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Influence of tillage and weed management practices on yield and economics of wheat in an aerobic rice-wheat system

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Abstract
A field experiment was conducted at Palampur during *rabi* 2023-24 to assess the effect of tillage and weed management practices on wheat yield and economics in an aerobic rice-wheat system under a strip plot design with fifteen treatment combinations. Tillage treatments comprised conventional tillage in rice and wheat (CT-CT), conventional tillage in rice and zero tillage with residue retention in wheat (CT-ZTR), zero tillage in both rice and wheat crops (ZT-ZT), zero tillage without residue in rice and with residue in wheat (ZT-ZTR), and zero tillage with residue in rice and wheat (ZTR-ZTR), while weed management included herbicide application in rice and wheat (H-H), herbicide application followed by hand weeding in rice and wheat crops (IWM-IWM), and hand weeding in both crops (HW-HW). Results showed that ZTR-ZTR significantly enhanced plant height, dry matter accumulation, yield attributes, and wheat grain equivalent yield compared to CT-CT. In terms of profitability, the ZT-ZTR system recorded the maximum net return (₹1,00,577 ha^{-1}) and benefit-cost ratio (2.18). Among weed management practices, herbicide application (H-H: clodinafop 60 g ha^{-1} + metsulfuron-methyl 4 g ha^{-1}) outperformed integrated and manual weed control methods in improving growth, yield, and monetary returns. Overall, the combination of conservation tillage with herbicide application (ZTR+H-ZTR+H) emerged as the most efficient practice for improving both productivity and profitability in the aerobic rice-wheat system.

Keywords: Conservation tillage, conventional tillage, crop profitability, residue, weed management

Introduction
The rice-wheat cropping sequence (RWCS) is the world's largest agricultural production system, occupying about 12.3 million hectares in India with nearly 85 per cent of this area lying in the Indo-Gangetic Plains (IGP) (Sarkar *et al*., 2025) [10]. Traditionally, crop production in this region has depended on intensive tillage, which helps in soil preparation, weed removal, and regulating air-water movement. However, continuous reliance on conventional tillage has led to several problems such as soil erosion, loss of soil carbon, breakdown of aggregates, higher cultivation costs, and residue burning-related pollution (Singh *et al*., 2017) [14].
To overcome these issues, many countries are now adopting conservation agriculture, which focuses on minimum soil disturbance and residue retention (Islam *et al*., 2023) [5]. Zero tillage, a central practice under this approach, reduces land preparation costs and energy use but needs proper residue cover, balanced fertilization, and effective weed management (Dhanda *et al*., 2022) [2]. In conventional wheat farming under RWCS, weeds are suppressed by tillage through mechanical uprooting and burial. But with reduced tillage and surface residues, weed pressure generally increases, and residues may even block herbicides from reaching the soil. Weeds are a major challenge, causing yield losses of up to 40 per cent in wheat alone (Ghosh *et al*., 2021) [3]. Therefore, managing weeds effectively is critical for sustaining yields. Keeping the aforementioned things in mind, the present study was undertaken to explore conservation agriculture practices for improving wheat productivity and profitability in aerobic rice-wheat system.

Materials and Methods

The long term study aimed to evaluate the effect of different tillage and weed management practices on the yield and economics of wheat (*Triticum aestivum* L.). At the commencement of the trial in 2013, the soil was moderately acidic with a pH of 5.6, containing a medium level of organic carbon (8.4 g kg^{-1}) and moderate fertility status, with available nitrogen at 233 kg ha^{-1}, phosphorus at 17 kg ha^{-1}, and potassium at 193 kg ha^{-1}. During the cropping season, the mean weekly maximum temperature fluctuated between 13.6 and 28.5°C, while the minimum temperature ranged from 1.8 to 16°C. The total rainfall received over the crop growth period was 352.8 mm.

The field experiment was conducted using a strip plot design with three replications, comprising fifteen treatment combinations. The horizontal plots consisted of five tillage systems: i) conventional tillage in both rice and wheat (CT-CT), ii) conventional tillage in rice followed by zero tillage with residue retention in wheat (CT-ZTR), iii) zero tillage in both crops (ZT-ZT), iv) zero tillage in rice and zero tillage with residue retention in wheat (ZT-ZTR), and v) zero tillage with one-third residue retention in both rice and wheat (ZTR-ZTR). The vertical plots included three weed management practices: i) herbicide use in both crops (H-H), ii) integrated weed management in both crops (IWM-IWM), and iii) hand weeding twice in rice (20-25 and 40-45 DAS) and once in wheat (30 DAS) (HW-HW).

In aerobic rice, pre-emergence pretilachlor (0.9 kg ha^{-1}) followed by post-emergence bispyribac-sodium (25 g ha^{-1}) was applied, while wheat received clodinafop (60 g ha^{-1}) + metsulfuron-methyl (4 g ha^{-1}). IWM included a mix of manual and chemical weed control methods in rice, and in wheat, mustard was intercropped in a 2:1 replacement series along with weed control measures.

The present investigation was conducted during *rabi* 2023-24 at the Experimental Farm of Agronomy, College of Agriculture, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur, under a long-term trial initiated in 2013. The experimental site is located at 32°6' N latitude, 76°3' E longitude, and an elevation of 1290 m above mean sea level, representing the mid-hills sub-humid agro-climatic zone with a wet temperate climate.

Conventional tillage involved one ploughing, two harrowings, and leveling, while zero-till wheat was grown after paraquat application. Wheat variety ‘HPW 368’ was sown in early November at 20 cm spacing using 100 kg seed ha^{-1}, with fertilizer applied at 120:60:30 kg $N:P_2O_5:K_2O$ ha^{-1} through urea, single super phosphate and muriate of potash, respectively. Mustard variety ‘KBS 3’ was also sown as an intercrop in 2:1 row replacement series.

Wheat grain equivalent yield (WGEY) was estimated by converting the intercrop yield into wheat-equivalent terms using the prevailing market prices at the end of the season (MSP: wheat ₹2125 q^{-1} and mustard ₹5450 q^{-1}). The economic analysis was performed based on the actual cost of inputs and prevailing market prices of the produce. For statistical analysis, analysis of variance (ANOVA) suitable for the strip plot design was performed following the procedure described by Gomez and Gomez (1984) [4]. Treatment effects were tested for significance using the critical difference (CD) at the 5% confidence level.

Results and Discussion

Data pertaining to the influence of different tillage and weed management practices on plant height & dry matter accumulation, yield attributes, wheat grain equivalent yield, and cost of cultivation, gross return, net return & benefit-cost ratio has been depicted in Tables 1,2,3 & 4, respectively.

Plant height

Wheat cultivated under zero tillage with residue retention of the preceding rice crop exhibited significantly greater plant height at 60, 90, and 120 DAS compared with conventional tillage and zero tillage without residue treatments (Table 1). It can be attributed to its positive residual effects on soil properties, including improved moisture conservation, moderated soil temperature, and reduced nutrient losses, which collectively created a favorable soil environment for crop growth. These improved soil conditions contributed to enhanced vegetative development, as reflected in increased plant height. Comparable results have been documented by Shukla *et al*. (2023) [13] and Kumari *et al*. (2024) [7]. In contrast, weed management practices did not exert a significant influence on wheat plant height across the different stages of observation. Similarly, the interaction effect between tillage and weed management practices was non-significant, indicating that variation in plant height was predominantly governed by tillage practices rather than by weed control methods.

Dry matter accumulation

A cursory glance at the data presented in Table 1 revealed that both tillage and weed control measures significantly influenced the dry matter accumulation of wheat at periodic intervals during *rabi* 2023-24, however the interaction between these two factors remained non-significant. Among different tillage practices, ZTR-ZTR system (zero tillage cultivation of rice and wheat along with retention of crop residue as mulch), recorded the highest dry matter accumulation of wheat crop and remained statistically similar to other treatments consisting of zero till cultivation of wheat with crop residue incorporation (ZT-ZTR & CT-ZTR) at 30 DAS and with ZT-ZTR at all stages of observation. This superiority of residue-retained zero tillage systems can be attributed to the favorable soil micro-environment created by surface residues, which conserve soil moisture, improves soil structure, enhances soil organic carbon, and stimulates microbial activity, thereby facilitating better nutrient cycling and sustained crop growth. Several studies have confirmed that conservation tillage with residue retention enhances biomass accumulation in wheat by improving water and nutrient availability as well as root-soil interactions (Jat *et al*., 2019; Sapkota *et al*., 2021) [6, 9]. On the other hand, conventionally raised wheat crop (CT-CT) significantly reduced the dry matter accumulation of wheat crop, likely due to higher soil disturbance, accelerated organic matter decomposition, and reduced soil moisture retention capacity, all of which limit the physiological efficiency of wheat plants (Shukla *et al*., 2023) [13].

Yield attributes

Different tillage and weed management practices exerted a significant influence on the major yield-attributing traits of wheat, except 1000-grain weight (Table 2). Wheat sown under zero tillage with rice residue retention (ZTR-ZTR) produced a significantly higher number of effective tillers (289.3 m^{-2}) and grains per panicle (51.1), which were statistically comparable with ZT-ZTR system. In contrast, the lowest number of effective tillers (258.4 m^{-2}) and grains per panicle (46.4) were observed under conventional tillage (CT-CT), which behaved statistically alike to ZT-ZT. The enhanced status of residue-retained zero tillage treatments may be attributed to better soil moisture conservation, improved nutrient availability, and reduced weed pressure. These favorable conditions likely enhanced photosynthetic activity and facilitated greater assimilation and translocation of photosynthates towards the reproductive organs, thereby improving yield attributes. Conversely, conventional tillage exposed buried weed seeds to the soil surface, resulting in higher weed emergence and intense crop-weed competition. This competition reduced resource availability and limited photosynthetic efficiency, ultimately lowering the values of key yield components. Similar trends have been documented by Singh *et al*. (2017) [14] and Singh *et al*. (2024) [15].

Among different weed control strategies, chemical control (H-H) significantly enhanced the number of effective tillers and grains per panicle (293.7 & 51.4, respectively), compared to the integrated weed management (IWM) approach, which involved mustard intercropping in a 2:1 ratio along with chemical control and manual weeding (Table 2). The reduction in yield-attributing traits under IWM may be explained by the replacement of wheat rows with mustard, which decreased plant population and consequently lowered the values of key yield attributes (Biswas *et al*., 2020) [1]. Furthermore, the interaction between tillage systems and weed management practices did not exhibit any significant effect on wheat yield attributes.

Wheat grain equivalent yield

Different tillage and weed management practices had a significant effect on the wheat grain equivalent yield (WGEY) as presented in Table 2. The lowest WGEY (3.5 t ha^{-1}) was obtained under the CT-CT system, followed by ZT-ZT (3.8 t ha^{-1}), which was statistically comparable with CT-ZTR (3.9 t ha^{-1}). In contrast, the highest yield (4.3 t ha^{-1}) was recorded under ZTR-ZTR, where wheat was grown with zero tillage and rice residue retention. The yield advantage under conservation tillage practices can be attributed to reduced weed biomass and improved yield attributes such as effective tillers, grains per panicle, and 1000-grain weight which collectively contributed to superior crop performance and higher productivity compared to conventional tillage. The present findings are consistent with those of Singh *et al*. (2024) [15].

With respect to weed control methods, the post-emergence application of clodinafop @ 60 g ha^{-1} in combination with metsulfuron-methyl @ 4 g ha^{-1} (H-H) significantly enhanced wheat grain equivalent yield (WGEY), recording a 17.1 per cent increase over the integrated weed management (IWM-IWM) practice (Table 2). The relatively lower yield under IWM-IWM was primarily due to wheat-mustard intercropping in a 2:1 replacement series, which reduced the number of wheat rows and consequently lowered the total number of effective tillers per unit area. Furthermore, competition between wheat and mustard negatively affected grain development, resulting in fewer grains per panicle and reduced 1000-grain weight compared to sole wheat under other weed management strategies. In addition, the lower productivity of mustard further limited the overall system yield, thereby reducing the effectiveness of IWM in enhancing wheat grain equivalent yield (Biswas *et al*., 2020) [1].

The interaction between tillage and weed management practices exerted a significant influence on WGEY (Table 3). The lowest WGEY was recorded when hand weeding (30 DAS) was practiced under conventional tillage in wheat (CT-CT). In contrast, the highest WGEY was obtained under ZTR-ZTR, where zero tillage with residue retention was combined with the application of clodinafop 60 g ha^{-1} and metsulfuron-methyl 4 g ha^{-1}. This treatment outperformed all other combinations and proved significantly superior in enhancing productivity. The superior performance of this system can be attributed to improved soil conditions under residue-retained zero tillage, along with effective weed suppression achieved through post-emergence herbicides. Similar results were reported by Shekhar *et al*. (2014) [12], who observed higher wheat yields under zero tillage when post-emergence herbicides were applied.

Economics

Cost of cultivation

Perusal of the data given in Table 4 disclosed that cultivation of wheat under the zero tillage system (ZT-ZT) incurred the lowest cost of production (₹44,515 ha^{-1}), primarily due to the elimination of preparatory tillage operations. In contrast, conventional tillage (CT-CT) requires two to three preparatory tillage operations prior to sowing, which substantially increases production costs (Sharma *et al*., 2015) [11]. However, incorporation of crop residues in treatments such as CT-ZTR, ZT-ZTR, and ZTR-ZTR resulted in higher cultivation costs (₹46,165 ha^{-1}) owing to the additional labor required for residue handling and management. Economic returns from any crop or cropping system are strongly influenced by both variable costs and the magnitude of economic yields of crops (Jat *et al*., 2019) [6].

Among weed management strategies, the integrated approach involving wheat-mustard intercropping combined with the post-emergence application of clodinafop @ 60 g ha^{-1} and a hand weeding at 45-50 DAS (IWM-IWM) resulted in the highest cost of cultivation (₹50,621 ha^{-1}). The increased cost was primarily due to the additional labor requirement for hand weeding alongside herbicide use. Chemical weed control (H-H) recorded the lowest cost of cultivation ₹41,121 ha^{-1}) due to reduced labour cost (Shekhar *et al*., 2014) [12].

Gross returns

The highest gross returns (₹1,46,713 ha^{-1}) were achieved under the ZT-ZTR system, closely followed by CT-ZTR (₹1,41,961 ha^{-1}), whereas the lowest returns were obtained under CT-CT (₹1,27,486 ha^{-1}). These findings are consistent with the observations of Mishra *et al*. (2021) [8]. who also reported that conservation agriculture-based practices provide greater economic benefits compared to conventional tillage.

Among weed control measures, the chemical control treatment (H-H) provided the highest economic advantage, with gross returns of ₹1,41,327ha^{-1} (Table 4). This was followed by manual weeding (HW-HW) and integrated weed management (IWM-IWM). Similar trends were also noted by Stanzen *et al*. (2016) [16], who reported maximum gross returns under post-emergence herbicide application followed by manual weeding.

Net returns

The highest net returns (₹1,00,577 ha^{-1}) were recorded under the ZT-ZTR system, followed by CT-ZTR (₹95,796 ha^{-1}), however CT-CT system resulted in the lowest net returns (₹80,601 ha^{-1}) among tillage practices (Table 4).

In case of weed management treatments, chemical weed control treatment (H-H) recorded the highest net returns of ₹1,00,206 ha^{-1}, followed by manual weeding (HW-HW) and integrated weed management (IWM-IWM).

Benefit-cost ratio

A cursory glance at Table 4 revealed that maximum benefit-cost ratio (2.18) was recorded under ZT-ZTR, highlighting its superiority in terms of profitability over other tillage systems (Jat *et al*., 2019) [6]. While, in case of wed management practices, post-emergence application of clodinafop 60 g ha^{-1} and metsulfuron-methyl 4 g ha^{-1} (H-H) provided the highest benefit-cost ratio of 2.44 (Stanzen *et al*., 2016) [16].

Table 1: Effect of tillage and weed control treatments on plant height and dry matter accumulation of wheat at periodic intervals

	Plant height (cm)					Dry matter accumulation (g m^{-2})				
Treatments (Rice-Wheat)	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**	**At harvest**	**30 DAS**	**60 DAS**	**90 DAS**	**120 DAS**	**At harvest**
Tillage										
T_1: CT-CT	13.0	23.3	52.2	86.5	87.5	11.3	52.5	230.4	508.5	735.7
T_2: CT-ZTR	13.3	24.7	57.8	89.2	89.8	13.1	58.2	257.1	558.7	814.1
T_3: ZT-ZT	12.8	23.7	56.4	86.6	87.7	12.2	56.8	249.6	541.1	783.1
T_4: ZT-ZTR	13.5	25.5	58.1	89.6	90.1	13.6	61.9	269.8	573.8	831.9
T_5: ZTR-ZTR	13.9	26.9	60.7	91.4	91.8	14.1	65.8	279.7	589.6	850.4
S.Em±	0.4	0.9	1.3	1.4	1.2	0.5	1.3	5.8	10.0	11.4
LSD (P=0.05)	NS	2.8	4.2	4.6	4.0	1.7	4.2	19.0	32.5	37.0
Weed management										
W_1: H-H	13.0	25.5	57.8	89.5	90.1	13.6	66.8	284.2	605.5	878.0
W_2: IWM-IWM	13.6	26.4	59.5	90.7	91.4	9.1	46.1	198.2	427.7	593.1
W_3: HW-HW	13.2	24.8	56.9	88.8	89.4	12.9	64.4	276.4	593.6	852.6
S.Em±	0.3	0.5	1.0	1.1	0.9	0.4	1.0	4.2	6.4	8.0
LSD (P=0.05)	NS	NS	NS	NS	NS	1.5	3.9	16.6	25.0	31.4
Interaction (T*W)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

CT: Conventional tillage, ZT: Zero tillage, ZTR: Zero tillage + residues, H: Herbicides (clodinafop 60 g ha^{-1} + MSM 4 g ha^{-1}), IWM: Integrated weed management [Wheat + Mustard (2:1) + Herbicide (clodinafop 60 g ha^{-1}) + Hand weeding (45-50 DAS)], HW: Hand Weeding (30 DAS)

Table 2: Effect of tillage and weed control treatments on yield attributes and grain equivalent yield of wheat

Treatments (Rice-Wheat)	No. of effective tillers m^{-2}	No. of grains panicle^{-1}	1000 grain wt. (g)	Wheat grain equivalent yield (t ha^{-1})
Tillage				
T_1: CT-CT	258.4	46.4	43.53	3.5
T_2: CT-ZTR	270.2	47.9	44.11	3.9
T_3: ZT-ZT	262.6	47.6	43.87	3.8
T_4: ZT-ZTR	276.1	50.4	45.01	4.0
T_5: ZTR-ZTR	289.3	51.1	45.18	4.3
S.Em±	4.9	0.9	1.50	0.08
LSD (P=0.05)	16.0	2.8	NS	0.2
Weed management				
W_1: H-H	293.7	51.4	45.23	4.1
W_2: IWM-IWM	206.8	49.8	44.64	3.5
W_3: HW-HW	286.2	50.8	45.12	4.0
S.Em±	3.2	0.4	1.1	0.05
LSD (p=0.05)	12.5	1.5	NS	0.2
Interaction (T*W)	NS	NS	NS	S

CT: Conventional tillage, ZT: Zero tillage, ZTR: Zero tillage + residues, H: Herbicides (clodinafop 60 g ha^{-1} + MSM 4 g ha^{-1}), IWM: Integrated weed management [Wheat + Mustard (2:1) + Herbicide (clodinafop 60 g ha^{-1}) + Hand weeding (45-50 DAS)], HW: Hand Weeding (30 DAS)

Table 3: Interaction effect of tillage and weed control treatments on wheat grain equivalent yield (t ha^{-1})

Weed management treatments (Rice-Wheat)	Tillage and residue management treatments (Rice-Wheat)					
	CT-CT	**CT-ZTR**	**ZT-ZT**	**ZT-ZTR**	**ZTR-ZTR**	**Mean**
H-H	3.8	4.0	4.0	4.4	4.7	4.1
IWM-IWM	3.4	3.5	3.5	3.6	3.7	3.5
HW-HW	3.3	4.2	3.8	4.1	4.5	4.0
Mean	3.5	3.9	3.8	4.0	4.3	
LSD (P=0.05)	Tillage (T) = 0.2		Weed (W) = 0.2			
T*W Tillage at same level of Weed = 0.4 W*T Weed at same/different levels of Tillage = 0.4						

CT: Conventional tillage, ZT: Zero tillage, ZTR: Zero tillage + residues, H: Herbicides (clodinafop 60 g ha^{-1} + MSM 4 g ha^{-1}), IWM: Integrated weed management [Wheat + Mustard (2:1) + Herbicide (clodinafop 60 g ha^{-1}) + Hand weeding (45-50 DAS)], HW: Hand Weeding (30 DAS)

Table 4: Impact of tillage and weed management practices on economics of wheat

Treatment (Rice -Wheat)	Cost of cultivation (₹ ha^{-1})	Gross return (₹ ha^{-1})	Net return (₹ ha^{-1})	B:C
Tillage				
T_1: CT-CT	46885	127486	80601	1.72
T_2: CT-ZTR	46165	141961	95796	2.08
T_3: ZT-ZT	44515	137235	92720	2.08
T_4: ZT-ZTR	46165	146713	100577	2.18
T_5: ZTR-ZTR	46165	141718	95553	2.07
Weed management				
W_1: H-H	41121	141327	100206	2.44
W_2: IWM-IWM	50621	113562	62941	1.24
W_3: HW-HW	46196	137615	91419	1.98

CT: Conventional tillage, ZT: Zero tillage, ZTR: Zero tillage + residues, H: Herbicides (clodinafop 60 g ha^{-1} + MSM 4 g ha^{-1}), IWM: Integrated weed management [Wheat + Mustard (2:1) + Herbicide (clodinafop 60 g ha^{-1}) + Hand weeding (45-50 DAS)], HW: Hand Weeding (30 DAS)

Conclusion

The findings of the study demonstrated that zero tillage combined with surface retention of rice residues significantly improved yield attributes, wheat grain equivalent yield, monetary returns, and the benefit-cost ratio. In contrast, conventional tillage (CT-CT) resulted in 18.6 per cent reduction in grain equivalent yield and a 15.6 per cent decline in net returns compared to zero tillage with residue retention (ZTR-ZTR). Among weed management options, post-emergence application of clodinafop 60 g ha^{-1} together with metsulfuron-methyl 4 g ha^{-1} proved most effective, as it enhanced plant height and yield attributes, thereby leading to higher economic returns. The integration of conservation tillage with efficient chemical weed management emerged as the most promising strategy to maximize both productivity and profitability in the aerobic rice-wheat system. Based on these results, the adoption of zero tillage with residue retention in combination with herbicide application (ZTR+H-ZTR+H) is recommended for optimizing yield and economic benefits under aerobic rice-wheat cropping system.

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