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Tillage and weed management effects on weed dynamics, yield and nutrient uptake of wheat

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Abstract

An experimental study was conducted during two consecutive rabi seasons (2022–23 and 2023–24) at Bihar Agricultural University (BAU), Sabour, Bhagalpur, India, to evaluate the effects of different tillage systems and weed management practices on weed infestation, wheat productivity and nutrient uptake. The experiment was laid out in a split-plot design comprising three tillage practices in the main plots and six weed control methods in the sub-plots. Zero tillage combined with paddy residue retention proved to be the most effective tillage practice for suppressing weed growth, recording the highest weed control efficiency (WCE) (74.19 %) and the lowest weed index (13.97 %). This treatment also resulted in significantly higher grain and straw yields along with greater nutrient uptake by the wheat crop. Among the herbicidal treatments, the combined application of sulfosulfuron (SS) with metsulfuron methyl (MSM) (30 + 2 g a.i. ha^{-1}) was the most effective in reducing weed density and biomass, followed by MSM plus iodosulfuron methyl sodium (12 + 2.4 g a.i. ha^{-1}). Overall, the results indicate that zero tillage with crop residue retention, coupled with the application of SS + MSM, is an effective and sustainable weed management strategy for enhancing wheat productivity in the eastern Indo-Gangetic Plains (IGP).

Keywords: crop residue retention; nutrient uptake; weed management; wheat productivity; zero tillage

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Introduction

Wheat (*Triticum aestivum* L.) is one of the most important staple cereal crops in India, serving as a major source of calories and protein for a large segment of the population. It ranks second only to rice in terms of its contribution to national food security and plays a pivotal role in sustaining livelihoods, particularly in the Indo-Gangetic Plains (IGP) (1). India is the second-largest wheat-producing country globally, contributing approximately 14.25 % of total world production, while Bihar alone accounts for about 5.83 % of the national wheat output (2). With India's food grain requirement projected to increase from 236.2 million tonnes in 2010 to nearly 303–318 million tonnes by 2030, enhancing wheat productivity in a sustainable manner has become a national priority (3).

Despite notable gains during the Green Revolution, wheat productivity in several regions of India has stagnated or declined in recent decades. This trend is primarily attributed to inappropriate tillage practices, imbalanced fertiliser use, declining soil health, water scarcity and severe weed infestation. Conventional tillage systems, although widely practiced, often disturb the soil excessively, thereby creating favourable conditions for weed seed germination and proliferation (4). In contrast, conservation agriculture practices such as zero tillage, which involve minimal soil disturbance and the retention of crop residues, have emerged as viable alternatives. Zero tillage reduces production costs, conserves soil moisture, improves soil structure and enhances microbial activity, making it particularly suitable for the rice-wheat cropping systems prevalent in northern and eastern India (5).

Weed infestation remains one of the most critical biological constraints in wheat production, with potential yield losses ranging from 15 % to more than 50 % if left unmanaged (6). In recent years, escalating labour costs and rural workforce migration have compelled farmers to rely increasingly on chemical weed control. Consequently, herbicide use in wheat has expanded rapidly across India. The excessive and indiscriminate use of herbicides has resulted in serious agronomic and ecological concerns, including herbicide resistance, shifts in weed flora and environmental contamination. The widespread resistance of *Phalaris minor* Retz. to isoproturon has necessitated the adoption of alternative post-emergence herbicides such as sulfosulfuron (SS) (7).

Several post-emergence herbicides, including Clodinafop, Metribuzin, Metsulfuron methyl (MSM), Mesosulfuron methyl (MM) and Iodosulfuron methyl sodium (IMS), have shown varying degrees of effectiveness against grassy and broad-leaved weeds. Sulfosulfuron has been reported to effectively control both grassy and certain broad-leaved weeds. However, the selective nature of individual herbicides often leads to shifts in weed flora, by favouring species that are not controlled by the applied herbicide. For example, repeated use of graminicides such as Clodinafop frequently results in an increased dominance of broad-leaved weeds. To overcome this limitation, broad-spectrum weed management strategies involving tank-mix or ready-mix herbicide combinations have been recommended. Pre-mixed formulations such as SS + MSM, Clodinafop + MSM and Mesosulfuron + Iodosulfuron methyl sodium provide effective control of both grassy and broad-leaved weeds while being economically viable and environmentally safer (8). Moreover, foliar post-emergence herbicide applications are preferred over soil-applied herbicides because of their reduced residual effects and lower risk of environmental contamination.

Although several studies have independently evaluated the effects of conservation tillage or herbicide combinations on weed management in wheat, systematic information on the interactive effects of tillage practices particularly zero tillage with crop residue retention and post-emergence herbicide combinations on weed dynamics, nutrient uptake and wheat productivity in the eastern IGP is limited. Furthermore, region-specific data for Bihar, where rice-wheat cropping systems predominate and weed flora is rapidly changing are scarce.

To address these gaps, the present study was undertaken to assess the combined effects of different tillage systems and post-emergence herbicide treatments on weed infestation, crop productivity and nutrient uptake in wheat. The findings aim to identify efficient, sustainable and location-specific weed management strategies that can enhance wheat productivity while maintaining soil health and environmental quality, thereby contributing to long-term food security in India

Materials and Methods

Experimental site and agro-climatic conditions

The field experiment was conducted during the rabi seasons of 2022–23 and 2023–24 at the Research Farm of Bihar Agricultural University (BAU), Sabour, Bhagalpur district, Bihar, India. The experimental site lies in the Southeast Alluvial Plain, classified as Agro-Climatic Zone IIIA of the Middle Gangetic Plains Region. The site is geographically located at 25°23′ N latitude and 87°05′ E longitude, at an altitude of 46 m above mean sea level.

Climatic conditions and weather parameters

The climate of the experimental area is subtropical humid, characterised by cool winters and hot summers. During the rabi seasons, weather remained generally favourable for wheat growth, with occasional cold spells during early crop establishment.

Weather data recorded from the Agrometeorological Observatory, BAU, Sabour, indicated that the mean weekly maximum temperature ranged from 18.4–29.8 °C, while the minimum temperature varied between 5.6 and 14.2 °C during the crop growth period. The lowest minimum temperatures were observed during late December and early January, coinciding with the early vegetative stage of wheat.

The total seasonal rainfall received during the crop growing period was 48.6 mm in 2022–23 and 62.3 mm in 2023–24, with most of the rainfall occurring during February and March. The mean relative humidity ranged from 58–89 %, while bright sunshine hours varied between 5.2 and 8.6 hr day^{-1}. These climatic conditions are typical of the wheat-growing environment of the Middle Gangetic Plains and were conducive to evaluating tillage and weed management practices.

Soil characteristics

The experimental field had silty clay loam soil. Composite soil samples were collected from the 0–15 cm soil depth prior to sowing and analysed using standard procedures. The soil was low in organic carbon (0.47 %) and available nitrogen (N) (191.86 kg ha^{-1}), while available phosphorus (P) and potassium (K) were moderate, recording 27.26 kg P_2O_5 ha^{-1} and 143.21 kg K_2O ha^{-1} respectively. The soil reaction was slightly alkaline (pH 7.89).

Experimental design and treatments

The experiment was laid out in a split-plot design with 3 replications. A total of 18 treatment combinations were evaluated in 54 plots, each measuring 3.0 × 4.0 m (12 m^2).

Main plot treatments (tillage practices)

- T_1: Conventional tillage
- T_2: Zero tillage without residue
- T_3: Zero tillage with paddy residue retention (30 %)

Sub-plot treatments (weed management practices)

- W_1: Clodinafop propargyl + Metsulfuron methyl (60 + 4 g a.i. ha^{-1}) as PoE at 30 days after sowing (DAS)
- W_2: Sulfosulfuron + Metsulfuron methyl (30 + 2 g a.i. ha^{-1}) as PoE at 30 DAS
- W_3: Mesosulfuron methyl + Iodosulfuron methyl sodium (12 + 2.4 g a.i. ha^{-1}) as PoE at 30 DAS
- W_4: Clodinafop propargyl + Metribuzin (54 + 120 g a.i. ha^{-1}) as PoE at 30 DAS
- W_5: Hand weeding at 20–25 and 40–45 DAS
- W_6: Weedy check (untreated control)

Salient features of the wheat variety under evaluation

The wheat variety HD 2967, released by ICAR-Indian Agricultural Research Institute (IARI), New Delhi, was used in the study. The variety is widely adapted to the

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Northwestern and Northeastern Plains Zone, including the Middle Gangetic Plains. It is a high-yielding, semi-dwarf variety with a medium maturity duration (140–145 days).

HD 2967 is characterised by good tillering ability, bold grains and strong straw strength, which makes it suitable for conservation agriculture practices. The variety exhibits moderate resistance to major wheat diseases, particularly leaf rust and stripe rust and has shown stable performance under timely sown conditions of eastern India.

Crop establishment and management

The wheat variety HD 2967 was sown on 6th December during both years using a zero-tillage seed drill, maintaining a seed rate of 125 kg ha^{-1} and row spacing of 20 cm. The crop was harvested on 10th April 2023 and 13th April 2024 respectively.

Under conventional tillage, the field was ploughed once with a soil-turning plough followed by two cross ploughings using a cultivator and rotavator and leveled by planking. No tillage operations or residue retention were practiced under zero tillage without residue, whereas 30 % of the paddy residue was retained on the soil surface under zero tillage with residue treatment.

Nutrient management

A uniform fertiliser dose of 150 kg N, 60 kg P_2O_5 and 40 kg K_2O ha^{-1} was applied across all treatments. Nitrogen, P and K were supplied through urea, diammonium phosphate (DAP) and muriate of potash (MOP) respectively. Half of the N, along with the full dose of P and K were applied as basal at sowing, while the remaining N was top-dressed in two equal splits at the tillering and spike initiation stages.

Weed control and herbicide application

Post-emergence herbicides were applied uniformly at 30 DAS using a knapsack sprayer fitted with a flat-fan nozzle, maintaining a spray volume of 500 L ha^{-1}. Herbicide doses were calculated based on active ingredient content. To prevent cross-contamination, the sprayer was thoroughly washed after each application. Hand weeding was carried out at 25 and 45 DAS, while weedy check plots were left untreated throughout the crop season.

Observations recorded

Weed density and dry matter accumulation were recorded at 30 and 60 DAS and at harvest using a 0.25 m^2 quadrat. Crop growth parameters, yield attributes and yield were recorded following standard agronomic procedures. Grain yield was adjusted to 12 % moisture content.

Statistical analysis

The data were subjected to analysis of variance (ANOVA) appropriate for a split-plot design and treatment means were compared using the critical difference (CD) test at the 5 % probability level.

Results and Discussion

Dominant weed flora

The predominant weed flora observed in the experimental wheat field comprised grassy weeds such as *Phalaris minor* Retz., *Polypogon monspeliensis* (L.) Desf. and *Cynodon dactylon* (L.) Pers.; the sedge, *Cyperus rotundus* L.; and several broad-leaved weeds, namely *Rumex dentatus* L., *Anagallis arvensis* L., *Medicago denticulata* Willd., *Solanum nigrum* L., *Melilotus indica* (L.) All., *Chenopodium album* L., *Physalis minima* L., *Vicia sativa* L., *Fumaria parviflora* Lam. and *Polygonum plebeium* R.Br.

Influence of tillage and weed management practices on weed dynamics in wheat

Zero tillage with paddy residue recorded significantly lower total weed densities of 109.65 and 86.8 m^{-2} and lower total weed dry matter accumulation of 62.60 and 123.86 g m^{-2} at 30 and 60 DAS respectively, compared with zero tillage without residue (Table 1). Across the tillage practices, conventional tillage consistently recorded the highest weed density and dry matter, whereas zero tillage with paddy residue recorded the lowest values at both observation stages. The reductions in weed density and biomass under residue-retained zero tillage was statistically significant and reflected the suppressive effects of reduced soil disturbance and surface residue cover on weed emergence.

Among weed management practices, hand weeding at 25 and 45 DAS resulted in the lowest total weed density and dry matter accumulation at all observation stages, indicating near-complete weed removal during the critical crop–weed competition period. At 60 DAS, the herbicide combination SS + MSM (30 + 2 g a.i. ha^{-1}) recorded the lowest weed density and dry matter among the chemical treatments, followed by MSM + Iodosulfuron methyl sodium (12 + 2.4 g a.i. ha^{-1}). All herbicidal treatments significantly reduced weed density and dry matter compared to the weedy check, confirming their effectiveness in suppressing weed growth (Table 1).

A significant interaction between tillage practices and weed management treatments was observed for total weed density and dry matter accumulation at 60 DAS, indicating the differential performance of weed control measures under varying tillage systems. However, tillage practices alone did not have a statistically significant effect on weed control efficiency (WCE) at 60 DAS or weed index at harvest. Numerically, zero tillage with paddy residue recorded the highest WCE and lowest weed index, followed by zero tillage without residue and conventional tillage respectively (Table 2).

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Table 1. Effect of tillage and weed management on weed density and dry weight at 30 and 60 days after sowing (DAS) (Pooled 2022–24)

Treatment	Total weed density (no. m^{-2})		Total weed dry matter (g m^{-2})	
Main plots: Tillage operations	30 DAS	60 DAS	30 DAS	60 DAS
CT	10.82 (134.12)	10.04 (127.69)	8.40 (81.50)	12.36 (203.28)
ZT	10.26 (121.21)	9.06 (98.69)	7.96 (72.27)	11.15 (158.70)
ZT + R	9.68 (109.65)	8.30 (86.85)	7.39 (62.60)	9.80 (123.86)
SEm (±)	0.65	0.29	0.55	0.20
C.D (p = 0.05)	NS	1.14	NS	0.79
Sub plots: Weed management practices				
Clodinafop propargyl + Metsulfuron methyl (60 + 4) g	12.46 (155.97)	8.90 (81.05)	9.51(91.32)	10.91 (120.98)
Sulfosulfuron + Metsulfuron methyl (30 + 2) g	11.71(138.37)	7.51(59.07)	9.05 (82.52)	9.58 (94.80)
Mesosulfuron methyl + Iodosulfuron methyl sodium (12 + 2.4) g	12.60 (159.56)	8.64 (78.55)	9.63 (93.11)	10.31 (109.32)
Clodinafop propargyl + Metribuzin (54 + 120) g	11.38 (130.63)	10.05 (101.96)	8.89 (79.76)	11.45 (131.70)
Hand weeding at 20–25 and 40–45 DAS	1.60 (2.14)	2.59 (6.44)	1.24 (1.07)	2.02 (3.83)
Weedy check	11.79 (143.27)	17.11 (299.41)	9.18 (84.97)	22.36 (511.03)
SEm (±)	0.37	0.35	0.26	0.46
C.D (p = 0.05)	1.06	1.00	0.75	1.33
Interaction	NS	S	NS	S

Data in parenthesis are original value and outside values are subjected to square root transformation (√x+ 0.5) before analysis. DAS: days after sowing; CT: conventional tillage; ZT: zero tillage; R: residue; NS: Non-significant; S: significant

Table 2. Effect of tillage and weed management on weed control efficiency (WCE) at 60 days after sowing (DAS) and weed index at harvest (Pooled 2022–24)

Treatment	Weed control efficiency (%) at 60 DAS	Weed index (%) at harvest
Main plots: Tillage operations		
CT	61.09	19.14
ZT	70.17	15.44
ZT + R	74.19	13.97
SEm (±)	1.79	0.71
C.D (p = 0.05)	7.04	2.77
Sub plots: Weed management practices		
Clodinafop propargyl + Metsulfuron methyl (60 + 4) g	75.38	11.25
Sulfosulfuron + Metsulfuron methyl (30 + 2) g	82.76	5.57
Mesosulfuron methyl + Iodosulfuron methyl sodium (12 + 2.4) g	78.65	8.24
Clodinafop propargyl + Metribuzin (54 + 120) g	74.91	19.91
Hand weeding at 20–25 and 40–45 DAS	99.19	0.00
Weedy check	0.00	52.13
SEm (±)	2.52	0.96
C.D (p = 0.05)	7.29	2.77
Interaction	NS	NS

DAS: days after sowing; CT: conventional tillage; ZT: zero tillage; R: residue; NS: Non-significant

With respect to weed management treatments, hand weeding achieved the highest WCE (99.19 %) and minimum weed index (0.00 %), reflecting almost complete yield protection through effective weed suppression. Among herbicides, SS + MSM (30 + 2 g a.i. ha^{-1}) recorded the highest WCE (82.76 %), followed by Mesosulfuron methyl + Iodosulfuron methyl sodium (12 + 2.4 g a.i. ha^{-1}). These treatments also registered lower weed index values, indicating improved crop performance due to the effective reduction of weed competition.

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Effect on yield attributes and yield of wheat

The superior performance of zero tillage with paddy residue retention observed in the present study is well supported by recent findings under rice–wheat systems of the IGP. Residue retention under zero tillage has been consistently reported to improve soil moisture conservation, soil organic carbon stabilisation and nutrient cycling, which collectively enhance tiller survival and spike density in wheat (5, 6). The higher number of spikes per square metre and grains per spike recorded in residue-retained plots may be attributed to moderated soil temperature and improved rhizospheric conditions, particularly during early vegetative growth (Table 3).

Recent long-term experiments have shown that zero tillage with crop residue reduces soil bulk density in the surface layer and improves root proliferation, resulting in improved N uptake and grain-filling efficiency (7, 8). This may explain why test weight remained statistically stable across tillage systems, as grain weight is largely governed by genotype and grain-filling duration, rather than tillage-induced changes alone (9, 10).

The marked yield advantage under hand weeding corroborates recent findings emphasising the critical importance of early-season weed control in wheat. Studies indicate that the first 30–45 DAS constitute the critical period of crop-weed competition, during which unchecked weed growth can reduce wheat yields by 30–60 % (11). Effective manual weeding ensures complete removal of both grassy and broad-leaved weeds, leading to improved light interception, higher photosynthetic efficiency and better assimilate translocation toward reproductive sinks.

Among the chemical weed management practices, the superior performance of SS + MSM aligns with recent evidence highlighting the effectiveness of herbicide mixtures with multiple modes of action. Sequential or tank-mix applications have been shown to provide broad-spectrum weed control, delay herbicide resistance and improve yield stability in wheat-based systems (12, 13). Specifically, SS-based combinations effectively suppress *Phalaris minor* and associated broad-leaved weeds, which are dominant yield-reducing species in North Indian wheat fields (14, 15).

The significantly lower yield attributes and grain yield under the weedy check highlight the severe impact of weed interference on crop growth (Table 4). Recent studies confirm that weed competition reduces leaf area index, radiation use efficiency and dry matter accumulation, ultimately leading to poor spike development and reduced grain number (15, 16). Higher weed index values under untreated plots reflected inefficient assimilate partitioning and excessive depletion of soil nutrients by weeds, particularly N and P.

Residue-mediated weed suppression may have also contributed to improved crop performance under zero tillage with residue retention. Surface-retained residues act as a physical and allelopathic barrier, reducing weed seed germination and early weed emergence (14). This synergistic interaction between conservation tillage and weed management has been increasingly recognised as a cornerstone of climate-resilient wheat production systems (17, 18).

Table 3. Effect of tillage and weed management on wheat yield components (Pooled 2022–24)

Treatment	No. of spikes per m^2	No. of grains per spike	Test weight (g)
Main plots: Tillage operations			
CT	238.05	44.07	40.18
ZT	250.76	47.20	40.95
ZT + R	256.45	49.08	41.20
SEm (±)	3.55	0.84	0.58
C.D (p = 0.05)	13.95	3.29	NS
Sub plots: Weed management practices			
Clodinafop propargyl + Metsulfuron methyl (60 + 4) g	249.01	47.80	40.84
Sulfosulfuron + Metsulfuron methyl (30 + 2) g	270.36	49.59	41.81
Mesosulfuron methyl + Iodosulfuron methyl sodium (12 + 2.4) g	256.98	49.16	41.32
Clodinafop propargyl + Metribuzin (54 + 120) g	245.79	44.96	39.83
Hand weeding at 20–25 and 40–45 DAS	280.31	50.79	42.54
Weedy check	188.08	38.40	38.31
SEm (±)	6.63	1.92	0.96
C.D (p = 0.05)	19.15	5.55	NS
Interaction	NS	NS	NS

DAS: days after sowing; CT: conventional tillage; ZT: zero tillage; R: residue; NS: Non-significant

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Table 4. Effect of tillage and weed management on wheat yield parameters (Pooled 2022–24)

Treatment	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Harvest index (%)
Main plots: Tillage operations			
CT	3170.50	4716.08	39.60
ZT	3400.94	4984.30	40.08
ZT + R	3640.86	5334.84	40.35
SEm (±)	65.05	114.22	0.32
C.D (p = 0.05)	255.41	448.48	NS
Sub plots: Weed management practices			
Clodinafop propargyl + Metsulfuron methyl (60 + 4) g	3593.09	5170.27	41.01
Sulfosulfuron + Metsulfuron methyl (30 + 2) g	3895.68	5408.76	41.88
Mesosulfuron methyl + Iodosulfuron methyl sodium (12 + 2.4) g	3713.00	5307.75	41.14
Clodinafop propargyl + Metribuzin (54 + 120) g	3236.94	5010.19	39.22
Hand weeding at 20–25 and 40–45 DAS	4045.17	5549.71	42.13
Weedy check	1940.73	3623.77	34.68
SEm (±)	57.72	97.89	0.90
C.D (p = 0.05)	166.71	282.73	2.60
Interaction	S	S	NS

DAS: days after sowing; CT: conventional tillage; ZT: zero tillage; R: residue; NS: Non-significant; S: Significant.

Overall, recent literature strongly supports the present findings that integrating zero tillage with residue retention and effective weed control strategies particularly hand weeding or diversified herbicide mixtures enhances yield components and productivity of wheat while ensuring long-term soil and system sustainability.

Crop-weed nutrient uptake under different tillage and weed management practices

The non-significant variation in N, P and K concentration (%) in wheat grain and straw across tillage and weed management treatments suggests that nutrient concentration is a relatively stable physiological trait, largely governed by genotype and grain-filling processes rather than agronomic interventions (Table 5). Similar observations have been reported in wheat and other cereal crops, where management practices primarily affected total nutrient uptake through changes in biomass and yield rather than altering nutrient concentration in plant tissues (16, 18). Accordingly, the statistically significant differences in total nutrient uptake (kg ha^{-1}) observed in the present study were mainly attributable to variations in grain and straw yields among treatments.

Among the tillage practices, zero tillage with paddy residue retention (ZTR) resulted in a significantly higher uptake of N, P and K than zero tillage without residue and conventional tillage. This enhanced uptake closely mirrored higher biomass production under ZTR, highlighting the role of residue retention in improving soil physical condition, microbial activity and nutrient mineralisation. Recent studies have demonstrated that surface residue retention increases soil organic carbon and microbial biomass, thereby enhancing nutrient availability and uptake efficiency in wheat (19, 20). These improvements translated into higher nutrient uptake despite similar nutrient concentrations, indicating that yield enhancement was the dominant factor.

Weed management practices exerted a pronounced effect on nutrient uptake by wheat. Hand weeding recorded the highest uptake of N (60.27 kg ha^{-1}), P (11.96 kg ha^{-1}) and K (21.77 kg ha^{-1}) in grain, with proportionate increases in straw uptake (Table 6). These values were statistically comparable with those obtained under SS + MSM and MSM + Iodosulfuron methyl sodium, suggesting that effective early-season weed suppression, rather than the specific control method, was the critical determinant of nutrient uptake. Several studies have shown that removal of weed competition during the critical period of 30–45 DAS significantly improves nutrient interception and crop productivity in wheat (21, 22).

The absence of significant differences in nutrient concentration (%) in weed biomass across treatments further confirms that nutrient depletion by weeds is primarily biomass-driven rather than concentration-driven (Table 7). Although hand-weeded plots exhibited relatively higher nutrient concentration in residual weed tissue, the total nutrient removal was negligible due to minimal weed biomass. Similar findings have been reported, emphasising that nutrient conservation in crops depends more on reducing weed biomass than altering weed nutrient composition (23, 24).

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Table 5. Effect of tillage and weed management practices on nitrogen (N), phosphorous (P) and potassium (K) content (%) in grain and straw of wheat (Pooled data of 2022–23 and 2023–24)

Treatment	Nitrogen content (%)		Phosphorus content (%)		Potassium content (%)	
Main plots: Tillage operations	**Grain**	**Straw**	**Grain**	**Straw**	**Grain**	**Straw**
CT	1.37	0.58	0.27	0.19	0.48	1.22
ZT	1.42	0.62	0.28	0.20	0.50	1.29
ZT + R	1.47	0.65	0.28	0.20	0.53	1.32
SEm (±)	0.04	0.02	0.004	0.004	0.01	0.04
C.D (p = 0.05)	NS	NS	NS	NS	NS	NS
Sub plots: Weed management practices						
Clodinafop propargyl + Metsulfuron methyl (60 + 4) g	1.42	0.62	0.27	0.19	0.50	1.27
Sulfosulfuron + Metsulfuron methyl (30 + 2) g	1.47	0.64	0.29	0.21	0.52	1.32
Mesosulfuron methyl + Iodosulfuron methyl sodium (12 + 2.4) g	1.46	0.63	0.28	0.20	0.51	1.31
Clodinafop propargyl + Metribuzin (54 + 120) g	1.39	0.59	0.26	0.18	0.49	1.24
Hand weeding at 20–25 and 40–45 DAS	1.49	0.68	0.30	0.22	0.54	1.34
Weedy check	1.31	0.55	0.25	0.17	0.47	1.20
SEm (±)	0.06	0.03	0.01	0.01	0.02	0.06
C.D (p = 0.05)	NS	NS	NS	NS	NS	NS
Interaction	NS	NS	NS	NS	NS	NS

DAS: days after sowing; CT: conventional tillage; ZT: zero tillage; R: residue; NS: Non-significant.

Table 6. Effect of tillage and weed management practices on nitrogen (N), phosphorous (P) and potassium (K) uptake (kg ha^{-1}) by wheat crop (Pooled data of 2022–23 and 2023–24)

Treatment	Nitrogen uptake (kg ha^{-1})		Phosphorus uptake (kg ha^{-1})		Potassium uptake (kg ha^{-1})	
Main plots: Tillage operations	**Grain**	**Straw**	**Grain**	**Straw**	**Grain**	**Straw**
CT	43.75	27.71	8.78	9.21	15.45	58.00
ZT	48.93	31.12	9.48	9.80	17.37	64.41
ZT + R	53.83	35.20	10.21	10.63	19.21	70.60
SEm (±)	1.20	0.89	0.12	0.16	0.23	1.47
C.D (p = 0.05)	4.69	3.51	0.47	0.63	0.90	5.77
Sub plots: Weed management practices						
Clodinafop propargyl + Metsulfuron methyl (60 + 4) g	51.03	32.29	9.87	10.04	17.92	65.92
Sulfosulfuron + Metsulfuron methyl (30 + 2) g	57.24	34.38	11.35	11.44	20.36	71.64
Mesosulfuron methyl + Iodosulfuron methyl sodium (12 + 2.4) g	53.94	33.46	10.35	10.55	18.83	69.53
Clodinafop propargyl + Metribuzin (54 + 120) g	44.72	29.75	8.46	9.09	15.95	61.78
Hand weeding at 20–25 and 40–45 DAS	60.27	38.06	11.96	12.00	21.77	74.52
Weedy check	25.82	20.11	4.93	6.16	9.21	42.62
SEm (±)	2.16	1.65	0.43	0.49	0.47	2.67
C.D (p = 0.05)	6.25	4.75	1.23	1.42	1.36	7.72
Interaction	NS	NS	NS	NS	NS	NS

DAS: days after sowing; CT: conventional tillage; ZT: zero tillage; R: residue; NS: Non-significant

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Table 7. Impact of tillage and weed management practices on nitrogen (N), phosphorous (P) and potassium (K) content (%) in weeds (Pooled data of 2022–23 and 2023–24)

Treatment	Nitrogen content (%)	Phosphorus content (%)	Potassium content (%)
Main plots: Tillage operations			
CT	0.53	0.16	0.31
ZT	0.53	0.17	0.32
ZT + R	0.54	0.18	0.32
SEm (±)	0.01	0.004	0.01
C.D (p = 0.05)	NS	NS	NS
Sub plots: Weed management practices			
Clodinafop propargyl + Metsulfuron methyl (60 + 4) g	0.52	0.17	0.31
Sulfosulfuron + Metsulfuron methyl (30 + 2) g	0.54	0.18	0.33
Mesosulfuron methyl + Iodosulfuron methyl sodium (12 + 2.4) g	0.53	0.17	0.32
Clodinafop propargyl + Metribuzin (54 + 120) g	0.52	0.16	0.30
Hand weeding at 20–25 and 40–45 DAS	0.58	0.20	0.34
Weedy check	0.49	0.16	0.28
SEm (±)	0.02	0.01	0.01
C.D (p = 0.05)	NS	NS	NS
Interaction	NS	NS	NS

DAS: days after sowing; CT: conventional tillage; ZT: zero tillage; R: residue; NS: Non-significant.

Assessment at 60 DAS, which corresponded to peak weed biomass, revealed that ZTR significantly reduced nutrient removal by weeds, recording the lowest uptake of N, P and K. This reduction can be attributed to mulch-induced suppression of weed emergence and growth, which limits early nutrient capture by weeds. In contrast, zero tillage without residue permitted greater weed proliferation and consequently higher nutrient depletion.

Among weed control treatments, hand weeding resulted in the lowest nutrient uptake by weeds, reflecting timely and effective removal of weed biomass during critical crop growth stages (Table 8). Among herbicidal treatments, SS + MSM and MSM + Iodosulfuron methyl sodium significantly minimised nutrient extraction by weeds due to their broad-spectrum weed control. Previous studies have reported that effective herbicide application can reduce nutrient removal by weeds by 60–80 % compared with untreated plots, thereby improving nutrient use efficiency in wheat (24).

Overall, the present findings clearly indicate that improved nutrient uptake under conservation tillage and effective weed management is primarily driven by enhanced biomass production and reduced weed competition, rather than changes in nutrient concentration. The integration of zero tillage with residue retention and efficient weed management thus represents a statistically robust and agronomically viable approach for improving nutrient use efficiency and sustainability in wheat-based cropping systems.

Conclusion

The results of the present investigation clearly indicate that the integration of zero tillage with paddy residue retention and the post-emergence application of Sulfosulfuron (SS) + Metsulfuron methyl (MSM) (30 + 2 g a.i. ha^{-1}) is an effective and agronomically sound strategy for weed management in wheat. This integrated approach significantly reduced weed density and dry biomass, thereby minimising crop weed competition during critical growth stages. Consequently, it improved in weed control efficiency (WCE), nutrient uptake and grain yield of wheat.

The synergistic effect of surface-retained paddy residues, which acted as a physical and ecological barrier to weed emergence, along with the broad-spectrum efficacy of the herbicide mixture, enhanced overall resource-use efficiency. Moreover, this practice contributed to improved system sustainability by reducing tillage intensity and optimising herbicide use.

Based on the consistent and statistically significant advantages observed, the adoption of zero tillage with residue retention combined with SS + MSM application is recommended for wheat cultivation under the agro-climatic conditions of the Southeast Alluvial Plain Zone of Bihar. This integrated weed and tillage management strategy provides a practical and sustainable approach for enhancing wheat productivity while supporting conservation-oriented and climate-resilient farming systems.

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Table 8. Impact of tillage and weed management practices on nitrogen (N), phosphorous (P) and potassium (K) uptake (kg ha^{-1}) by weeds (Pooled data of 2022–23 and 2023–24)

Treatment	Nitrogen uptake (kg ha^{-1})	Phosphorus uptake (kg ha^{-1})	Potassium uptake (kg ha^{-1})
Main plots: Tillage operations			
CT	10.16	3.11	5.93
ZT	8.20	2.68	4.82
ZT + R	6.42	2.20	3.74
SEm (±)	0.69	0.17	0.31
C.D (p = 0.05)	2.72	0.66	1.23
Sub plots: Weed management practices			
Clodinafop propargyl + Metsulfuron methyl (60 + 4) g	6.35	2.05	3.81
Sulfosulfuron + Metsulfuron methyl (30 + 2) g	5.14	1.65	3.14
Mesosulfuron methyl + Iodosulfuron methyl sodium (12 + 2.4) g	5.73	1.90	3.43
Clodinafop propargyl + Metribuzin (54 + 120) g	6.80	2.16	4.00
Hand weeding at 20–25 and 40–45 DAS	0.24	0.07	0.13
Weedy check	25.31	8.15	14.45
SEm (±)	1.04	0.27	0.63
C.D (p = 0.05)	3.00	0.77	1.82
Interaction	NS	NS	NS

DAS: days after sowing; CT: conventional tillage; ZT: zero tillage; R: residue; NS: Non-significant

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Authors' contributions

SK and BK conceptualised the study. SK and NP collected and analysed the data. NP, MKS, AK[1], AK[2], S, PK and DP contributed to the study design and drafted the manuscript. All authors have read and approved the final manuscript [AK[1] stands for Alisha Kumar and AK[2] stands for Anil Kumar].

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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