



RESEARCH ARTICLE

Optimising irrigation and conservation tillage for enhanced wheat yield and profitability in Eastern India

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Abstract

Wheat a vital cereal crop globally, but conventional practices like chemical fertiliser reduction and intensive tillage can damage the environment. Conservation tillage offers a sustainable alternative to enhance wheat production. This study evaluated the effects of different tillage methods and irrigation schedules on wheat growth, yield and economic returns over 2 years. The M₃ tillage recorded superior yield traits, while M₂ produced the highest grain yield (4056.12 kg ha⁻¹) and M₁ the highest straw yield (5982.33 kg ha⁻¹). Irrigation at 25 % depletion of available soil moisture (DASM) (I₁) consistently improved yield characteristics and economic returns. The highest grain yield (4184.47 kg ha⁻¹) was observed under the combined M₁I₁ treatment in 2023–24. Over 2 years, M₁I₁ and M₂I₁ treatments yielded the highest gross and net returns, with M₂I₂ showing the best benefit-cost ratio (2.57). These results concluded that integrating conservation tillage with optimised irrigation schedules can significantly improve wheat productivity and profitability while supporting sustainable agriculture.

Keywords: benefit-cost ratio; economic returns; irrigation schedules; sustainable production; tillage methods

Introduction

Wheat (*Triticum aestivum* L.) is a crucial and economically beneficial rabi crop in northern India. It is the second most vital cereal crop after rice and is cultivated under diverse agroclimatic conditions. In India, wheat spans approximately 31.13 million hectares, achieving a production of 109.59 million tonnes with an average yield of 3421 kg ha⁻¹ during the 2021–2022 period (1). Wheat accounts for 20 % of the daily protein and calorie intake for 4.5 billion people. It is the foremost cereal worldwide and acts as a staple food for approximately one-third of the global population (2–3). Wheat productivity depends on financial and nonfinancial inputs, tillage methods, irrigation practices and agronomic management techniques. This crop is vital to the livelihoods of millions of Indian farmers and is cultivated primarily through intensive agricultural tillage practices. Conventional tillage alters soil structure and affects soil temperature, mechanical properties, macropore continuity and the capacity of the soil to retain water, as well as the growth and distribution of roots (4–6).

Wheat productivity in India, including in the state of Bihar, is often hindered by low moisture levels and traditional tillage methods. Plant growth relies heavily on the availability of water and nutrients, as crops with adequate water can effectively absorb nutrients from both the soil and fertilisers. Even minor water stress can disrupt plant growth, as any water shortage can interfere with

plant functions and life processes. These challenges in conventional farming practices ultimately lead to reduced crop yields. In several wheat-growing regions, the overuse and mismanagement of groundwater have resulted in a declining water table and environmental degradation (7). These challenges underscore the importance of adopting conservative agricultural practices to ensure sustained productivity, profitability and soil health (8). Conservation tillage, a method that involves leaving about 30 % of the previous crop's residue on the field before and after planting the next crop, shows potential in conserving moisture for future crops. This approach enhances water infiltration and retention in the soil, minimises evaporation and improves nutrient balance and availability, thereby boosting water-use efficiency (WUE). There is a significant gap in research concerning the integration and systematic assessment of irrigation methods, especially within conservation tillage systems for wheat cultivation in northern India, including Bihar. Productivity in this area is often limited by moisture stress and traditional tillage practices. Although conservation tillage is recognised for its advantages in improving soil moisture retention, water-use efficiency and nutrient availability, there is a lack of empirical evidence on how to optimise irrigation schedules and water management in these systems to enhance both productivity and profitability. This study is unique in its thorough investigation of irrigation practices combined with conservation tillage techniques,

aiming to develop innovative strategies for moisture conservation that address water scarcity and soil health challenges, with the objective of sustainably increasing wheat yield and economic returns under the region's agroclimatic conditions. It supports nutrient uptake and enhances water productivity owing to a favourable soil water balance. Numerous studies conducted in India and globally have highlighted the role of conservation tillage in wheat farming in preserving soil moisture and reducing soil erosion and runoff. Sustainable soil management can be achieved through conservation tillage, high crop residue returns and crop rotation (9). Conservation tillage systems are effective in enhancing soil moisture conditions (10). By improving infiltration and soil water retention, reducing evaporation and enhancing nutrient balance and availability, conservation tillage can increase water-use efficiency (11). As a rabi crop, wheat experiences limited rainfall and requires 4–6 irrigations but cannot withstand prolonged soil moisture stress. Moisture stress affects photosynthesis and reduces the WUE and harvest index of plants (12–14). Therefore, there is an urgent need to develop innovative strategies to conserve soil moisture. To some extent, conservation tillage and irrigation practices have been implemented to assess their effectiveness in addressing these challenges.

Materials and Methods

An experiment was conducted at the research farm of Bihar Agricultural University in Sabour, Bhagalpur, Bihar, during the rabi seasons of 2023–2024 and 2024–2025. The soil at this location was classified as a sandy loam. The study employed a split-plot design (SPD), incorporating three main plot treatments and four sub-plot treatments, each replicated 3 times. The main plot treatments focused on different tillage methods: M_1 - conventional tillage, M_2 - zero tillage and M_3 - raised bed method. The subplot treatments explored various irrigation strategies: (I_0) rainfed (no irrigation), (I_1) irrigation at 25 % depletion of available soil moisture (DASM), (I_2) irrigation at 40 % DASM and (I_3) irrigation at 50 % DASM which was depicted in Fig. 1. The sandy loam soil of the experimental field had a medium organic carbon content of 0.45 %, low available nitrogen at 194.98 kg ha⁻¹ and medium levels of available P₂O₅ and K₂O at 6.53 kg ha⁻¹ and 145.75 kg ha⁻¹, respectively, with a pH of 7.5. In both years, crop residue was removed from the zero-tillage plots. At the beginning of the main plot treatments, the initial organic carbon content was 0.40 %, with available nitrogen, phosphorus and K levels of 175, 15.4 and 156 kg ha⁻¹, respectively. The experiment spanned the academic years 2023–2024 and 2024–2025, consisting of 12 treatment combinations derived from the 3 main plots and 4 sub-plots. The entire setup was replicated in the second year to validate the findings. The wheat variety used was DBW 187, a high-yielding strain developed by IIWBR in Karnal. Karan Vandana (DBW 187) is the latest wheat variety released for irrigated, timely sown conditions in the northeastern plain's zones. Randomization principles were followed for the allocation of treatments among the experimental units. The analysis considered the effects of block borders, field borders, plot borders and irrigation channels.

Biometric evaluations were conducted to assess yield and its contributing traits by counting the number of spikes or ear heads per square meter. This involved selecting 1 m row sections at 5 random spots within the net plot area before harvesting. The

average number of ear heads per square meter was determined. Ten ear heads were randomly removed from the peduncle at the base of the rachis, their lengths were measured from the base of the lowest spikelet to the tip of the apical spikelet and the average length was recorded. To ascertain the number of grains per ear, 10 spikes were chosen and each was individually threshed to count the grains, with the average number of grains per spike calculated and expressed. After threshing each net plot, the harvested grains were sun-dried. A sample of 1000 grains was meticulously counted, weighed and recorded as the test weight in grams per 1000 grains. The grain harvested from each net plot was sun-dried, weighed using an electronic balance and expressed as grain yield in kg ha⁻¹ after threshing and winnowing. Straw yield was determined by subtracting the crop yield from the corresponding biological yield per plot and was expressed in kg ha⁻¹. Grain, straw and biological yields were used to compute the harvest index and harvest ratio (15).

Harvest index (HI)(%)=

$$\frac{\text{Grain Yield}}{\text{Biological (Grain+Straw)yield}} \times 100$$

An economic analysis of each treatment was conducted for both years of research, considering the prevailing prices of inputs and production. To evaluate the economic impact of the treatments, the specific costs of cultivation were considered. The economic outcomes of the treatments are presented as gross returns per hectare, net returns per hectare and benefit-cost ratio. Gross returns per hectare were calculated based on the minimum support price of wheat grain and the current market price of straw. The net returns from the different treatments were determined by subtracting the cost of cultivation from their corresponding gross returns using the following formula: Net returns (Rs. ha⁻¹) = gross return (Rs. ha⁻¹), cost of cultivation (Rs. ha⁻¹). The benefit-cost ratio (B:C) was calculated using the following formula: benefit-cost ratio = net return (Rs. ha⁻¹) / Cost of Cultivation (Rs. ha⁻¹). The data from various observations were statistically analysed using analysis of variance for split-plot design (SPD) (16). For significant 'F' tests, the critical difference (CD) was reported at a 5 % probability level.

Results and Discussion

Impact of tillage and irrigation in wheat on yield attributes characters

Table 1 represents the findings on how tillage and irrigation influence wheat yield attributes. Analysing the combined data from 2 years, it was found that zero tillage plots (M_2) had a significantly higher average of ear heads per square meter (291.09 m⁻²) compared to ridge plots (259.98 m⁻²) and were comparable to conventional tillage plots (290.04 m⁻²). In terms of irrigation, the highest average number of ear heads per square meter (288.79 m⁻²) was observed with irrigation at 25 % DASM (I_1), followed by 40 % DASM (I_2), both outperforming other treatments. The no-irrigation treatment (I_0) had the lowest count of ear heads (271.24 m⁻²). The average ear length was notably greater on ridges (11.47 cm) than that under zero tillage (10.80 cm) or conventional tillage (10.65 cm). This increase in ear length on raised beds may be due to its positive effects on soil physicochemical properties and the steady supply of essential

Table 1. Effect of tillage practices and irrigation regime on no. of ear head (m⁻²), ear length (cm), no. of grains per ear head, test weight (g) of wheat

Treatments		Ear head (m ⁻²)		Ear length (cm)		Grains ear ⁻¹		Test weight (g)		
		2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled
Tillage practices										
M ₂		288.13	291.96	290.04	10.35	10.96	10.65	41.22	40.45	40.83
		286.56	296.62	291.09	10.49	11.11	10.8	42.80	43.69	43.24
M ₃		255.68	264.29	259.98	11.15	11.80	11.47	43.07	43.99	43.53
SEm ±		4.67	4.91	4.79	0.16	0.16	0.16	0.69	0.70	0.69
CD (p = 0.05)		18.34	19.29	18.81	0.61	0.64	0.62	2.69	2.75	2.72
Irrigation regime										
I ₀		267.55	274.94	271.24	9.62	10.21	9.91	41.08	41.44	41.26
I ₁		284.99	292.60	288.79	12.03	12.69	12.36	43.42	43.75	43.58
I ₂		279.10	286.95	283.02	11.00	11.63	11.31	42.93	43.32	43.12
I ₃		275.53	282.69	279.11	10.00	10.61	10.30	42.01	42.34	42.17
SEm ±		3.52	3.57	3.54	0.16	0.17	0.16	0.52	0.52	0.52
CD (p=0.05)		10.44	10.61	10.52	0.48	0.51	0.49	1.55	1.55	1.55
Interaction		NS	NS	NS	S	S	NS	NS	NS	NS

M₁: Conventional tillage; M₂: Zero tillage; M₃: Raised bed method; I₀: Rainfed (no irrigation); I₂: Irrigation at 25 % DASM; I₃: Irrigation at 50 % DASM.

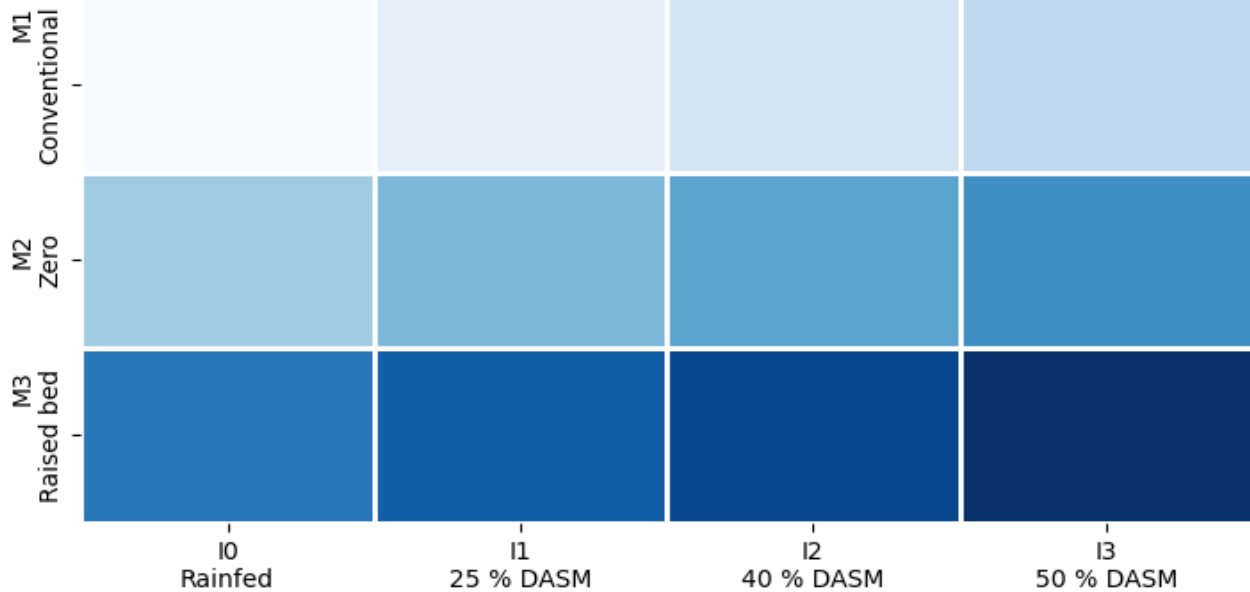
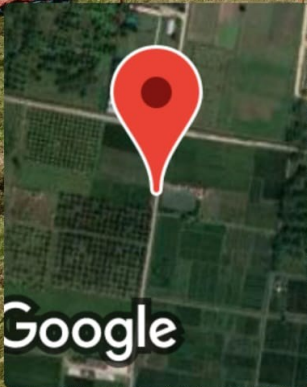


Fig. 1. Field layout showing soil sample collection locations and split-plot experimental design. Each subplot is marked with a unique colour to facilitate clear identification and separation of treatments. The grid layout provides a systematic representation of the experimental design with corresponding treatment labels for easy reference.

nutrients, facilitated by favourable hydrothermal conditions (17, 18). The benefits of conservation tillage practices are likely linked to enhanced physical, chemical and biological soil properties (19). Among irrigation methods, the longest ear lengths (12.36 cm and 11.31 cm) were recorded with irrigation at 25 % DASM (I_1) and 40 % DASM (I_2), respectively, both significantly better than other treatments. The shortest ear length was observed in the no-irrigation (I_0) treatment (9.91 cm). These findings align with those of other studies that also reported increased spike length with more irrigation (20, 21).

The number of grains per ear observed in the raised bed system (43.53) was comparable to that in zero tillage (43.24) and significantly surpassed the count in conventional tillage (40.83). This increase in grains per ear in the raised bed system could be attributed to enhanced soil characteristics-physical, chemical and biological-along with improved moisture retention and temperature regulation due to the residue cover on the surface, unlike in conventional tillage (22). Regarding irrigation methods, the (I_1) irrigation at 25 % DASM resulted in a significantly higher grain count per ear (43.58) than the no irrigation treatment (41.26). The reduced grain number in the absence of irrigation might be due to moisture stress, which could have expedited primordia development, leading to inadequate pollination, fertilisation and seed formation (23, 24). The test weight in the raised bed plot was notably higher (40.22) than that in zero tillage (39.08) and conventional tillage (37.82). The increased grain weight under conservation tillage practices can be linked to improved plant growth, nutrient uptake and photosynthate translocation for grain formation owing to higher moisture levels and superior soil properties. Among the irrigation treatments, (I_1) irrigation at 25 % DASM recorded the highest test weight (40.10 g) compared to no irrigation (38.13 g), likely due to enhanced nutrient absorption and translocation within the plants, facilitated by higher moisture content at critical growth stages and better movement of photosynthates towards the grains.

Effect of tillage methods and irrigation on grain and straw yield in wheat

Across a two-year period, the combined data indicated that plots managed with zero tillage achieved the highest grain yield, reaching 4056.12 kg ha⁻¹. This was notably greater than the yield from plots with conventional tillage, which was 3956.68 kg ha⁻¹ and those with raised bed treatment, which produced 3589.45 kg ha⁻¹ (Table 2). The superior yield in zero-tillage plots compared to conventional and raised-bed methods is likely due to enhanced soil moisture absorption during the crop growth period (25, 26). In terms of irrigation practices, the greatest grain yield of 4135.31 kg ha⁻¹ was recorded with irrigation at 25 % DASM (I_1), followed by 40 % DASM (I_2), both significantly outperforming other methods. The lowest grain yield was found in the no irrigation (I_0) treatment, at 3475.72 kg ha⁻¹ (27, 28). Tillage is known to improve soil structure and bolster plant resilience to water stress (29). Both tillage and irrigation are crucial management strategies that influence crop yield and the hydro-physical properties of the soil (30). The study also found that conventional tillage plots had the highest straw yield of 5982.33 kg ha⁻¹, significantly exceeding other treatments. Similarly, the highest straw yield among irrigation methods was 5864.25 kg ha⁻¹ with irrigation at 25 % DASM (I_1), followed by 40 % DASM (I_2), both significantly better than other treatments.

Interaction effect and economics

The study revealed that wheat plants in the plot with (I_1) irrigation at 25 % DASM and (M_3) ridge, termed M_{3I_1} , reached the maximum ear length of 13.39 cm during the 2023–2024 period, as shown in Fig. 2a and b marking the sole significant interaction for ear length. In the subsequent period of 2024–2025, wheat plants in the plot with (I_1) irrigation at 25 % DASM and raised bed (M_3), also M_{3I_1} , recorded the longest ear length of 14.09 cm. Fig. 3 to 8 provided evidence that the interaction between tillage and irrigation regime had a notable impact on both grain and straw yield in wheat. The variance analysis indicated that the interactions, zero tillage and various irrigation regimes had statistically significant effects. The variation in rainfall patterns over the 2 years contributed to the significance of the interaction between the measured parameters. In terms of grain yield, the results showed that wheat plants with (I_1) irrigation at 25 % DASM and (M_1) conventional tillage, or M_{1I_1} , achieved the highest yield of 4184.47 kg ha⁻¹ for 2023–2024. Similarly, in 2024–2025, wheat plants with (I_1) irrigation at 25 % DASM and zero tillage (M_2), or M_{2I_1} , attained the highest yield of 4623.77 kg ha⁻¹. Similar trends were observed for straw yield, particularly for M_{1I_1} in 2023–2024. Over the two-year period of 2023–2025, M_{2I_1} had the highest average grain yield of 4339.90 kg ha⁻¹, while M_{3I_1} had the highest harvest index mean of 42.14 %. Fig. 9 to 15 confirmed that the interaction between tillage and irrigation regime was also significant for economic outcomes. The variance analysis demonstrated that the interactions, zero tillage and different irrigation regimes were statistically significant. Regarding gross returns, wheat plants in the plot with (I_1) irrigation at 25 % DASM and (M_1) conventional tillage, or M_{1I_1} , had the highest gross returns of Rs. 123149 for 2023–2024. In 2024–2025, wheat plants in the plot with (I_1) irrigation at 25 % DASM and (M_2) zero tillage, or M_{2I_1} , achieved the highest gross return of Rs. 132486. Additionally, wheat plants in plots M_{2I_1} and M_{2I_2} had the highest net return and B:C ratio, respectively, for 2024–2025. For the average gross and net returns over the 2 years, 2023–2025, M_{1I_1} and M_{2I_1} had the highest returns, respectively. Furthermore, M_{2I_2} exhibited the highest mean B:C ratio of 2.57 over the 2 years, 2023–2025. Finally, data on treatment combinations regarding the cost of cultivation, gross returns, net returns and B:C ratio are presented in Table 3. The highest gross returns (Rs. 118375 ha⁻¹), net returns (Rs. 83933 ha⁻¹) and B:C ratio (2.43) was recorded when wheat was grown using zero tillage with irrigation at 25 % DASM. The lowest gross returns (Rs. 104184 ha⁻¹), net returns (Rs. 69742 ha⁻¹) and B:C ratio (2.02) was observed in raised bed tillage without irrigation.

Examining the average gross and net returns, as well as the B:C ratio over the 2023–2025 period, highlights the significant impact of tillage and irrigation techniques on wheat yield and profitability. The findings indicate that the M_{1I_1} and M_{2I_1} treatments yielded the highest average gross and net returns, respectively, underscoring the value of optimised management practices in enhancing economic outcomes. Notably, the M_{2I_2} treatment achieved the highest mean B:C ratio (2.57), reflecting superior economic efficiency. The greatest gross returns (Rs. 118375 ha⁻¹), net returns (Rs. 83933 ha⁻¹) and B:C ratio (2.43) was recorded under zero tillage with irrigation at 25 % DASM. This suggests that zero tillage, when paired with timely irrigation, can improve resource use efficiency and crop profitability, likely due to better soil moisture retention and reduced cultivation costs. Conversely, the lowest economic returns and B:C ratio (2.02) were

Table 2. Effect of tillage practices and irrigation regime on grain yield, straw yield and harvest index of wheat

Treatments	Grain yield (kg ha ⁻¹)			Straw yield (kg ha ⁻¹)			Harvest index (%)		
	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled
Tillage practices									
M ₁	3786.01	4127.36	3956.68	5831.11	6133.56	5982.33	39.29	40.15	39.72
M ₂	3758.33	4353.92	4056.12	5652.30	6003.57	5827.93	39.90	42.01	40.95
M ₃	3237.75	3941.16	3589.45	4662.21	5424.21	5043.21	41.01	42.08	41.54
SEm ±	68.35	73.15	70.75	102.20	93.68	97.94	0.63	0.64	0.63
CD (p=0.05)	268.36	287.24	277.8	401.31	367.82	384.56	2.49	2.51	2.5
Irrigation regime									
I ₀	3202.41	3749.03	3475.72	4966.02	5693.72	5329.87	39.31	39.71	39.51
I ₁	3887.21	4383.42	4135.31	5744.12	5984.38	5864.25	40.36	42.30	41.33
I ₂	3748.84	4264.24	4006.54	5542.55	5904.24	5723.39	40.34	41.95	41.02
I ₃	3537.66	4166.55	3852.10	5274.81	5832.78	5553.79	40.25	41.70	40.97
SEm ±	48.62	38.32	43.47	36.07	63.50	49.79	0.31	0.33	0.32
CD (p=0.05)	144.45	113.85	129.15	107.17	188.68	147.92	0.93	0.97	0.95
Interaction	S	S	S	S	NS	NS	S	NS	S

M₁: Conventional tillage; M₂: Zero tillage; M₃: Raised bed method; I₀: Rainfed (no irrigation); I₂: Irrigation at 25 % DASM; I₃: Irrigation at 50 % DASM.

Table 3. Effect of tillage practices and irrigation regime on benefit-cost (B:C) ratio of wheat

Treatments	Cost of cultivation (Rs. ha ⁻¹)			Gross Return (Rs. ha ⁻¹)			Net return/Benefit (Rs. ha ⁻¹)			B:C Ratio		
	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled	2023-24	2024-25	Pooled
MAIN PLOT – Tillage practices												
M ₁	38846	38846	38846	112448	121470	116959	73602	82624	78113	1.89	2.12	2.05
M ₂	34442	34442	34442	110945	125804	118375	76503	91362	83932.5	2.22	2.65	2.43
M ₃	34442	34442	34442	94541	113827	104184	60099	79385	69742	1.74	2.31	2.02
SEm ±	-	-	-	1597	1587	1592	1597	1587	1592	0.04	0.05	0.04
CD (p = 0.05)	-	-	-	6272	6232	6252	6272	6232	6252	0.18	0.18	0.18
SUB-PLOT – Irrigation regime												
I ₀ - Rainfed (No irrigation)	33934	33934	33934	95283	110947	103115	61349	77013	69181	1.81	2.28	2.04
I ₁ - Irrigation at 25 % DASM	37582	37582	37582	114239	126357	120298	76657	88775	82716	2.04	2.37	2.20
I ₂ - Irrigation at 40 % DASM	36366	36366	36366	110187	123334	116761	73821	86968	80394.5	2.04	2.41	2.22
I ₃ - Irrigation at 50 % DASM	35758	35758	35758	104202	120828	112515	68444	85070	76757	1.92	2.38	2.15
SEm ±	-	-	-	1133	936	1034.5	1133	936	1034.5	0.03	0.03	0.03
CD (p = 0.05)	-	-	-	3367	2781	3074	3367	2781	3074	0.09	0.08	0.08
Interaction	-	-	-	S	S	S	NS	S	S	NS	S	S

M₁: Conventional tillage; M₂: Zero tillage; M₃: Raised bed method; I₀: Rainfed (no irrigation); I₂: Irrigation at 25 % DASM; I₃: Irrigation at 50 % DASM.

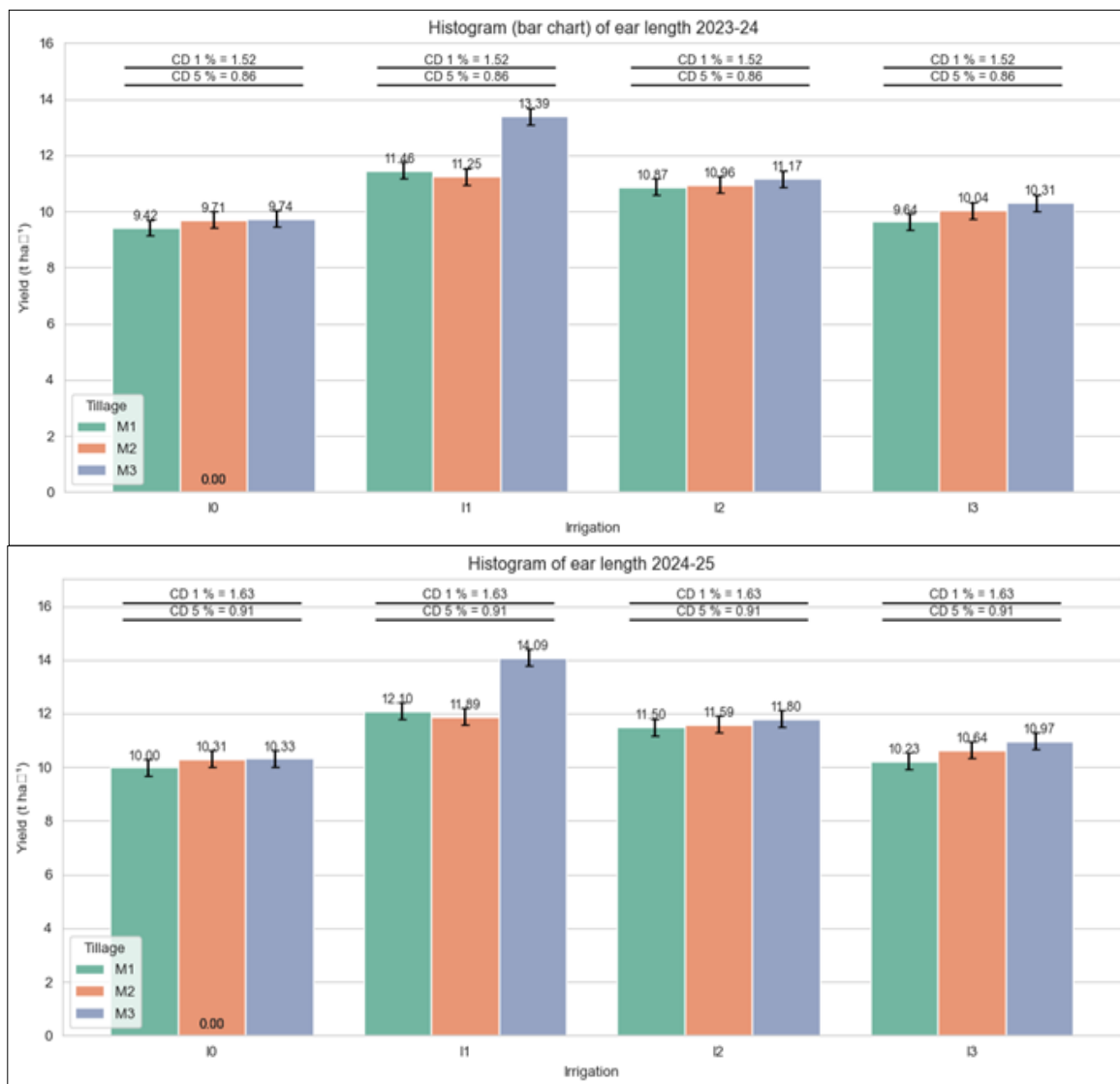


Fig. 2. Interaction effect of tillage practices and irrigation regimes on ear length of wheat during (a) 2023–2024; (b) 2024–2025. Bars represent treatment means, whiskers indicate $\pm$ standard error of mean (SEM) and horizontal caps denote the critical difference (CD) at 5 % and 1 % levels of significance.

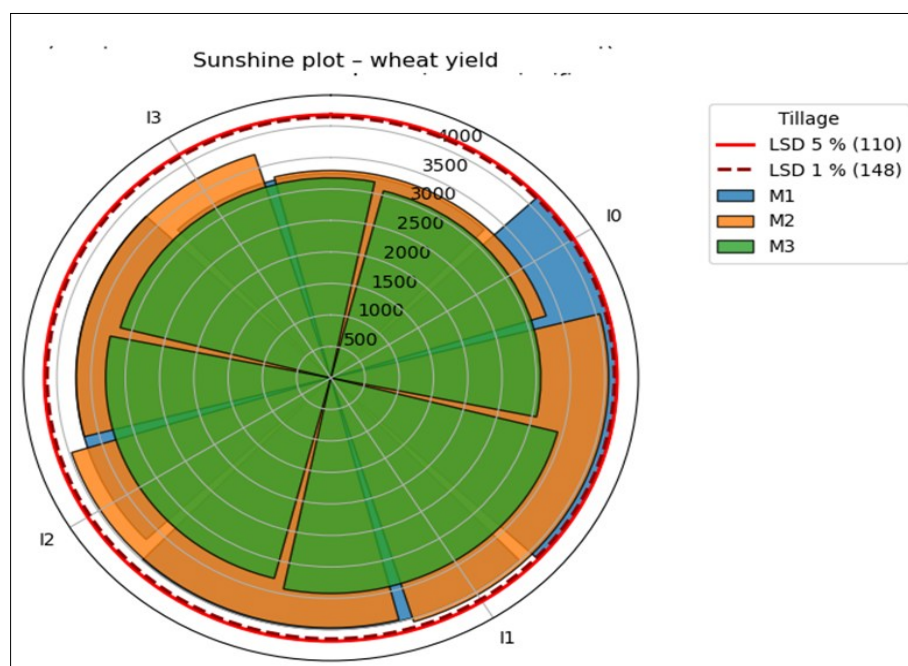


Fig. 3. Interaction effect of tillage practices and irrigation regimes on grain yield (kg ha^{-1}) during 2023–2024 illustrated using a polar sunshine plot. Each ray represents an irrigation regime and is divided into coloured sectors corresponding to different tillage methods. The red circles indicate significance thresholds, where the solid circle represents the least significant difference (LSD) at 5 % and the dashed circle represents LSD at 1 % level of significance.

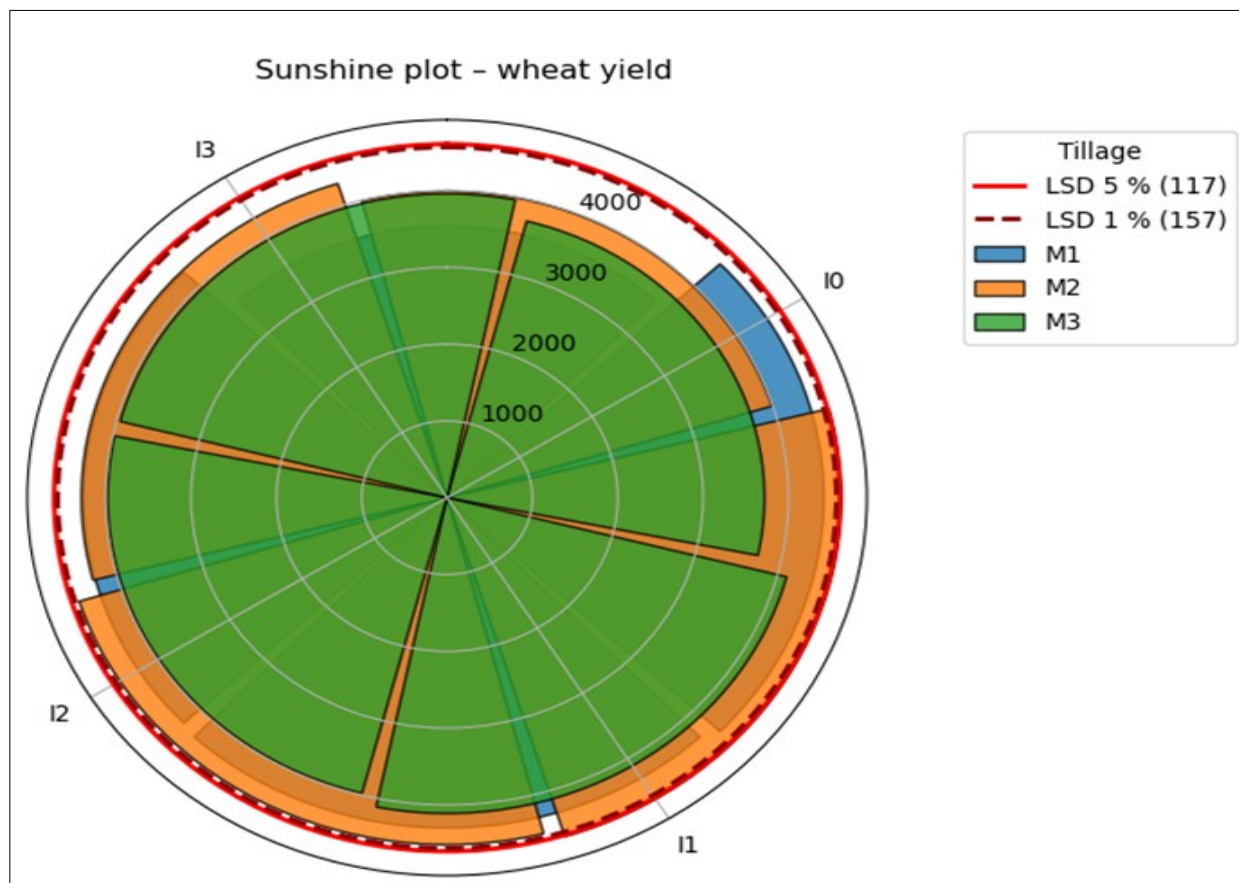


Fig. 4. Interaction effect of tillage practices and irrigation regimes on grain yield (kg ha^{-1}) during 2024–2025 illustrated using a polar sunshine plot. Each ray corresponds to an irrigation regime (I_0 to I_3) and each ray is divided into coloured sectors representing tillage methods (M_1 , M_2 and M_3). The solid red circle indicates the least significant difference (LSD) at 5 % level of significance, whereas the dashed dark red circle indicates LSD at 1 % level of significance.

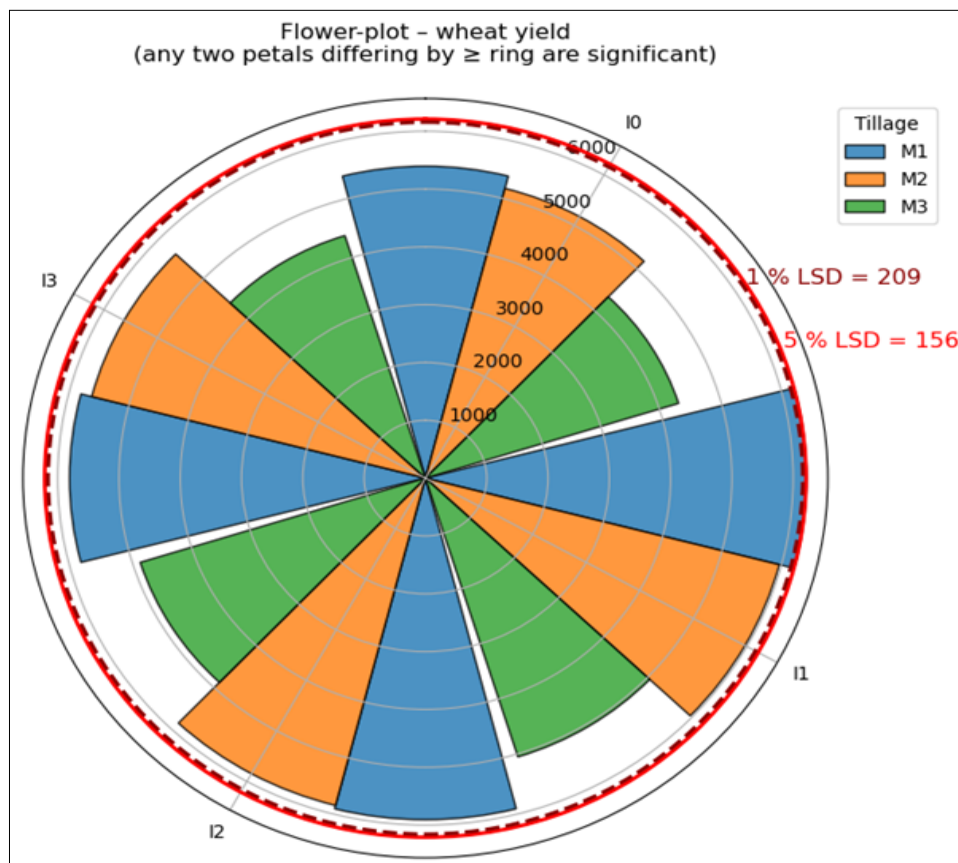


Fig. 5. Interaction effect of tillage practices and irrigation regimes on straw yield (kg ha^{-1}) during 2023–2024 represented using a flower-plot visualization. Each ray represents an irrigation regime (I_0 to I_3) and coloured petals within each ray represent tillage methods (M_1 , M_2 and M_3). The solid red circle indicates the least significant difference (LSD) at 5 % level of significance, while the dashed dark red circle indicates LSD at 1 % level of significance.

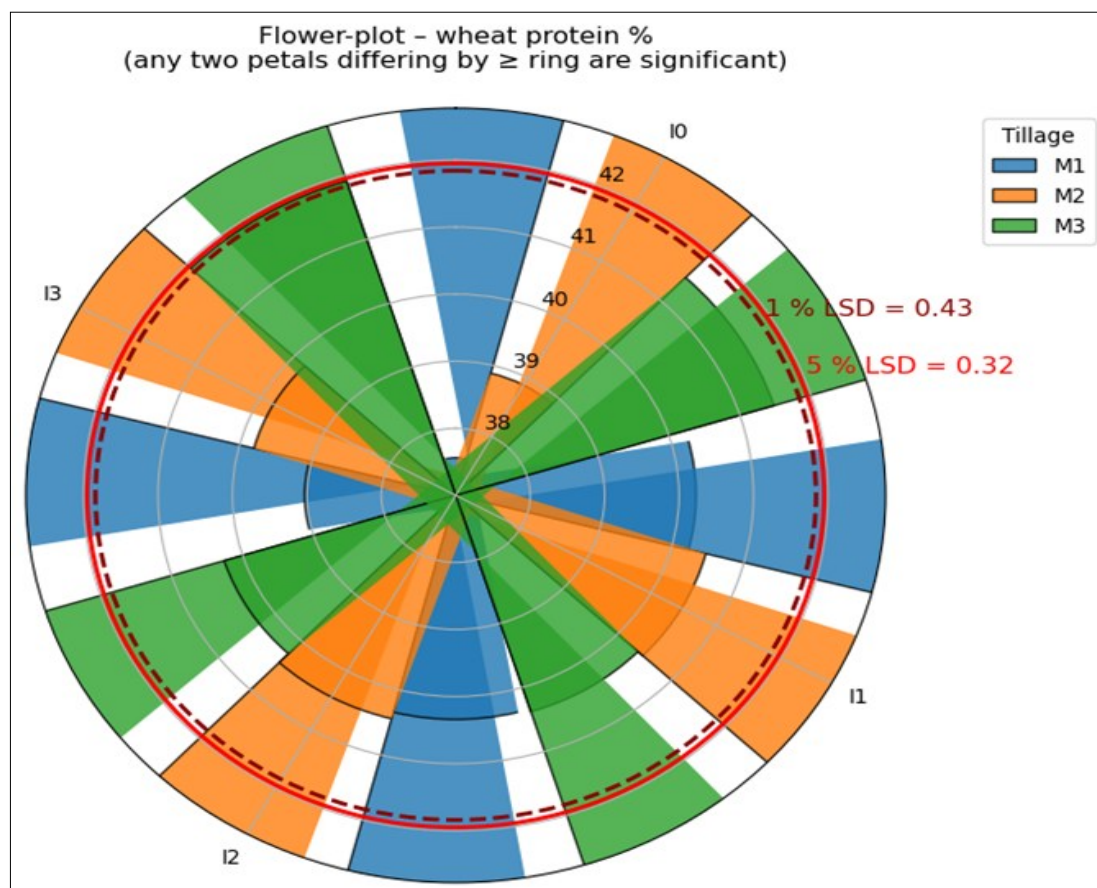


Fig. 6. Interaction effect of tillage practices and irrigation regimes on harvest index during 2023–2024 represented using a flower-plot format. Each ray corresponds to an irrigation regime (I_0 to I_3) and coloured petals within each ray represent tillage methods (M_1 , M_2 and M_3). The solid red circle indicates the least significant difference (LSD) at 5 % level of significance, while the dashed dark red circle indicates LSD at 1 % level of significance.

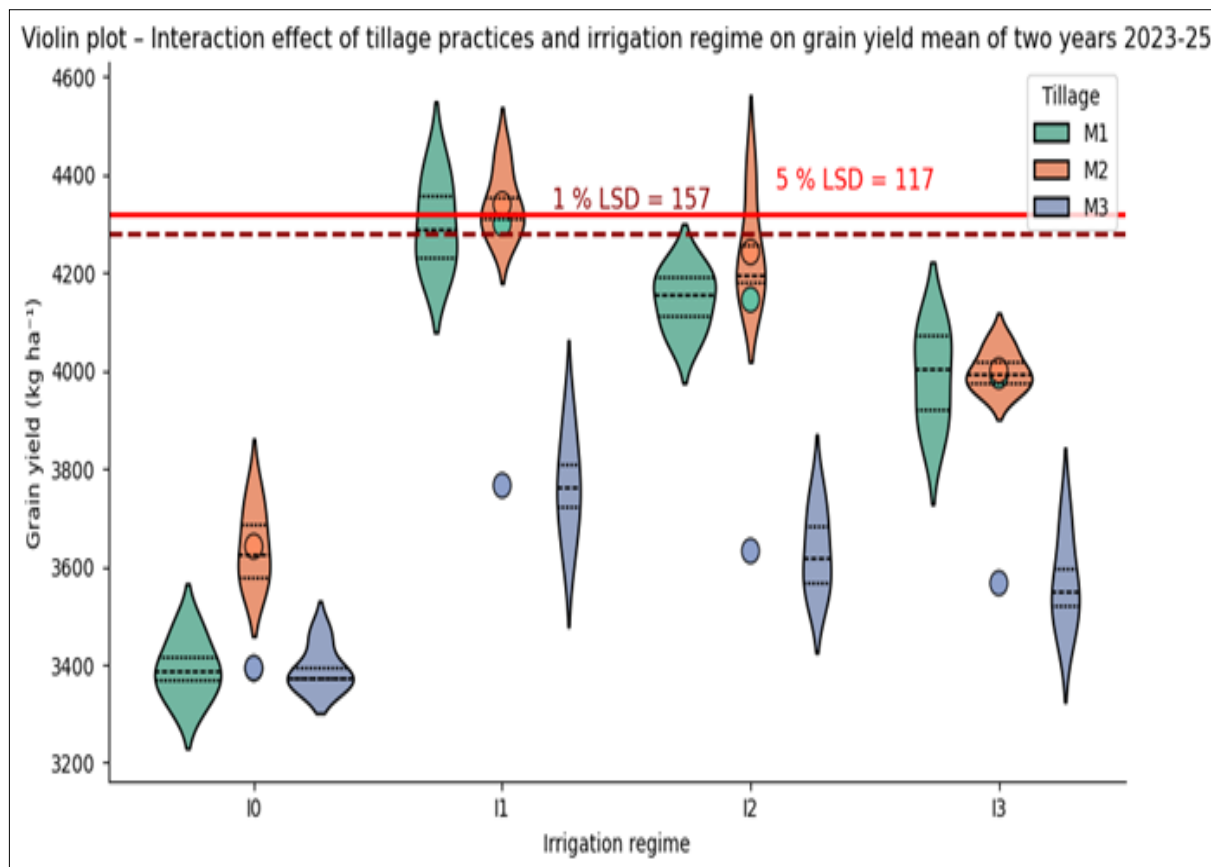


Fig. 7. Interaction effect of tillage practices and irrigation regimes on mean grain yield (kg ha^{-1}) over two years (2023–2025) represented using a violin plot with least significant difference (LSD) indicators. Each violin represents the distribution of replicates for each treatment, with the white dot indicating the median and the thick bar representing the interquartile range. The solid red horizontal line indicates LSD at 5 % level of significance, while the dashed dark red line indicates LSD at 1 % level of significance.

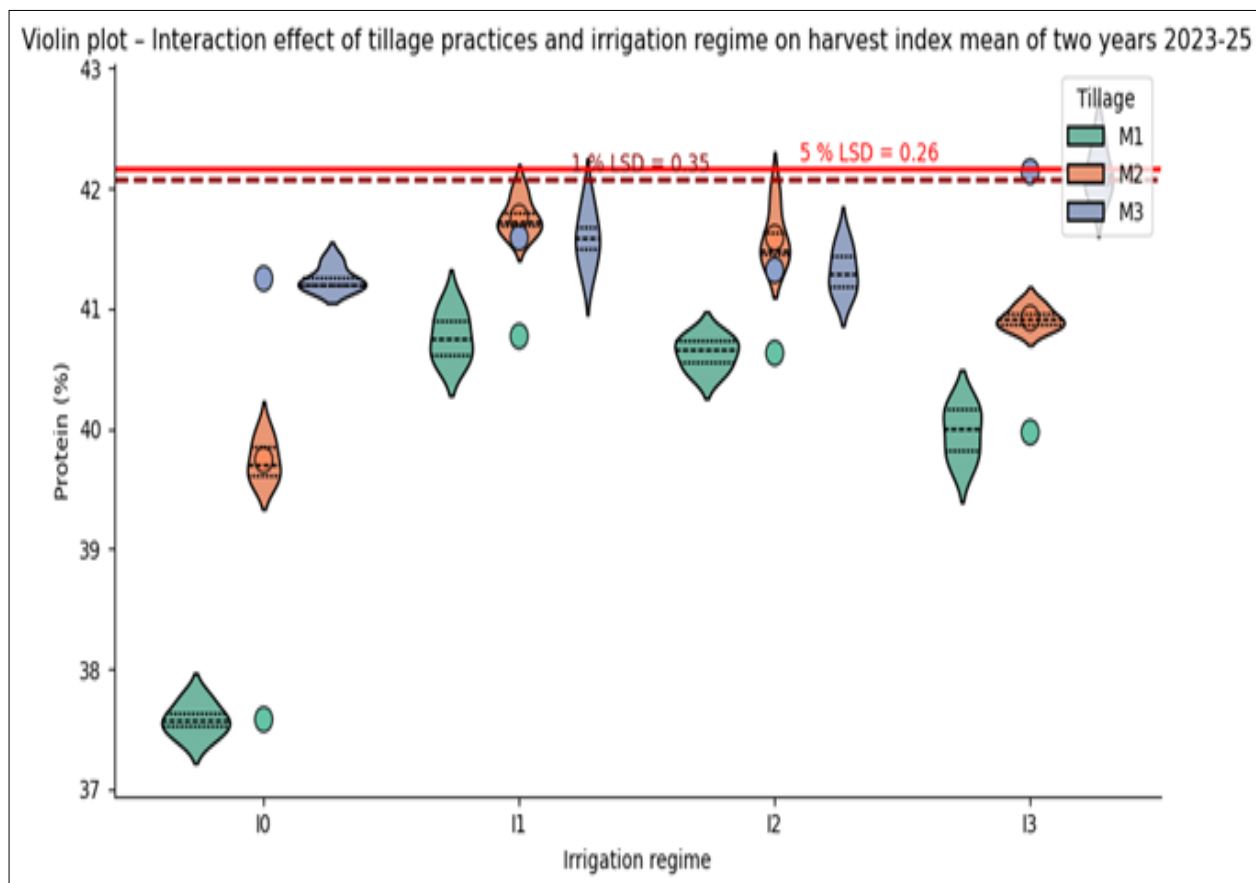


Fig. 8. Interaction effect of tillage practices and irrigation regimes on mean harvest index over the two-year period (2023–2025) represented using a violin plot with least significant difference (LSD) indicators. Each violin represents the distribution of replicates for each treatment, with the median and interquartile range indicated. The solid red and dashed dark red horizontal lines represent LSD at 5 % and 1 % levels of significance, respectively.

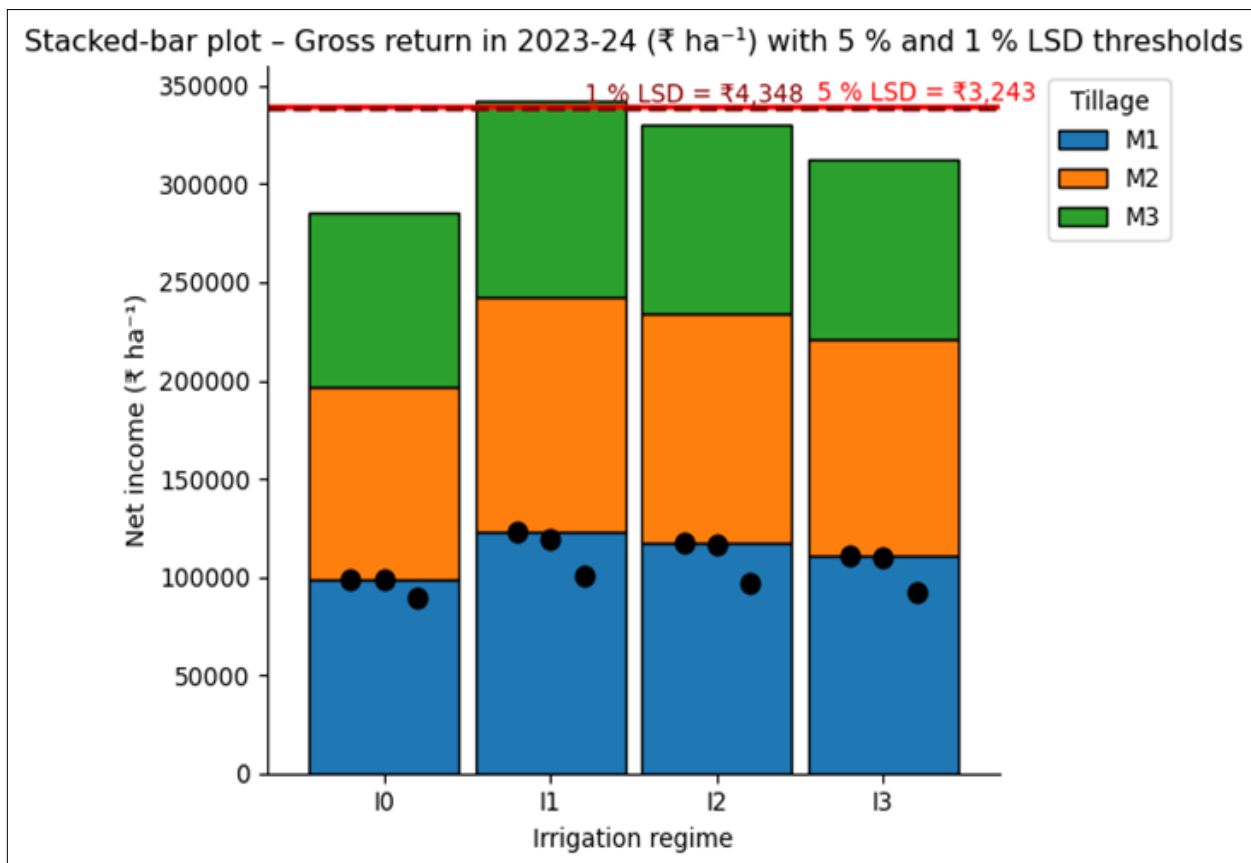


Fig. 9. Shows the interaction effect of tillage practices and irrigation regimes on gross return during 2023–2024 using a stacked bar chart with LSD indicators. Each bar represents an irrigation regime and the coloured segments represent tillage methods (M1, M2 and M3). The solid red line and dashed dark-red line indicate the 5 % and 1 % LSD levels, respectively. Differences between treatment means exceeding these lines are considered statistically significant, indicating the interactive effect of tillage and irrigation on gross return.

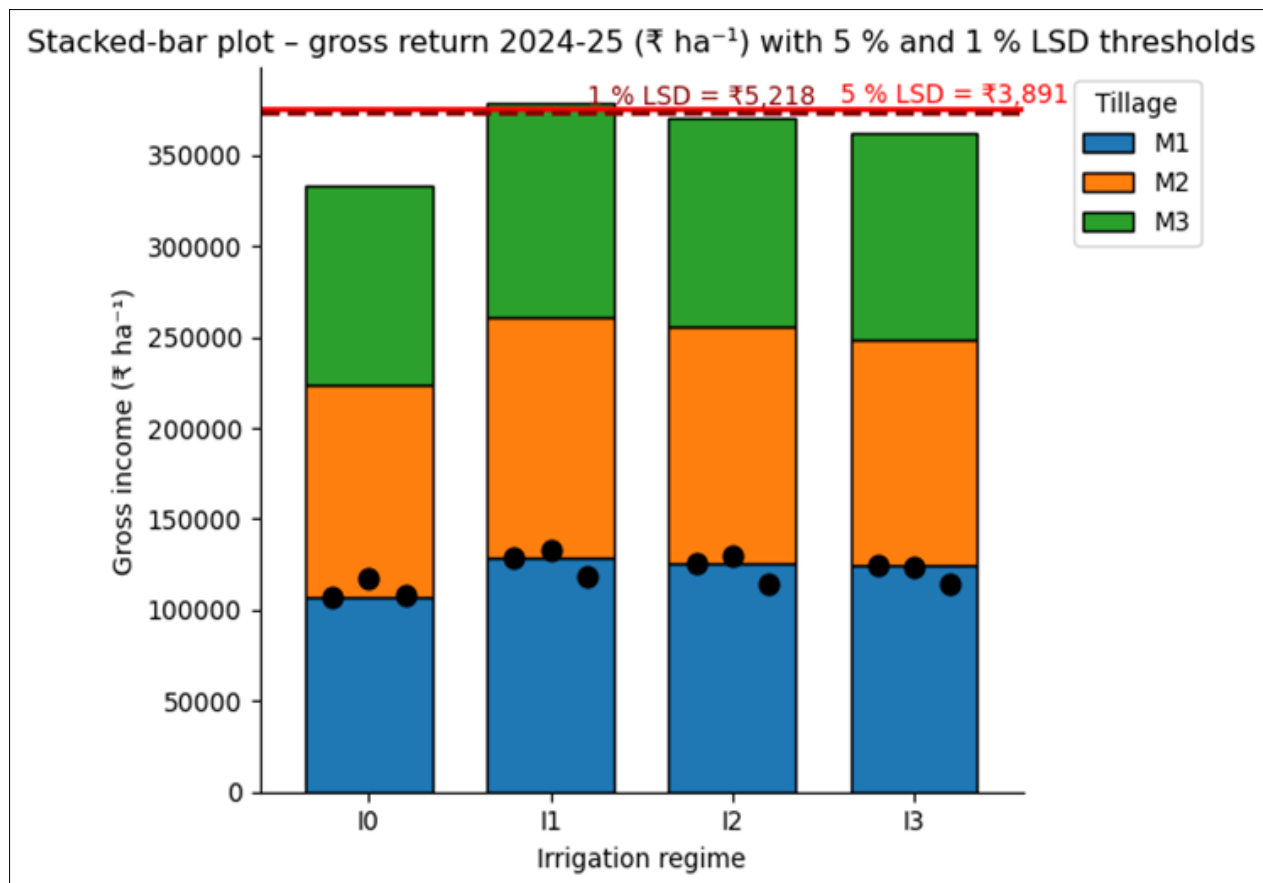


Fig. 10. shows the interaction effect of tillage practices and irrigation regimes on gross return for 2024–2025 using a stacked bar chart with LSD indicators. Each bar represents an irrigation regime and the coloured segments represent the tillage methods. The solid red and dashed dark-red horizontal lines indicate the 5 % and 1 % LSD levels, respectively. Differences between treatment means exceeding these lines are considered statistically significant, indicating the interactive effect of tillage and irrigation on gross return.

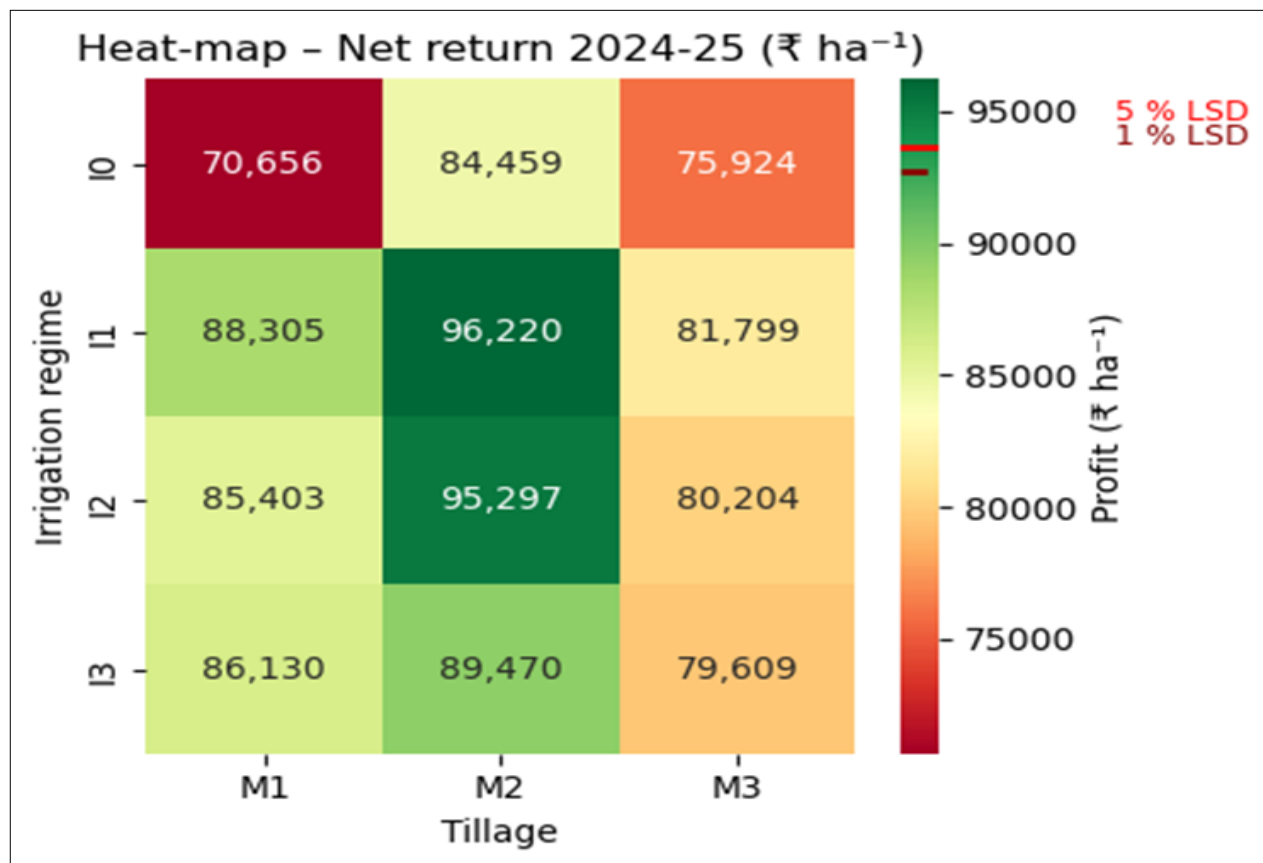


Fig. 11. Shows the interaction effect of tillage practices and irrigation regimes on net return for 2024–2025 using a heat map with LSD indicators. In the heat map, darker green shades represent higher net return, while darker red shades represent lower net return. The red and dark-red ticks on the colour bar indicate the 5 % and 1 % LSD levels, respectively. Differences in colour intensity exceeding these thresholds indicate statistically significant differences between treatments, showing the interactive effect of tillage and irrigation on net profitability.

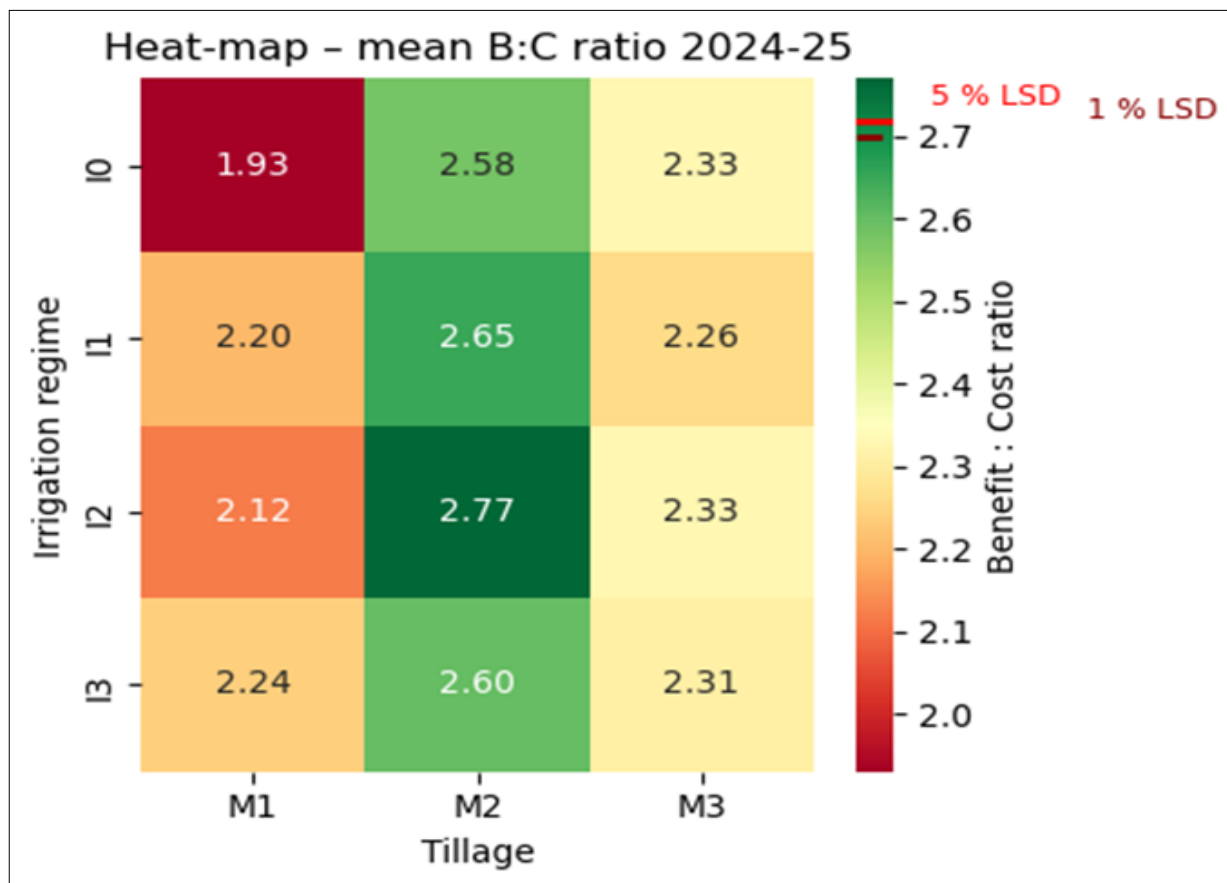


Fig. 12. Shows the interaction effect of tillage practices and irrigation regimes on the benefit–cost (B:C) ratio for 2024–2025 using a heat map with LSD indicators. Darker green shades represent higher B:C ratios, whereas darker red shades represent lower B:C ratios. The red and dark-red ticks on the colour bar indicate the 5 % and 1 % LSD levels, respectively. Differences in colour intensity exceeding these levels indicate statistically significant differences between treatments.

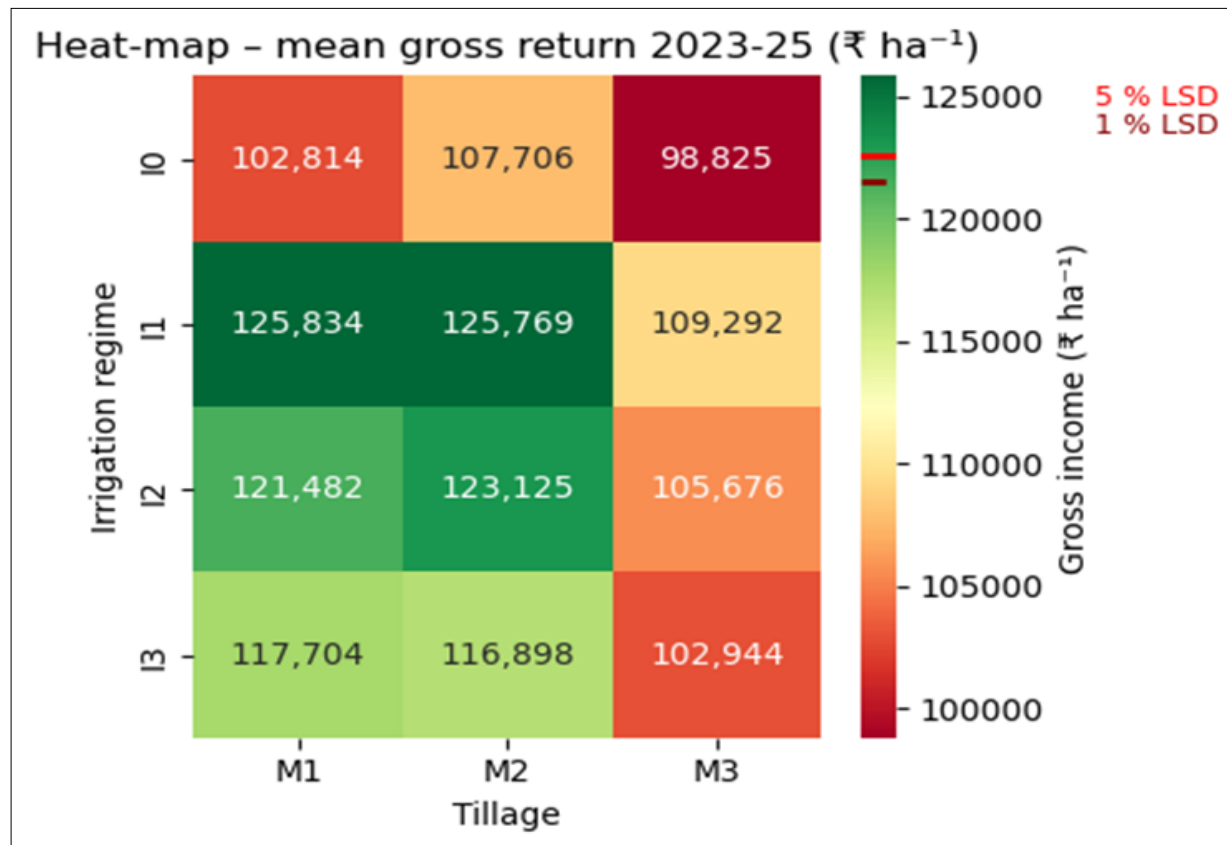


Fig. 13. Shows the interaction effect of tillage practices and irrigation regimes on the mean gross return over the two-year period (2023–2025) using a heat map with LSD indicators. Darker green shades represent higher gross return, whereas darker red shades represent lower gross return. The red and dark-red ticks on the colour bar indicate the 5 % and 1 % LSD levels, respectively. Differences in colour intensity exceeding these levels indicate statistically significant differences between treatments, showing the interactive effect of tillage and irrigation on mean gross return over the two-year period.

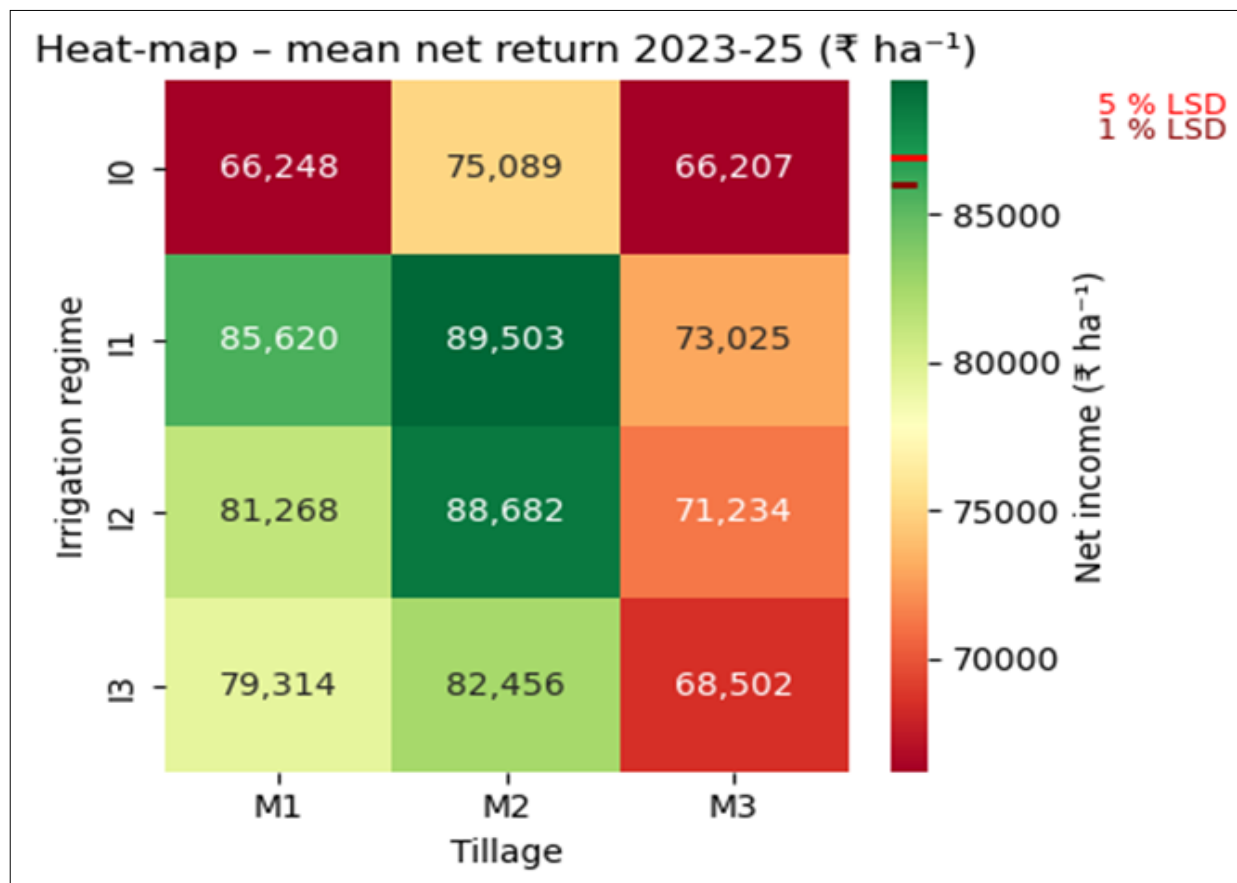


Fig. 14. Shows the interaction effect of tillage practices and irrigation regimes on the mean net return over the two-year period (2023–2025) using a heat map with LSD indicators. Darker green shades represent higher net return, whereas darker red shades represent lower net return. The red and dark-red ticks on the colour bar indicate the 5 % and 1 % LSD levels, respectively. Differences in colour intensity exceeding these levels indicate statistically significant differences between treatments, showing the interactive effect of tillage and irrigation on mean net return.

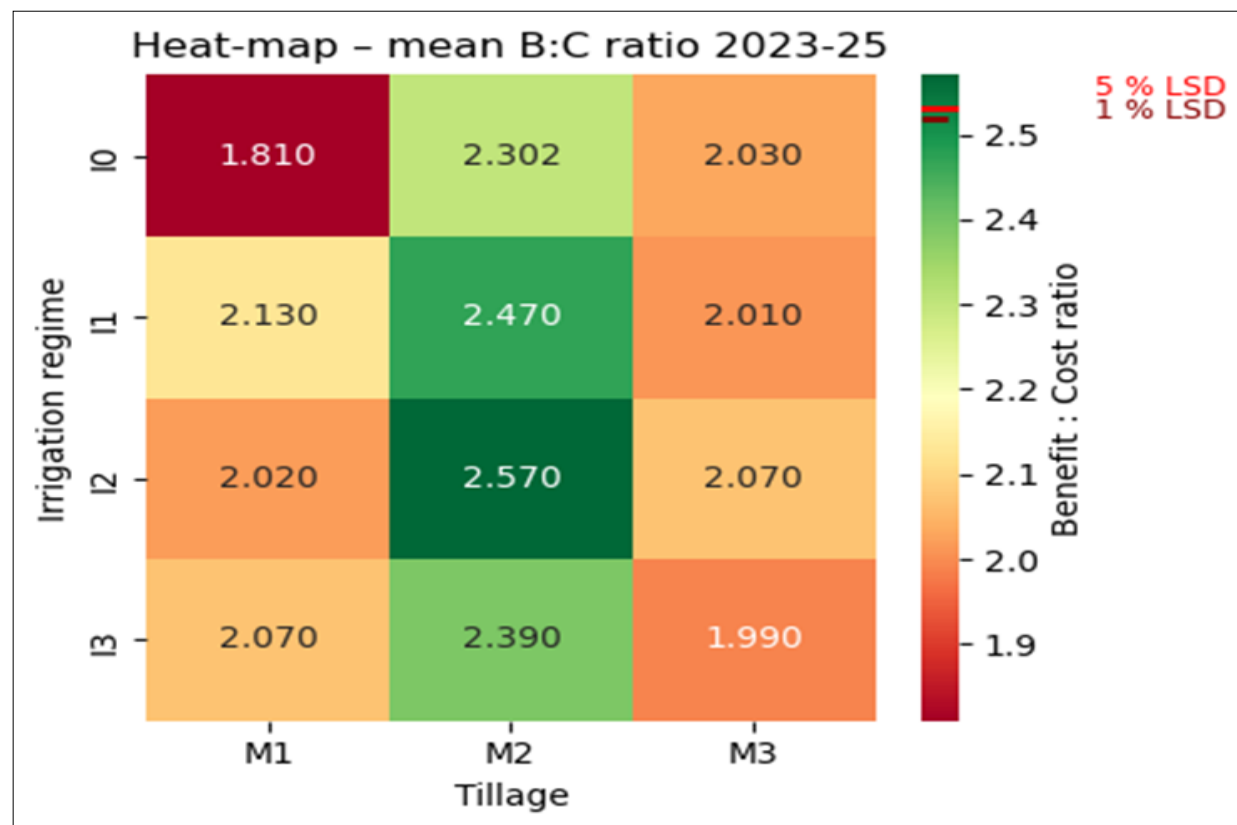


Fig. 15. Shows the interaction effect of tillage practices and irrigation regimes on the mean benefit–cost (B:C) ratio over the two-year period (2023–2025) using a heat map with LSD indicators. Darker green shades represent higher B:C ratios, whereas darker red shades represent lower B:C ratios. The red and dark-red ticks on the colour bar indicate the 5 % and 1 % LSD levels, respectively. Differences in colour intensity exceeding these levels indicate statistically significant differences between treatments, showing the interactive effect of tillage and irrigation on economic efficiency.

observed with raised bed tillage, indicating that this method may be less effective in the study's context. These results align with previous research emphasising the importance of conservation tillage and precise irrigation scheduling in semi-arid regions to optimise WUE and crop yield (31–34). For instance, they also showed that adaptive management practices considering climate variability can stabilise maize yields, paralleling the benefits of zero tillage and optimised irrigation in wheat production. Similarly, they emphasised the critical role of irrigation management in enhancing water use and biomass partitioning, reinforcing the economic advantages of the current study's irrigation treatments. Overall, combining zero tillage with suitable irrigation scheduling has emerged as a promising approach to boost wheat productivity and profitability in the Shivalik foothills and similar agroecological zones.

Conclusion

This research concludes that different tillage techniques and irrigation schedules have an impact on wheat yield characteristics, grain and straw production and economic outcomes over a 2 year period (2023–2025). Among the conservation tillage methods, zero tillage led to a greater number of ear heads per square meter compared to the raised bed approach and was comparable to conventional tillage. Irrigation at 25 % and 40 % DASM surpassed the results of no irrigation in terms of ear head per square meter, ear length, grain per ear and test weight. Raised-bed plots showed better ear length, grain per ear and test weight than plots managed with zero tillage and conventional tillage. Zero tillage achieved the highest grain yield ($4135.31 \text{ kg ha}^{-1}$), while conventional tillage resulted in the greatest straw yield ($5864.25 \text{ kg ha}^{-1}$). The highest grain and straw yields were recorded under irrigation at 25 % DASM. The combination of zero tillage and 25 % DASM irrigation yielded the highest gross returns, net returns (Rs 82716 ha^{-1}) and B:C ratio (2.20). Therefore, it can be determined that zero tillage, when combined with 25 % DASM irrigation, represents an economically viable and agronomically efficient practice for the Eastern Indo-Gangetic Plains. This approach optimises resource utilisation and enhances crop performance under prevailing agroecological conditions.

Limitations: This study was limited to a single site with sandy loam soil and focused solely on one wheat variety, DBW 187, leaving the effects of tillage and irrigation on other varieties unexplored. Conducted over two consecutive rabi seasons, this study did not assess long-term impacts on soil health, crop yield, or economic outcomes. In the zero-tillage plots, crop residue was removed, potentially affecting soil organic matter dynamics and not representing typical zero-tillage practices that retain residue. The economic analysis considered gross returns, net returns and the benefit-cost ratio based on current market prices, without accounting for potential long-term economic impacts such as soil degradation or sustainability costs. Environmental variability, especially changes in rainfall over the 2 years, influenced the results, but other factors, such as temperature fluctuations or pest pressures, were not specifically analysed or controlled. While yield and its components were thoroughly measured, other agronomic factors, such as soil microbial activity, nutrient cycling and water use efficiency, were not investigated. Some significant interactions between tillage and irrigation were observed; however, their

complexity and underlying mechanisms require further exploration. Finally, the absence of multi-location trials limits the applicability of these findings across different agroclimatic conditions. Future studies should include additional environmental variables, such as temperature fluctuations and pest pressure, to better understand their combined effects. Long-term monitoring across various climatic conditions would further clarify the influence of environmental variability on the results.

Authors' contributions

SK conducted the research trials and collected field data. MKS supervised the research and reviewed the methodology. BK analysed meteorological data and developed the irrigation schedule. RK contributed to field experimentation and soil analysis. AKP monitored crop maturation and physiological observations. SS performed statistical analysis and data interpretation. JNS reviewed and approved the research program. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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