, WDW in T_0 plots was 16.87 % and 37.80 % lower than T_1 plots respectively (21). Even under weedy-check condition, T_0 plots recorded 10.13 % lower WDW than T_2 plots. WDW from T_2 plots treated with W_1 was significantly greater than most other tillage operations (T) × herbicides combinations except for T_0W_3. Apart from weedy-check and weed–free plots; the increase in WDW T2 × W1 combinations ranged from 7.60 % to 58.46 % (22, 23).

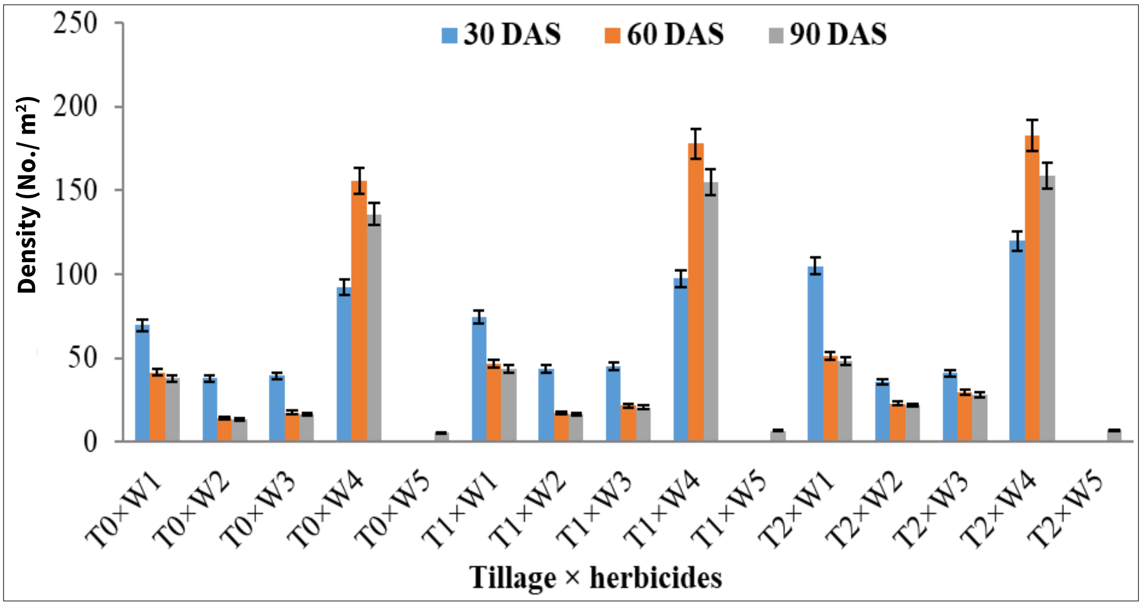

Fig. 7. Interaction of tillage and herbicides on total weed density (No./m^2).

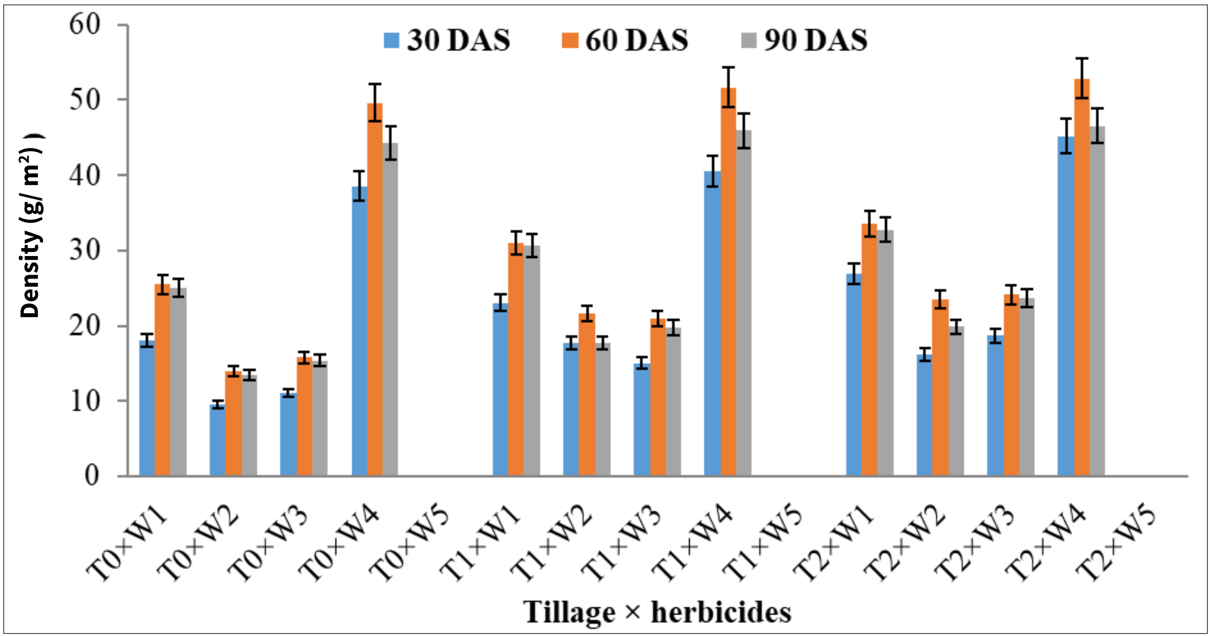

Fig. 8. Interaction of tillage and herbicides on total weed dry weight (g/m^2).

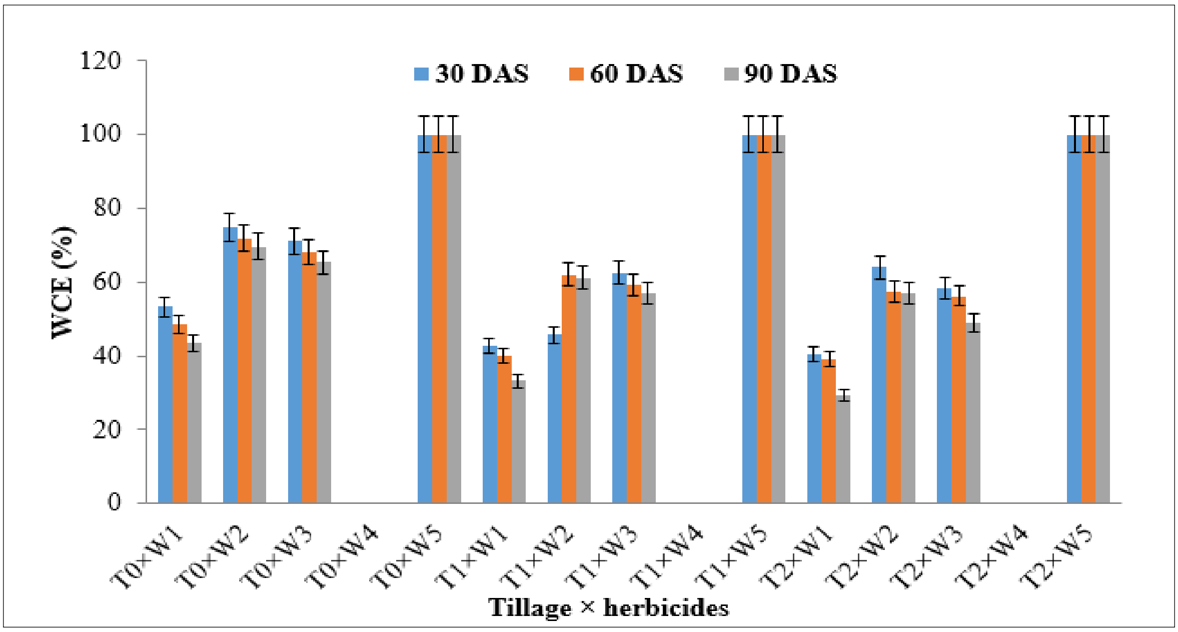

Fig. 9. Interaction effect of tillage and herbicides on WCE (%).

Crop growth

Tillage operations and herbicides treatments had a significant effect on the growth characteristics of wheat. Among tillage operation, treatment ZT showed the highest leaf area index (LAI), as shown in Fig. 10, along with superior plant height, number of tillers and dry matter accumulation (DMA), as summarized in Table 1. This was followed by MT and CT respectively. The enhanced crop growth and yield under ZT can be attributed to improved soil structure, better moisture conservation and more efficient nutrient cycling (10, 24). Moreover, reduced weed interference in ZT systems allows wheat plants to allocate greater resources to growth and grain formation, corroborating findings reported from similar agro-ecological conditions (25, 26).

Among the herbicidal treatment, pendimethalin at 1.0 kg active ingredient/ha followed by SFS at 0.025 kg active ingredient/ha recorded the highest values for LAI, plant height, tillers and DMA and was at par with SFS + MSM at 0.032 kg active ingredient/ha. These improvements in crop growth can be attributed to reduced crop-weed competition for light, water and nutrients, thereby enhancing physiological and morphological growth parameters (27, 28).

Yield

On average, ZT increased grain yield by 13.59 % over MT and 20.32 % over CT, respectively (2, 4, 14). Herbicidal treatments also had a significant impact on grain yield. The sequential application of pendimethalin at 1.0 kg active ingredient/ha followed by SFS at 0.025 kg active ingredient/ha resulted in a substantial increase in grain yield compared to both the weedy-check and the sole application of pendimethalin at 1.5 kg active ingredient/ha and was at par with SFS + MSM at 0.032 kg active ingredient/ha. Evidently, the highest grain yield was produced in weed-free plots, which were noticeable higher than yield under any herbicidal treatment (Table 2). Nevertheless, the initial phase of ZT adoption is often challenged by persistent weed pressure, necessitating the use of effective herbicide regimes during the early stages (11, 25).

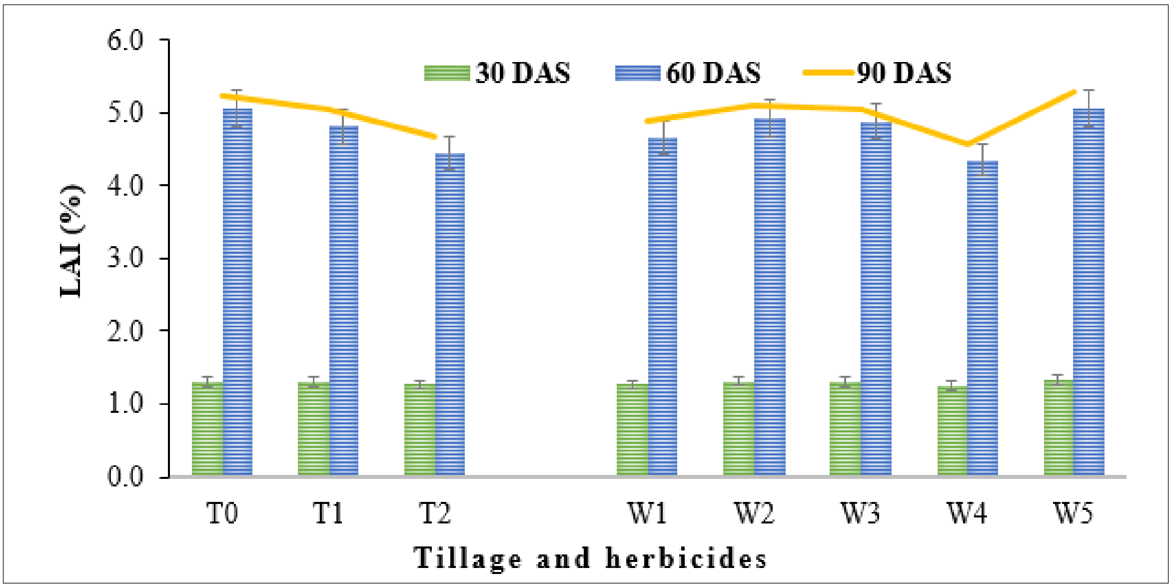

Fig. 10. Effect of tillage and herbicides on leaf area index.

Table 1. Effects of tillage and herbicides on plant height, tillers, dry matter accumulation at harvest and grain yield

Treatments	Plant height (cm)	Tillers (No./m²)	DMA (g/m²)	Grain yield (kg/ha)
Tillage operations (T)				
T_0	81.83	295.46	862.37	3834
T_1	78.82	280.28	803.58	3376
T_2	67.73	274.28	738.03	3187
SEm±	1.04	1.80	8.03	44
CD (p=0.05)	4.08	7.05	31.51	172
Herbicides (Ws)				
W_1	72.66	271.83	752.54	3162
W_2	79.51	292.64	859.59	3687
W_3	78.37	286.19	821.18	3488
W_4	65.11	254.14	700.76	2988
W_5	84.98	311.89	872.55	4003
SEm±	0.99	2.63	9.28	38
CD (p=0.05)	2.88	7.69	27.09	110
Interaction (T× Ws)				
SEm±	1.71	4.56	16.07	65
CD (p=0.05)	4.99	13.32	46.92	190

T_0: Zero-tillage (No tillage), T_1: Minimum tillage (2 ploughing), T_2: Conventional tillage (4 ploughing) with broadcast seeding; W_1: Pendimethalin at 1.5 kg active ingredient/ha (PE), W_2: Pendimethalin at 1.0 kg active ingredient/ha (PE) followed by sulfosulfuron at 0.025 kg active ingredient/ha (PoE), W_3: Sulfosulfuron + metsulfuron at 0.032 kg active ingredient /ha (PoE), W_4: Weedy-check, W_5: Weed–free.

Table 2. Interaction tillage operations and herbicides on total weed density and dry weight at 60 DAS and grain yield of wheat

T/Ws	Total weed density (No./m²)			Total weed dry weight (g/m²)			Grain yield (kg/ha)		
	T_0	T_1	T_2	T_0	T_1	T_2	T_0	T_1	T_2
W_1	6.48 (41.50)*	6.87 (46.80)	7.20 (51.36)	5.09 (25.49)	5.60 (30.97)	5.83 (33.51)	3617	3045	2824
W_2	3.84 (14.30)	4.19 (17.10)	4.86 (23.10)	3.80 (13.92)	4.46 (19.43)	4.90 (23.51)	3921	3700	3440
W_3	4.25 (17.60)	4.71 (21.70)	5.45 (29.40)	4.03 (15.77)	4.63 (20.97)	4.96 (24.10)	3807	3358	3300
W_4	12.51 (156.00)	13.35 (178.00)	13.54 (183.00)	7.07 (49.58)	7.22 (51.69)	7.46 (55.17)	3378	2820	2765
W_5	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	4449	3954	3605
CD (p=0.05)	0.50 (10.30)			0.27 (3.60)			190		

*Data under parenthesis are the original $\sqrt{(x+0.5)}$ value which were transformed by for analysis.

Tillage and herbicides have the significant interaction effect on wheat grain yield. T_0W_1 produced the highest wheat grain yield, which was 12.27 % more than all MT and herbicides combinations, including the weed-free plots. Additionally, the yield under this combination of treatments was the same as the yield from T_1W_5. Furthermore, as per the findings of Table 2, the yields under both the weed-free and weedy-check plots were higher in MT by 8.83 % and 1.95 % respectively than under CT (29, 30).

Conclusion

The findings of this study demonstrate that tillage practices and herbicide applications significantly influence weed dynamics and wheat growth. ZT increased grain yield by 12.29 % and 18.63 % compared to MT and CT respectively. Among the herbicide strategies tested, the sequential application of pendimethalin at 1.0 kg active ingredient/ha followed by sulfosulfuron at 0.025 kg active ingredient/ha (W_2) was the most effective, leading in the lowest weed infestation, highest weed control efficiency (WCE) and maximum grain yield.

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Authors' contributions

MV carried out the research work in the field and laboratory and drafted the manuscript. MV, SKV, CB and SKR developed the methodology and contributed to visualization. MV, SKV and SKR performed software analysis. MV, SKV, CB, SKR and SBS provided validation. MV, SKV, CB and SS conducted formal analysis. MV, SKV, CB, SKR and SQ carried out the investigation. MV, SKV, CB and SQ provided resources. SKV, MV and SBS curated the data. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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