European Journal of Agronomy 159 (2024) 127256

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

On-farm evidence on breaking yield barriers through optimizing wheat cropping system in Indo Gangetic Plain

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ARTICLE INFO

Keywords:
Crop diversification
Environmental footprints
Legume inclusion
Water use
Weed dynamics
Zero-tillage

ABSTRACT

The wheat production in the food basket of South Asia has plateaued with threats of environmental sustainability and posing a serious challenge to future food security. For sustainable wheat production in conventional rice-wheat (CTRW) systems under changing climatic scenario, atwo-year on-farm study was conducted. We evaluated system optimization practices (SOP) of legume inclusion with CTR-zero-tillage (ZT) wheat-mungbean (CTR-ZTWMb) and direct seeded rice-ZT wheat-mungbean (DSR-ZTWMb) and triple ZT (raised bed) based futuristic systems of maize-wheat-mungbean (ZTMWMb) and soybean-wheat-mungbean (ZTSWMb). The global warming potential (GWP) of wheat production was significantly reduced by 811 kg CO_2 eq/ha (783−861) in the SOP compared to CTRW. Moreover, the water usein wheat reduced by 85.9 and 85.2 ha-mm/ha in CTR-ZTWMb and DSR-ZTWMb with higher reduction in ZTMWMb and ZTSWMb by128.7 and 118.0 ha-mm/ha, respectively over CTRW. Similarly, the total weed density was reduced at 60 (39 and 52 %) and 90 (38 and 49 %) days after sowing with CTR-ZTWMb and DSR-ZTWMb over CTRW. However, the weed density reduction was lesser with ZTSWMb and ZTMWMb at 60 (3.0 and 23.6 %), and 90 (9.8 and 31.0 %) days after sowingcompared to the CTRW.The partial factor productivity (PFP) of NPK applied was 8.5–19.0 % higher under SOP over the CTRW. The use of non-renewable energy in wheat cultivation was reduced by 24.4–28.9 % with SOP over CTRW. The enhancement in wheat grain yield (7.4–11.8 %) and net returns (98–169 US$/ha) was also recorded with CTR-ZTWMb and DSR-ZTWMb and this gain in futuristic systems (ZTMWMb and ZTSWMb) was much higher in grain yield (17.2–21.0 %) as well as in net returns (283 and 362 US$/ha) over CTRW. The adoption of these SOPs on 1 million ha could produce 0.37–1.05 million t additional wheat over CTRW. The on-farm study evidenced thatwheat production with system optimization practices of legume inclusion and zero tillage are better alternatives to achieve higher productivity and profitability with a lesserenvironmental footprint in Indo-Gangetic Plains and similar agroecological regions.

1. Introduction

South Asia is home to about a quarter of the world's population, with about 22 % of the world's wheat acreage. India is one of the world's second-largest wheat producers after China and has the potential to increase its production in the coming years. Of the 30 million hectares under wheat, 42 % is under the rice-wheat (RW) cropping system in India's western IGP (Jat et al., 2020a). The country produced about 108 million tonnes of wheat in 2021–22, which is a record high. It also has significant export potential due to rising global demand. India has emerged as a major wheat exporter and exported around 30 lakh tonnes in 2022 (Agricultural and Processed Food Products Export Development Authority). However, wheat production in this region faces several challenges, including declining water tables, rising cultivation costs, shifts in weed flora, herbicide-resistant weeds and the threat of climate change in this agroecology (Jat et al., 2019a, 2020a; Shyamsundar et al., 2019). Continuous cultivation of RW with conventional tillage (CT) and traditional farming practices coupled with on-farm burning of crop

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https://doi.org/10.1016/j.eja.2024.127256
Received 24 July 2023; Received in revised form 12 June 2024; Accepted 17 June 2024

residues has led to degradation of soil health and air quality, depletion of the water table, and high costs of cultivation and energy consumption in the western IGP (Kakraliya et al., 2018; Jat et al., 2020b). In addition, intensive puddling for rice increases soil strength and reduces aquifer recharge, decreasing hydraulic conductivity and infiltration rates, leading to water stagnation, poor wheat root development and artificial water stress in the wheat crop, resulting in lower wheat yield. Kakraliya et al. (2018) reported that the traditional practices of the RW system not only increase the cost of cultivation but also reduce wheat yield by 12–15 %.

Despite these challenges, the government has set a target of producing 140 million tonnes of wheat by 2024–25 (Ministry of Agriculture & Farmers Welfare). Therefore, the sustainability of wheat production in the RW system has become an urgent concern. To address these concerns and ensure sustainable wheat production, sustainable intensification based on conservation agriculture (CA) is a system optimization approach that has been promoted and adopted as a promising technology to stabilize yields while protecting natural resources for sustainable crop production (Kassam et al., 2020). Many researchers have demonstrated that CA-based sustainable intensification with improved management practices ensures food and nutrition security, increases productivity with efficient use of available resources, improves soil water infiltration, conserves soil moisture, and improves environmental quality by saving water, labour, fuel, energy and mineral nitrogen in agriculture, and leads to a reduction in greenhouse gas emissions (GHG) (Kakraliya et al., 2022; Jat et al., 2020b). Additionally, they reported that CA-based wheat crops are better able to cope with extreme weather events under climate change. Datta et al. (2022) reported higher wheat yield at CA compared to conventional wheat with 63 % lower GHG emissions compared to CT. In addition, rice residue retention in ZT wheat eliminates the need to burn residues to clear fields for tillage, thus helping to improve environmental quality (Shyamsundar et al., 2019). Zero-till sowing of wheat using mechanized panting implements (turbo-happy seeder and direct-drillingrotary disc for bed planting) is a time and cost-effective method for better establishment of the crop. Many researchers have shown that the yield performance of wheat under ZT with residue retention was better than under CT (Shyamsundar et al., 2019; Jat et al., 2020a).

Currently, the maize-wheat cropping system is practiced on about 1.86 million ha in the IGP (Jat et al., 2020b). This system can potentially replace rice from the RW system in some niches of western IGP, especially in areas where wheat suffers yield losses due to late sowing because of late rice harvest. Pathak et al. (2003) reported a yield loss of 15–60 kg/ha/day due to delayed sowing (after mid-November), and in this situation, maize fits well as it is mature by mid-October. Optimizing the diversified system with wheat to include maize or soybean with permanent beds has great potential to achieve higher productivity than the rice-wheat system, as early wheat sowing is possible to escape terminal heat stress (Dutta et al., 2023). In the monsoon season, waterlogging is one of the major constraints to maize cultivation in the IGP, but there is evidence that it can be managed through CA-based management practices (Gathala et al., 2014; Kumar et al., 2018; Radheshyam et al., 2023). Maize residues have a lower C: N ratio than rice and faster decomposition, so they can add organic carbon to the soil and thus improve soil quality(Jat et al., 2021). Many researchers have suggested that maize-wheat systems provide flexible seeding options for wheat as well as a window of opportunity for integrating summer mungbean to optimize the sustainable intensification of cereal-based systems (Choudhary et al., 2018; Jat et al., 2019a; Kadam et al., 2023). Mungbean residue optimizes the C: N ratio of crop residues to accelerate mineralization and nutrient recycling, thereby increasing bioavailability (Kadam et al., 2023). Soybean, which is a legume crop, also maintains soil organic matter status through extensive recycling of leaf and root biomass in the rhizosphere (Carlos et al., 2022) and releases 45–60 kg residual N/ha to the following crop while creating a favorable physico-chemical environment in the soil (Simon-Miquel et al., 2023). Moreover, the economic yield of wheat after soybean has been reported to be 11 % higher than after maize (Prasad et al., 2016), mainly due to the effect of legumes in terms of N fixation and improved soil health. Thus, the development of efficient production technologies for future-oriented cropping system optimization could help to incorporate part of the RW system acreage into maize or soybean-wheat systems for sustainable wheat production in the western IGP.

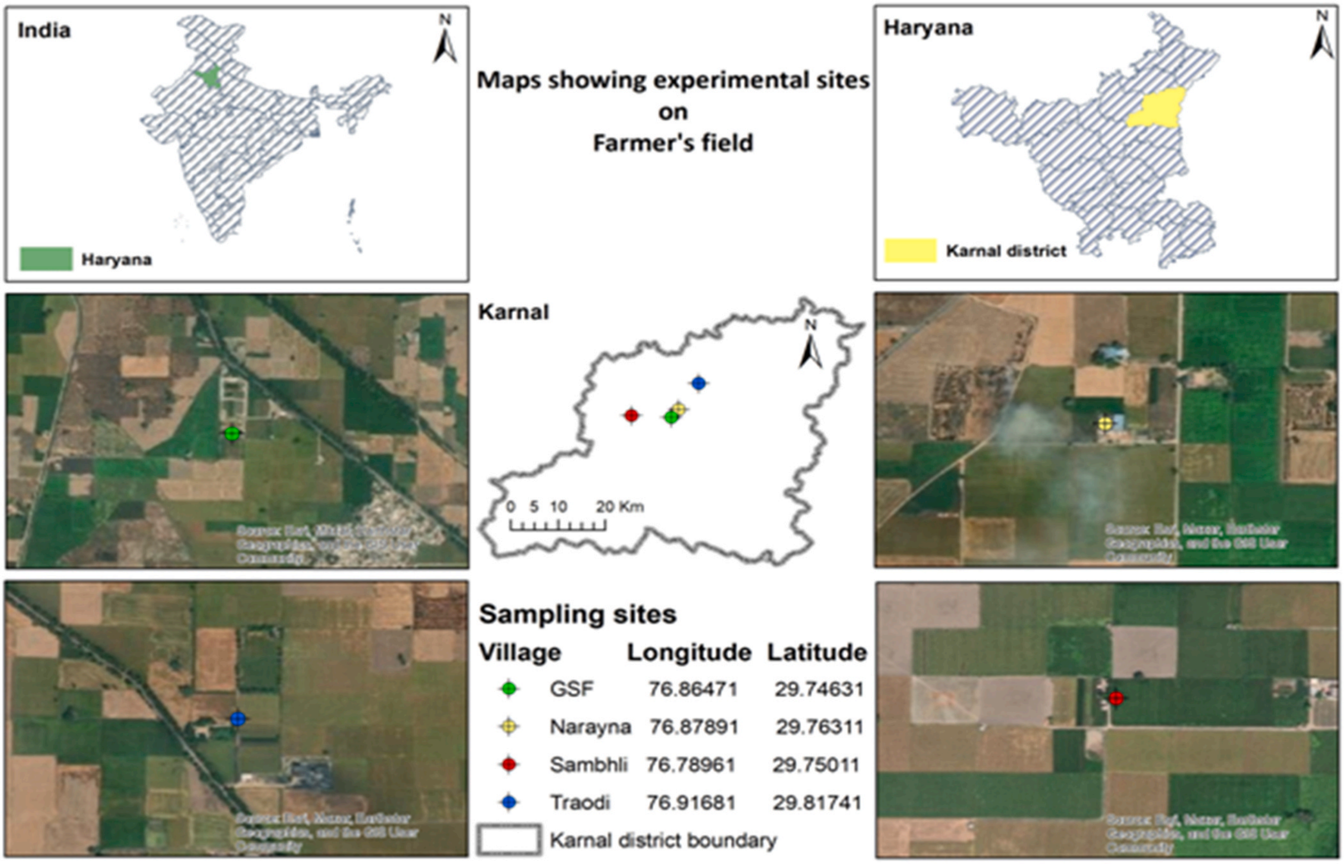
The large yield gaps in wheat with a range of 14–47 % mainly attributed to water and nutrient management (Kakraliya et al., 2022). Many researchers showed that the ZT with permanent bed planting and residue retention and crop diversification better alternative to CT wheat for higher crop and water productivity and improves soil health (Parihar et al.,2016; Das et al., 2018; Jat et al., 2020b). ZT can help to reduce water use and improve water productivity by reducing water evaporation and improving soil moisture retention and nutrient uptake which enhances luxury crop growth (Choudhary et al., 2018). Additionally, the balanced use of fertilizers through the adoption of precision nutrient management practices (Nutrient expert and Green-seeker-based recommendation) under CA helps to improve crop yield and net returns of wheat while reducing environmental footprints (Mohanty et al., 2015; Parihar et al., 2017; Radheshyam et al., 2023). Weed management is another critical component of sustainable wheat production. The initial adoption of CA changes the weed flora composition and increases their abundance and subsequent adoption of weed management practices may reduce the weed infestation (Chhokar et al., 2021; Mishra et al., 2022).Mtambanengwe*et al.* (2015) reported that long-term adoption of CA with appropriate weed management minimized the weed density by 6–51 % in CA over conventional tillage. Practices such as crop diversification, residue retention, better crop establishment, and precision input management are the time and cost-effective approaches for sustainable weed management (Khedwal et al., 2023).

However, the potential benefits of system optimization involving maize or soybean for sustainable wheat production in on-farm research have received lesser attention. This is especially true when research is conducted in the farmer's field. Therefore, a holistic approach to proper crop establishment and diversified system optimization in farmers' fields is needed not only to develop sustainable practices but also to promote their adoption through participatory technology development. Therefore, an on-farm study was conducted in IGP combining best cropping practices, residue recycling, legume incorporation and crop diversification with better water and nutrient management to develop a sustainable alternative to conventional wheat cultivation that improves water productivity, economic viability, nutrient productivity, environmental quality and weed dynamics.

2. Materials and methods

Field experiments were conducted at the four locations of farmer's fields as depictedin the map in Karnal districts of Haryana, Indiaduring 2019–20 and 2020–21 (Fig. 1). The experimental sites were typically in the rice-wheat cropping system for the last 30 years, and have a semiarid sub-tropical climate with an average annual rainfallof 650–750 mm. The seasonal mean maximum temperature was 24.1 and 27.5°C while the seasonal mean minimum temperature was 11.4 and 12.7°C with a mean relative humidity of 60 and 43 % in 2019–20 and 2020–21, respectively. The composite soil samples were drawn at 0–30 cm soil depth and analyzed using the standard procedures before the start of the experiment in June 2019.The soil of the experimental field was sandy loam to clay loam in texture with an organic carbon content of 0.59±0.01 %, pH (1:2, soil: water) of 7.76±0.07, and EC of 0.5±0.1 dS/m. The field had low available nitrogen (141±12 kg/ha), medium available phosphorus (22±5 kg/ha) and medium available potassium (269±72 kg/ha) at 0–15 cm soil profile.

Experimental details: The experiment was conducted at the farmer's field with six treatments/cropping systems referred to as scenarios (Sc).



Sampling sites

	Village	Longitude	Latitude
●	GSF	76.86471	29.74631
●	Narayna	76.87891	29.76311
●	Sambhli	76.78961	29.75011
●	Traodi	76.91681	29.81741
☐	Karnal district boundary		

Fig. 1. Schematic map of experimental sites on farmer's field at Karnal (Haryana).

These scenarios were placed at four farmers' fields and each location was designated as a replication in a randomized complete block design. The net plot size for each experimental unit was 400–450 m^2 at each location. The treatment details for different scenarios (Sc) are given in Table 1.

Residue management: In both years of the experimentation, the residue from the previous crop was used as residue input for the subsequent crop. After the combined harvest, 20 % of the rice stubble remained on the soil surface and was incorporated in CTRW before wheat seeding. However, 100 % of the rice residue was retained and 100 % mungbean residue was incorporated in CTR-ZTWMb and DSR-ZTWMb. The 65 % of maize stalks (lower part) in ZTMWMb, 35 % of soybean residues (leaf fall) in ZTSWMb and 100 % of mungbean residues were retained in both these scenarios. In all the scenarios, wheat stubbles left out after combine harvesting were retained.

*Wheat crop establishment:*The wheat variety HD 2967was planted in

Table 1
Treatment details for different scenarios during 2019–20 and 2020–21.

Scenarios (Sc)	Sc 1	Sc 2	Sc 3	Sc 4	Sc 5
cropping systems	CTRW (Rice-wheat)	CTR-ZTWMb (Rice-wheat-mungbean)	DSR-ZTWMb (Rice-wheat-mungbean)	ZTMWMb (Maize-wheat-mungbean)	ZTSWMb (Soybean-wheat-mungbean)
Tillage and crop establishment practices	Conventional tillage in both the crops	Conventional tillage in rice, zero tillage in wheat and mungbean (Double zero-tillage)	Zero tillage in all 3 crops (Triple zero-tillage)	Permanent beds (Triple zero-tillage)	Same as Sc 4
Crop residue management	Removal of rice and wheat residue (except stubbles of both crops)	The full residue of rice and stubbles of wheat retained on the surface, full mungbean residues incorporated	The full residue of rice, stubbles of wheat, and full residues of mungbean are retained on the soil surface	65 % residue of maize, stubbles of wheat, and full residues of mungbean retained on the soil surface	35 % residue of soybean, stubbles of wheat, and full residues of mungbean retained on the soil surface
Irrigation method	flood irrigation	Same as Sc 1	Same as Sc 1	furrow irrigation	furrow irrigation
Total water (Irrigation water) use (ha-mm)	2019–20: 489 (273) 2020–21: 421 (349)	2019–20: 396 (181) 2020–21: 342 (269)	2019–20: 400 (185) 2020–21: 339 (267)	2019–20: 357 (142) 2020–21: 295 (222)	2019–20: 365 (150) 2020–21: 309 (237)
Nutrient management (Fertilizers applied kg/ha) in wheat	FFPs N:P:K (kg/ha) (178:25:0)	PNM (*NE*+*GS*) N:P:K (kg/ha) (125:29:47)	Same as Sc 2	PNM (*NE*+*GS*) N:P:K (kg/ha) (125:29:55)	PNM (*NE*+*GS*) N:P:K (kg/ha) (125:25:55)
Herbicide application	PoE: pinoxaden 5.1 % EC 45 g/ha and metsulfuron-methyl 20 % WP 4 g/ha at 30 DAS	PPA: Glyphosate (1.25 l/ha) PoE: pinoxaden 5.1 % EC 45 g/ha and metsulfuron-methyl 20 % WP 4 g/ha at 30 DAS	Same as Sc 2	Same as Sc 2	Same as Sc 2

* FFPs: Farmers fertilizers practices; PNM: Precision nutrient management; NE: Nutrient Expert; GS: Green-Seeker; PoE: Post-emergence; PPA: Pre-plant application.

the first week of November by manual broadcasting followed by rotavating through rotavater in the CT plots (CTRW) and by drill seeding in 20 cm wide rows using Turbo Happy Seeder in the ZT plots (CTR-ZTWMb and DSR-ZTWMb)with a seed rate of 100 kg/ha. In the diversified scenarios (ZTMWMb and ZTSWMb), a rotary disc bed-planter was used to sow two rows of wheat with 30 cm row spacing planted on each side of the beds at a seed rate of 80 kg/ha.

*Weed management:*A pre-plant application of glyphosate(1.25 l/ha) was applied to each experimental unit in all ZT wheat plots (Sc2 to Sc5) for weed control before seeding. A tank mix of pinoxaden 5.1 % EC 45 g/ha and metsulfuron-methyl 20 % WP 4 g/ha was applied at 25–30 days after sowing of wheat to control both grassy and broadleaf weeds in all scenarios.

Nutrient management: In the ZT wheat scenarios (CTR-ZTWMb and DSR-ZTWMb) and the diversified scenarios (ZTMWMb and ZTSWMb), nutrients were applied according to the recommendations of the precision nutrient management tools using NE (Nutrient Expert) and GS (Green-seeker). The nutrient expert takes into account the residue retained from the previous crop as one of the variables in deciding NPK doses. The full dose of phosphorus by diammonium phosphate (46 % P_2O_5) and potassium by muriate of potash (60 % K_2O)was applied as a basal dressing at the time of wheat seeding. Thesplit application of nitrogen in the form of urea (46 % N) based on Green-seeker was applied in two splitsatthe vegetative and reproductive stages of wheat in all scenarios except CTRW. However, in CTRW, nutrients were applied based on farmers' fertilizers practices. The total amount of phosphorus by diammonium phosphate (DAP) was applied at basal while nitrogen in the form of urea was applied in two splits. The potassium was not applied in the CTRW scenario. The amount of fertilizers applied in each scenario is presented in Table 1.

Yield estimation: The growth and yield attribute of wheat were recorded from the net plot area at the vegetative, reproductive and harvest stages of wheat.The wheat was harvested manually from randomly selected three places within an experimental unit from 5.00 × 5.00 m (Sc1 to Sc3) and 5.00 × 5.36 m (Sc4 and Sc5) for estimation of the yields. The harvested was bundled and sun-dried in the field before threshing with the help of a mini plot thresher. Before threshing, the sun-dried weight of each bundle was recorded to obtain biological yield. The grain yield and moisture content were measured in each sample and adjusted to report yield at 13 % moisture content. The harvest index was computed by dividing the grain yield by the total biological yield and expressed in percentage.

Production economics: The economics of different scenarios were calculated using variable costs including human labour, tractor operational charges, cost of production inputs, harvesting, and threshing, etc. The fixed cost was also taken into consideration which includes land rent and interest on working capital. The cost of human labour was based on man-days/ha assuming an 8-hour working day (350 Indian Rupees/day in 2019–20 and 360 Indian Rupees/day in 2020–21). The net returns (NR) were calculated as the difference between the gross returns (GR) and the total cost (NR = GR−Total cost). The benefit-cost ratio (BCR) was calculated based on NRs in the particular scenario.

Water use and water productivity: The amount of irrigation water applied to each plot during the whole *rabi* season was measured using a water meter. Water management protocols for each scenario are presented in (Table 1). In flood irrigation in flat-bed sown plots 5–7 cm while in raised bed furrow irrigated plots 5–6 cm irrigation water was applied. The total amount of water applied was computed by summing the irrigation (I) water and effective rainfall (ER)as calculated by using the FAO-CropWatsoftware. The total water productivity (WP_{I+ER}) was calculated by using the Eq. 1.

$$\text{Total water productivity}(\text{kg grain}\Big/\text{m3}) = \frac{\text{Grain yield}(\text{kg/ha})}{\text{Irrigation water} + \text{effective rainfall}(\text{m3/ha})} \tag{1}$$

Partial factor productivity: The partial factor productivity (PFP) of the applied nitrogen (N), phosphorus (P), and potassium (K) nutrients by fertilizers was obtained by using Eq. 2.

$$\text{PFP}(\text{kg grains}\Big/\text{kg NPK applied}) = \frac{\text{Grain yield}(\text{kg/ha})}{\text{NPK fertilizers applied}(\text{kg/ha})} \tag{2}$$

Environmental footprints: The Global warming potential (GWP) of wheat in different cropping systemswas estimated by using all the sources and sinks of greenhouse gases (GHG) emissionsdirectly from soil (C-sequestration and soil flux GHG), crop residues retention/incorporation and land use management or system. The indirect GHG emissions from input used for wheat production in each scenario were accounted for by the use of renewable energy inputs (irrigation, seeds, labour and crop residues) and non-renewable energy inputs (fossil fuel, electricity, fertilizer and pesticide) were calculated by using Climate Change Agriculture and Food Security (CCAFS)-Mitigation Options Tool-MOT (Feliciano et al., 2017). In this tool, many empirical models are combined to compute GHG emissions in any production system. The tool considers specific factors like; climatic conditions, soil characteristics, crop production inputs, fertilizers production and transportation and other management activities that influence emissions (Jat et al., 2020a). The totalGWP was calculated by using Eq. 3 while GHG emission intensity was calculated by Eq. 4.

$$\text{GWP}(\text{kg CO2eq/ha}) = \{\text{CO2}\quad(\text{kg/ha}) + \text{N2O}(\text{kg/ha}) \times 298 + \text{CH4}\quad(\text{kg/ha}) \times 34\} \tag{3}$$

$$\text{GHG emission intensity} = \frac{\text{GWP}(\text{kg CO2eq/ha})}{\text{Grain yield}(\text{kg/ha})} \tag{4}$$

Eco-efficiency: The term eco-efficiency is defined as a ratio between economic returns and environmental degradation (Kakraliya et al., 2022). The eco-efficiency was computed by using the Eq. 5.

$$\text{Eco} - \text{efficiency} = \frac{\text{Net returns}(US\$/\text{ha})}{\text{GWP}(\text{kg CO2eql./ha})} \tag{5}$$

Weed dynamics: The weed density in wheat under different cropping system scenarios was recorded by using 0.25 m^2 quadrate at randomly selected three spots in a plot at 60, 90 and 120 days after sowing in wheat during both the years of the experimentation. The collected data on weed density were transformed by using square root transformation to have the normal distribution before analysis and expressed as the number of weeds per meter square area.

Statistical analysis: The data for different parameters were statistically analyzed using the SAS software in the SSCNARS portal. Combined analysis for two years was performed and reported pooled data for all the parameters except weed parameters. The Least Significant Difference (LSD) test was used as a post hoc mean separation test ($P<0.05$) to decipher treatment effects. The Figures were generated using the 'R' software to account for the variation and stability of individual treatment across years and replication.

3. Results

3.1. *Crop growth and yield attributes*

The plant growth responds to the growing environment which leads to higher productivity and resource use efficiency. The taller wheat plant was recorded in ZTSWMb which was statistically at par with ZTMWMb while the smallest plant was in CTRW (Table 2). Wheat plant height increased by 16.2 and 19.2 %, 6.8 and 11.0 %, 8.6 and 11.0 %, and 5.7 and 7.0 % in ZTMWMb and ZTSWMb at 30, 60, 90 and 120 days after sowing compared to CTRW, respectively.Similarly, significantly increased dry matter accumulation (DMA) by 11.5 and 18.9 %, 14.3 and 22.0 %, 8.7 and 10.6 % and 11.9 and 14.8 % at 30, 60, 90 and 120 days

Table 2
Effect of different cropping systems, tillage, and crop establishment practices on growth and yield attributes of wheat(pooled data of two years).

Treatments	Plant height (cm)				Dry matter accumulation (g/m^2)				Effective tillers/m^2	Ear bearing (%)	Spike length (cm)	Spikelets/ spike	Grains/ spike	1000-grains weight (g)
	30 DAS	60 DAS	90 DAS	120 DAS	30 DAS	60 DAS	90 DAS	120 DAS						
Cropping system scenarios (Sc)														
CTRW	19.8^{e}	44.4^{d}	79.3^{d}	98.0^{e}	31.2^{d}	152^{e}	611^{d}	899^{d}	399^{d}	77.4^{d}	9.4^{d}	17.5^{a}	45.0^{e}	40.2^{c}
CTR–ZTWMb	21.6^{d}	45.9^{c}	85.1^{c}	100.7^{d}	32.5^{c}	160^{d}	630^{c}	924^{c}	438^{c}	78.4^{c}	9.6^{d}	17.8^{a}	49.9^{c}	41.0^{b}
DSR–ZTWMb	22.4^{c}	46.4^{c}	85.0^{c}	102.2^{c}	32.6^{c}	167^{c}	626^{c}	923^{c}	463^{b}	81.0^{b}	10.0^{c}	17.8^{a}	46.8^{d}	41.3^{b}
ZTMWMb	23.0^{b}	47.4^{b}	86.1^{b}	103.6^{b}	34.8^{b}	174^{b}	664^{b}	1007^{b}	445^{c}	81.2^{b}	10.4^{b}	18.0^{a}	53.1^{b}	41.8^{a}
ZTSWMb	23.6^{a}	49.5^{a}	88.0^{a}	104.9^{a}	37.1^{a}	186^{a}	676^{a}	1033^{a}	491^{a}	82.1^{a}	11.2^{a}	18.5^{a}	56.5^{a}	42.1^{a}
Year (Y)														
Year-1	21.8^{b}	45.8^{b}	83.8^{b}	100.9^{b}	32.8^{b}	165^{b}	639^{a}	956^{a}	439^{a}	79.2^{b}	10.1^{a}	17.9^{a}	49.8^{a}	40.6^{a}
Year-2	22.3^{a}	47.6^{a}	85.5^{a}	102.8^{a}	34.5^{a}	171^{a}	644^{a}	958^{a}	455^{a}	80.8^{a}	10.1^{a}	17.9^{a}	50.8^{a}	41.9^{a}
Interaction (Y × Sc)														
LSD (*P*=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

*DAS: Days after sowing, Similar letters within the column represents non-significant difference amongst different treatments as per the LSD (P=0.05).

after sowing was recorded in ZTMWMb and ZTSWMb, respectively compared to CTRW.Likewise, significantly higher effective and ear-bearing tillers were recorded in ZTSWMb which was followed by DSR-ZTWMb while minimum in CTRW. The effective tillers increased by 63, 46 and 92 tillers/m^2 in DSR-ZTWMb, ZTMWMb and ZTSWMb, respectively compared to CTRW.

Amongst the spike characteristics, the wheat spike length and grains/spike were recorded higher in ZTSWMb followed by ZTMWMb while the lowest was recorded in CTRW. Significantly increased spike length by 10.7 and 17.9 % and grains/spike by 19.7 and 25.6 % were observed in ZTMWMb and ZTSWMb, respectively over CTRW. However, the spikelets/spike were statistically similar to CTRW. The 1000-grains weight was significantly increased in ZTMWMb and ZTSWMb by 3.8 and 4.7 %, respectively over CTRW (Table 2).

3.2. *Crop yield*

The variability in growth and yield attributes in different scenarios leads to differential response for wheat yield as yield is a function of many of these characteristics.Significantly higher wheat grain yield was

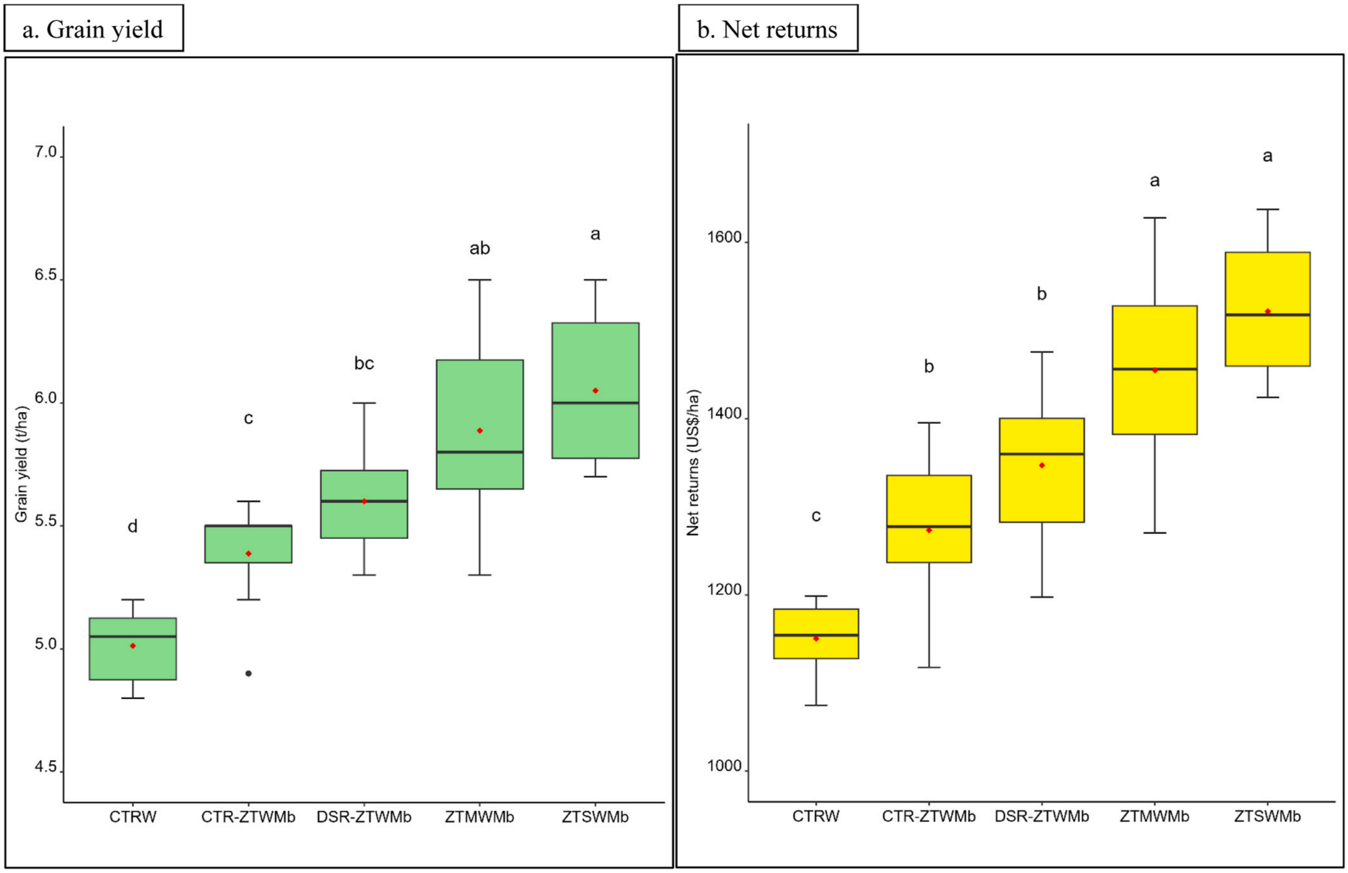


Fig. 2. Effect of different cropping systems, tillage, and crop establishment practices on grain yield and net returns in wheat (n=8).Similar letter above the boxplots represents non-significant difference amongst different treatments as per the LSD (p = 0.05).

recorded in ZTSWMb followed by ZTMWMb, while the significantly lowest yield was in CTRW. Grain yield was significantly higher by 7.4 and 11.8 % with CTR-ZTWMb and DSR-ZTWMb, respectively over CTRW (Fig. 2a).

Wheat grain yield increased over the CTRW by 21 % with the inclusion of soybean (ZTSWMb), and by 17.2 % with the inclusion of maize (ZTMWMb) compared to CTRW. A significantly higher biological yield was recorded in ZTSWMb, which was statistically on par with ZTMWMb, while the lowest was with CTRW (Table 3). The biological yield increased significantly by 6.6 and 7.6 % with ZTMWMb and ZTSWMb, respectively compared to CTRW. A significantly higher harvest index (HI) was recorded in ZTSWMb followed by ZTMWMb, while significantly lower in CTRW. The HI was 6.7 % higher in ZT wheat scenarios (CTR-ZTWMb and DSR-ZTWMb) and 9.7 and 12.4 % with ZTMWMb and ZTSWMb in ZT wheat with diversified scenarios, respectively compared to CTRW.

3.3. Economic profitability

The economic profitability of any production practice is the key to immediate adoption on a scale which needs appropriate consideration. Two-year pooled cultivation costs for wheat were significantly higher in CTRW than other treatments (Table 3). The cost of cultivation decreased by 15.6 and 14.6US$/ha in CTR-ZTWMb and DSR-ZTWMb while in the diversified scenarios, it was significantly decreasedby60.7 and 92.7US$/ha with ZTMWMb and ZTSWMb, respectively compared to the CTRW. The significantly higher net returns and benefit-cost ratio (BCR) were recorded in ZTSWMb and ZTMWMb, while significantly lower in CTRW. In our study, the net returns in CTR-ZTWMb and DSR-ZTWMb were significantly higher by 98 and 169 US$/ha, respectively (Fig. 2b) and the BCR by 12.4 and 18.9 %, respectively over the CTRW. In the diversified scenarios, the net returns were significantly increased by 283 and 362 US$/ha, and the BCR was 42.8 and 62.2 % higher with ZTMWMb and ZTSWMb, respectively over the CTRW.

3.4. Nutrients productivity

The enhancement of the nutrient use efficiency in the production systems of wheat not only helps in reducing the burden of fertilizersubsidybut also improves the environmentquality by indirectly reducing pollution in manufacturing these synthetic fertilizers. Significantly higher partial factor productivity (PFP) of total NPK applied in wheat was recorded in ZTSWMb followed by ZTMWMb, while the significantly lower PFP of total NPK applied was recorded in CTRW (Table 3). The PFP of total NPK applied was 8.5 and 13 % higher in CTR-ZTWMb and DSR-ZTWMb, respectively over the CTRW. However, the PFP of total NPK applied with diversified scenarios increased significantly by 13.8 and 19.0 % in ZTMWMb and ZTSWMb, respectively compared to CTRW.

3.5. Non-renewable energy use

The information on energy use in different management scenarios and crop productivity are important indicators to assess the system's ecological performance. The intensive tillage operation with higher use of fertilizers and electricity is the major source of non-renewable energy usage in CTRW. The use of finite resources of non-renewable energy in crop production implies not only increased cost but for sustainable food production for future generations. In our study, significantly higher non-renewable energy use was recorded in CTRW while the lowest in ZTSWMb and ZTMWMb (Fig. 3). The non-renewable energy was significantly reduced in CTR-ZTWMb and DSR-ZTWMb by 24.5 and 24.4 % while it was reduced by 28.9 and 28.7 % in ZTMWMb and ZTSWMb, respectively over the CTRW.

3.6. Water use and water productivity

In the scenario of lowering the water table in the wheat production belt of South Asia, the enhancement in water productivity could be a key for sustaining the food security of the region. Significantly highest total water use with the lowest total water productivity (TWP) was recorded with CTRW, while the significantly lowest total water use with the highest TWP was recorded in ZTMWMb, which was statistically at par with ZTSWMb (Table 3). The total water use was reduced by 85.9 and 85.2 ha-mm/ha (Fig. 4a), with higher TWP by 32.4 and 37.8 % with

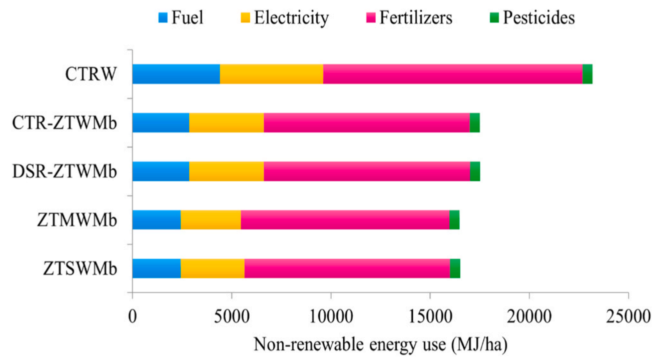


Fig. 3. Effect of different cropping systems, tillage, and crop establishment practices on non-renewable energy use in wheat.

Table 3

Effect of different cropping systems, tillage and crop establishment practiceson yield, economics, nutrients productivityand environmental footprintsin wheat (pooled data of two years).

Treatments	Biological yield (t/ha)	Harvest index (%)	Cost of cultivation (US$/ha)	BC ratio	Total water productivity (kg/m^3)	PFP of total NPK (kg of grain/kg NPK applied)	Total CO_2 emissions (kg/ha)	Emission intensity (kg CO_2eql/t yield)	Eco-efficiency (US$/ha GWP)
Cropping system scenarios (Sc)									
CTRW	11.28^c	44.5^d	529.4^a	2.01^e	1.11^d	24.7^d	2019.5^a	0.458^a	0.463^e
CTR–ZTWMb	11.33^c	47.5^c	513.8^b	2.26^d	1.47^c	26.8^c	1416.4^b	0.279^c	0.776^d
DSR–ZTWMb	11.82^b	47.5^c	514.8^b	2.39^c	1.53^b	27.9^b	1417.4^b	0.266^d	0.825^c
ZTMWMb	12.03^a	48.8^b	468.7^c	2.87^b	1.84^a	28.1^b	1343.1^d	0.257^e	0.890^b
ZTSWMb	12.14^a	50.0^a	436.7^d	3.26^a	1.83^a	29.4^a	1369.0^c	0.310^b	0.996^a
Year (Y)									
Year-1	11.60^b	47.7^a	483.7^b	2.55^a	1.41^b	27.1^a	1458.2^b	0.306^b	0.802^a
Year-2	11.84^a	47.6^a	501.6^a	2.57^a	1.70^a	27.6^a	1568.0^a	0.322^a	0.779^b
Interaction (Y × Sc)									
LSD (*P*=0.05)	NS	NS	1.1	NS	NS	NS	NS	NS	NS

*Similar letters within the column represents non-significant difference amongst treatments as per the LSD (P=0.05).

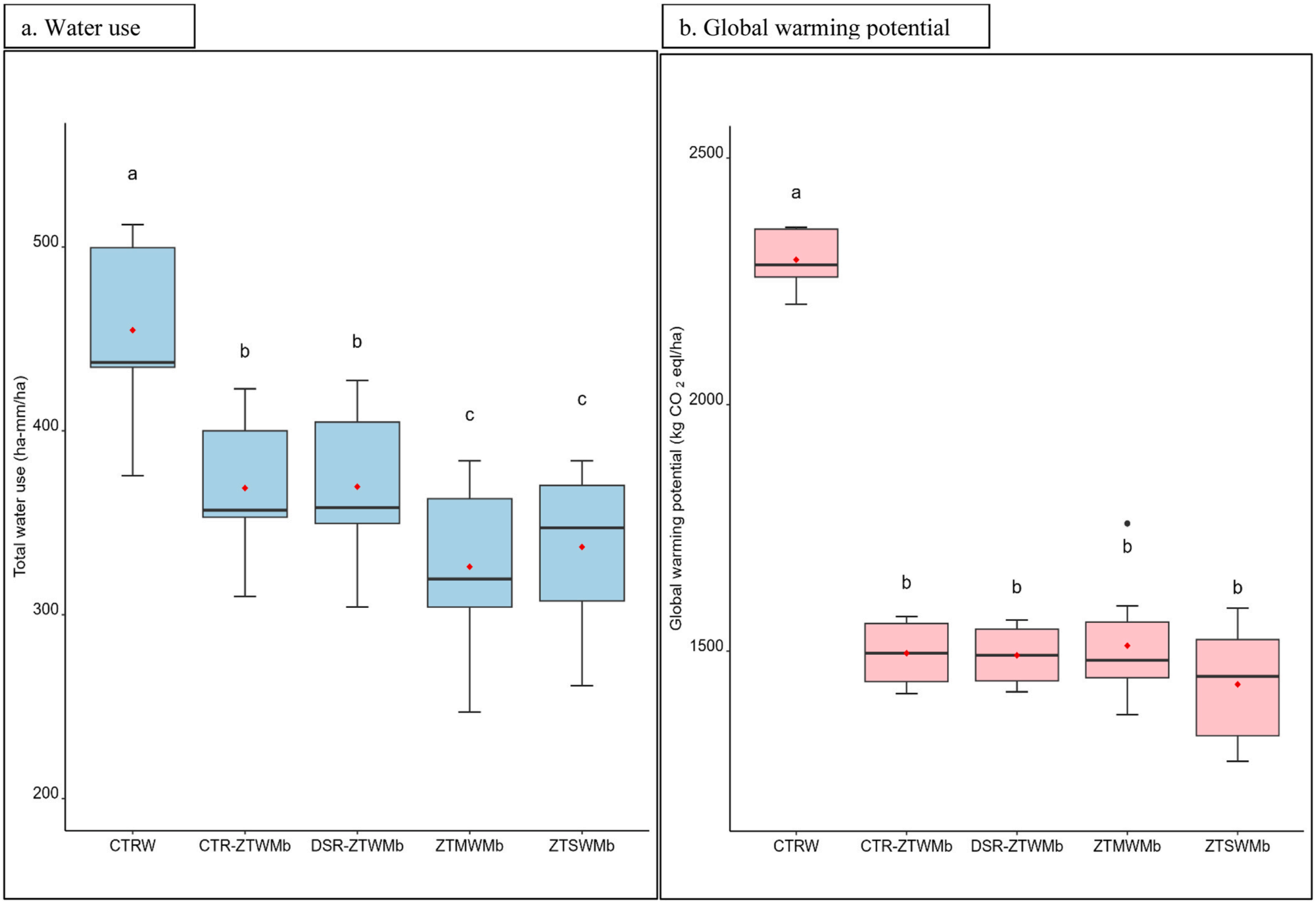


Fig. 4. Effect of different cropping systems, tillage, and crop establishment practices on total water use and global warming potential (n=8) in wheat.Similar letter above the boxplots represents non-significant difference amongst different treatments as perthe LSD (p = 0.05).

CTR-ZTWMb and DSR-ZTWMb, respectively compared to CTRW. In diversified scenarios, total water use was significantly reduced by 128.7 and 118.0 ha-mm/ha with higher TWP by 65.8 and 64.9 % with ZTMWMb and ZTSWMb, respectively over the CTRW.

3.7. *Environmental footprints*

The assessment of the environmentalfootprints is very important for the long-term suitability of any management practices. Significantly higher global warming potential (GWP) and emission intensity (EI) were recorded in CTRW and the significantly lower GWP was recorded in ZTSWMb followed by DSR-ZTWMb and CTR-ZTWMb, while the significantly lower EI was recorded in ZTMWMb, which was statistically par to DSR-ZTWMb and CTR-ZTWMb. GWP was significantly reduced with CTR-ZTWMb and DSR-ZTWMb (798–802 kg CO_2 eq/ha) (Fig. 4b), while EI was reduced (39.1–41.9 %), respectively, compared to CTRW (Table 3). In the diversified scenarios, GWP was significantly reduced with ZTMWMb and ZTSWMb (783–861 kg CO_2 eql/ha), while EI reduced (43.9–32.3 %), respectively, over the CTRW. Conversely, significantly higher total CO_2 emission was observed in CTRW, while significantly lower total CO_2 emission was observed in ZTMWMb and ZTSWMb. Total CO_2 emissions were significantly reduced by 29.9 % in both ZT wheat scenarios (DSR-ZTWMb and CTR-ZTWMb) compared to CTRW. However, total CO_2 emissionwasreduced significantly in the ZT wheat with diversified scenarios ofZTMWMb and ZTSWMb by 33.5 and 32.2 %, respectively compared to CTRW.

The significantly higher eco-efficiency was recorded in ZTSWMb followed by ZTMWMb while the significantly lower eco-efficiency was recorded in CTRW (Table 3). Moreover, the eco-efficiency was significantly increased by 67.6 and 78.2 % in CTR-ZTWMb and DSR-ZTWMb, respectively compared to CTRW. Significant increase in eco-efficiency with diversified scenarios by 92.2 and 115.1 % in ZTMWMb and ZTSWMb, respectively compared to CTRW.

3.8. *Weed dynamics*

Grassy weed density: Significantly higher grassy weed density in wheat was recorded in CTRW, while it was significantly lower in DSR-ZTWMb, which was statistically at par on CTR-ZTWMb, at different stages of observation during both the years of experimentation (Table 4). Compared to CTRW,the grassyweed density significantly decreased on the pooled basis in CTR-ZTWMb and DSR-ZTWMb by 45.9 and 66.9 %, 43.7 and 60.0 %, and 40.1 and 50.8 % at 60, 90 and120 days after sowing,respectively.Similarly, the weed density was significantly reducedin the diversified system of ZTMWMb and ZTSWMb by 45.5 and 32.3 %, 42.5 and 29.3 % and 41.6 and 41.1 % at 60, 90 and120 days after sowing,respectivelyover the CTRW.In the second year of experimentation, the grassy weeds density in DSR-ZTWMb was decreased by 32.3, 20.3 and 19.5 % at 60, 90 and 120 days, respectively. Similarly, in diversified scenarios of ZTMWMb, the weed density decreased by 22.3, 9.1 and 24.5 % in the second year of the study, whileitincreased in CTRW by 11.8, 10.9 and 13.3 % at 60, 90 and 120 days after sowing, respectively.

Broad-leaved weed density: The higher broad-leaved weeds (BLWs) density in wheat was recorded in ZTSWMb which was statistically at par with ZTMWMb and CTRW. However, the significantly lower BLWs density was recorded in DSR-ZTWMb and CTR-ZTWMb at different observation stages during both the years of study (Table 4). The

Table 4
Effect of different cropping systems, tillage, and crop establishment practices on grassy and broad-leaved weeds density at different intervals in wheat crop.

Treatments	Grassy weed density (No./m^2)									Broad-leaved weeds density (No./m^2)								
	60 DAS*			90 DAS			120 DAS			60 DAS			90 DAS			120 DAS		
	2019–20	2020–21	Pooled	2019–20	2020–21	Pooled	2019–20	2020–21	Pooled	2019–20	2020–21	Pooled	2019–20	2020–21	Pooled	2019–20	2020–21	Pooled
Cropping system scenarios (Sc)																		
CTRW	6.96^{a}	7.78^{a}	7.37^{a}	8.09^{a}	8.97^{a}	8.53^{a}	7.77^{a}	8.80^{a}	8.29^{a}	6.65^{b}	4.94^{b}	5.80^{c}	6.20^{b}	4.78^{b}	5.49^{b}	4.52^{c}	4.52^{b}	4.52^{c}
CTR–ZTWMb	4.19^{c}	3.78^{c}	3.98^{c}	4.63^{d}	4.97^{c}	4.80^{c}	5.15^{bc}	4.79^{b}	4.97^{b}	4.62^{c}	3.44^{d}	4.03^{d}	4.39^{d}	3.51^{c}	3.95^{d}	4.10^{c}	2.67^{d}	3.39^{d}
DSR–ZTWMb	2.91^{d}	1.97^{d}	2.44^{d}	3.80^{e}	3.03^{d}	3.41^{d}	4.52^{c}	3.64^{c}	4.08^{c}	3.39^{d}	4.23^{c}	3.81^{e}	3.51^{e}	4.06^{c}	3.79^{d}	3.39^{d}	2.87^{c}	3.13^{e}
ZTMWMb	4.52^{c}	3.51^{c}	4.01^{c}	5.14^{c}	4.67^{c}	4.91^{c}	5.51^{b}	4.16^{c}	4.84^{b}	6.95^{b}	5.13^{b}	6.04^{b}	5.44^{c}	3.98^{c}	4.71^{c}	5.23^{b}	4.28^{b}	4.76^{b}
ZTSWMb	5.19^{b}	4.78^{a}	4.99^{b}	6.40^{b}	5.67^{b}	6.03^{b}	4.72^{c}	5.04^{b}	4.88^{b}	8.56^{a}	7.02^{a}	7.79^{a}	7.44^{a}	5.78^{a}	6.61^{a}	7.38^{a}	5.60^{a}	6.49^{a}
Year (Y)																		
Year-1			4.75^{a}			5.61^{a}			5.53^{a}			6.04^{a}			5.40^{a}			4.92^{a}
Year-2			4.36^{b}			5.46^{a}			5.29^{a}			4.95^{b}			4.42^{b}			3.99^{b}
Interaction (Y × Sc)																		
LSD (P=0.05)			0.14			0.09			0.13			0.14			0.13			0.11

[*] DAS: days after sowing. The weed observations were taken from three randomly selected spot and averaged for each experimental unit during both the years of the study (n=4). The data were transformed using square root transformation. Similar letters within the column represents non-significant difference amongst treatments as per LSD (P=0.05).

significantly decreased BLWs density on the pooled basisin CTR-ZTWMb and DSR-ZTWMbby 30.5 and 34.3 %, 28.0 and 31.0 % and 25.0 and 30.6 % at 60, 90 and 120 days after sowing,respectivelyover the CTRW. However, the BLWs density was increased in ZTMWMb and ZTSWMb by 4.2 and 34.4 %and 5.4 and 43.7 % at 60 and120 days after sowing, respectivelyover the CTRW. However, at 90 days after sowing, the BLWs density decreased in ZTMWMb and ZTSWMb by 20.4 and 14.1 %, respectively over the CTRW. In the second year of the study, the BLWs density decreased at 60, 90 and 120 days after sowing, respectively by 25.7, 22.9 and 0.0 % in CTRW, 25.5, 20.0 and 34.9 % in CTR-ZTWMb while itincreased by 24.8 and 15.7 % at 60 and 90 days and the decreased by 15.3 % at 120 daysin DSR-ZTWMb. In diversified scenarios, the BLWsdensity was decreased during the second year of experimentation at 60, 90 and 120 days, respectively by 26.2, 26.8 and 18.2 % in ZTMWMb and 18.0, 22.3 and 24.1 % in ZTSWMb system.

Total weed density: Significantly lower total weed density was recorded in DSR-ZTWMb followed by CTR-ZTWMbwhile the total weed density was recorded significantly higher in CTRW during both the years of experimentation (Fig. 5). Compared to CTRW, the total weed density was significantly decreased in CTR-ZTWMb and DSR-ZTWMbby 39 and 52 %, 38 and 49 % and 35 and 44 % at 60, 90 and 120 days after sowing, respectively. The significantly decreased total weed density in diversified scenarios ofZTSWMb and ZTMWMb was observedby 3.0 and 23.6 %, 9.8 and 31.0 %, and 11.2 and 25.1 % at 60, 90 and 120 days after sowing, respectivelyover the CTRW.Among all the scenarios, the highest decreasein total weed density was observed in ZTMWMb by 24.7, 18.2 and 21.3 % at 60, 90 and120 days after sowing, respectively. However, the weed density was slightly decreased by 6.6 and 3.8 % at 60 and 90 days while itincreased by 8.4 % at 120 days after sowing in CTRW.

4. Discussion

4.1. *Crop growth and yield attributes*

The zero-tillage (ZT) rotary disk bed planter facilitated the early wheat seeding with proper seed and fertilizer placement in the narrow slit on the permanent bed (PB) resulting in the early emergence under residual soil moisture that led to vigorous crop growth. Wheat plant height was found significantly higher in SOP during the second year of the study which might be attributed to reduced weed pressure by crop residue retention as well as the legume-lag effect that led to luxurious crop growth. The longer spikes due to the better establishment with wider spacing, better light interception and more uptakes of nutrients resulted in vigorous growth of PB wheat. These results show that over the year adoption of SOP in wheat like ZT/PB with residue retention and diversified cropping system led to improvement of crop growth and yield attributes. Ram et al. (2012) also reported longer spikes under PB compared to flat beds. The increase in the length of the spike also contributed to an increase in the number of grains/spikes owing to more partitioning of photosynthates to the reproductive parts for better grain filling and higher yield (Kumar et al., 2013; Kakraliya et al., 2018). Moreover, the wheat after maize or soybean had a better quality of crop residue having a lower C: N ratio which increased mineralization and bio-availability of nutrients (Choudhary et al., 2018; Kakraliya et al., 2018). However, the shallow hard pan caused by repeated wet tillage/puddling reduced the root growth and poor crop establishment resulted in reduced crop growth and ultimately lower yield attributes of wheat in CTRW (Gathala et al., 2014; Kakraliya et al., 2018).

4.2. *Crop yield*

The system optimization practices (SOP) of zero tillage/PB and legume inclusion recorded higher yields due to early wheat seedling emergence and crop growth owing to a larger area of exposure to sunlight. Higher wheat yields on PB could be due to the combined effects of

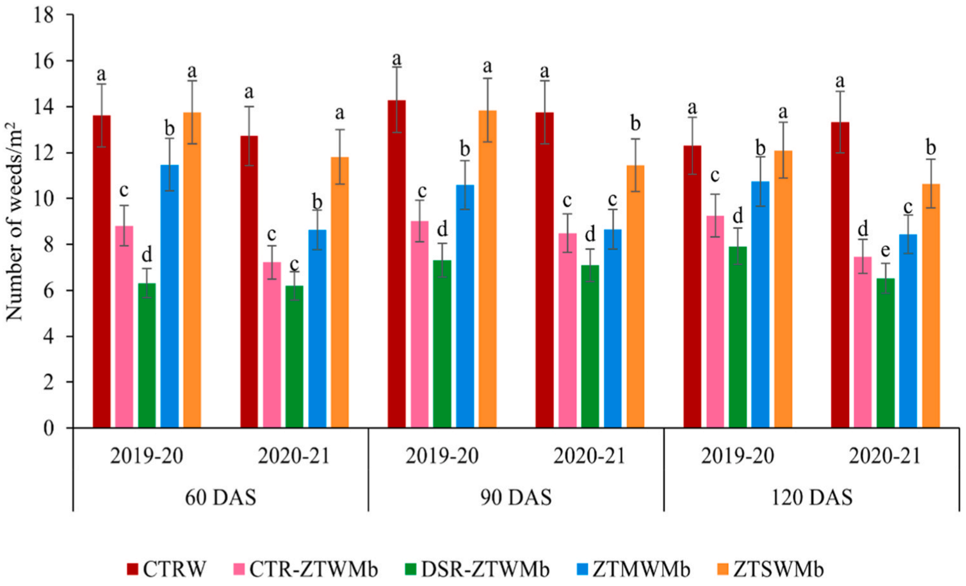


Fig. 5. Effect of different cropping systems, tillage and crop establishment practices on total weed density in wheat. The vertical bar on each histogram indicates the standard error (n=4). Similar letter above the bars within each year represents non-significant difference amongst treatments as per LSD ($p = 0.05$). The weed observations were taken from three randomly selected spot and averaged for each experimental unit during both the years of the study.

better crop establishment, optimal plant population, better water and air regime (Jat et al., 2020a), lower biotic and abiotic stresses, lower weed pressure, improved nutrient uptake (Jat et al., 2019a) and improved physical soil health (Jat et al., 2013) compared to CTRW. The significant enhancement of growth and yield attributes in PB or ZT treatment in our study over CTRW might have led to increased yield under these treatments by better source-sink relationship.Additionally, the maize-wheat system provides opportunities for early wheat sowing and provides an additional opportunity window for summer mungbean integration through system optimization (Choudhary et al., 2018).

Similarly, the inclusion of the soybean in the rainy season on PB led to the highest wheat productivity in our study which is mainly attributed to the legume-lag effect. The recycling of leaf/rhizosphere root biomass of soybean leaves 45–60 kg residual N/ha for the following crop (Carlos et al., 2022) and creates a favourable soil physico-chemical environment for plant growth (Simon-Miquel et al., 2023). Dhadli et al. (2009) also reported 16 % higher wheat yields after soybean on raised beds compared to CT in a soybean-wheat rotation. Similarly, Prasad et al. (2016) reported 11 % higher wheat yield after soybean compared to after maize mainly due to the legume-lag effect in terms of N fixation and improved soil health. Additionally, the lower C: N ratio residue of maize or soybean enriched with the integration of summer mungbean had a synergistic soil nutrient transfer effect on the subsequent wheat crop to improve nutrient availability, resulting in better plant growth and yield (Jat et al., 2019b; Kadam et al., 2023).

The ZT after rice facilitated the early wheat seeding by 15 days which led to enhanced crop duration and resulted in higher yield (7.4–11.8 %) in CTR-ZTWMb and DSR-ZTWMb over CTRW. In the western IGP, ZT allows two weeks of advanced wheat planting and along with residue mulching, it results in better germination, plant stand and root development, reduced weed pressure, improved nutrients and water uptake and better temperature regulation and eliminates chances of "terminal heat stress" during wheat grain filling (Kumar et al., 2018; Jat et al., 2020a). Bakht et al. (2009) reported 1.31 times increased wheat yield by crop residue incorporation than CT wheat. In IGP, many studies have shown that growing rice as direct seeding (DSR) has a positive effect on the subsequent wheat crop by avoiding soil compaction as well (Kakraliya et al., 2018).

4.3. *Economic profitability*

Lower production costs are associated with the saving of tillage cost in SOP as ZT/PB, even after accounting for the cost of residue retained. The ZT facilitates early wheat seeding in residual moisture which saves pre-seeding irrigation water, electricity, and labour costs as well as cost saving on crop residue removal. Gathala et al. (2014) reported that about 85 % of costs associated with tillage and crop establishment can be reduced by adapting ZT in wheat.

In our study, about 15 and 30 % higher net returns in wheat were obtained in PB over the ZT flat-bed and CT-flat, respectively. The higher net returns in PB were due to the lesser cost of cultivation associated with tillage, irrigation water, weed management, fertilizers and increased wheat grain yield. Similar findings were also been reported by many researchers in the same ecology (Ram et al., 2013; Parihar et al., 2016; Das et al., 2018) in diversified systems in IGP. The study recorded that the effect of year and interaction (cropping system × year) was found significant with the cost of cultivationdue to reduced fertilizers and labour costs during the second year of the experimentation.

4.4. *Water use and water productivity*

Significantly lower total water use with higher total water productivity (TWP)obtainedin SOPof ZT/PB compared to CT wheat. The ZT facilitates early wheat sowing immediately after rice harvest which saves pre-sowing irrigation water in IGP (Erenstein and Laxmi, (2008); Jat et al. (2013) and Jat et al. (2020a). The residue retention further reduces the area of evaporation as well as increasesirrigation water application efficiency. Higher TWP associated with lower water use and higher grain yields of wheat under PB systems could be due to saving of the irrigation water due to higher application efficiency in bed-furrow systems compared to flat areas (Jat et al., 2013). Choudhary et al. (2018) found that CA-based SOP has the potential to save irrigation water and improve the water productivity of wheat. Similarly, Ram et al. (2012) also reported lower water use and high water productivity in wheat on PB under a soybean-wheat system. In our two-year on-farm study, the total water use and TWP were significantly influenced by the year effect. The improvement of soil physical properties and residue retention over the years might have helped in reducing water use and enhancing yield which in turn increased water productivity in subsequent years. This led to higher grain yield during the second year of the experimentation with lesser water use in our study.

4.5. Nutrient productivity

The rice residue (either retention or incorporation) can supply a sufficient amount of K to wheat resulting in less application of K fertilizer and an increase in partial factor productivity (PFP) of K in wheat. The precision nutrient management (PNM) by NE+GS facilitates the balanced fertilization and better synchronization of nutrients with plant needs which results in higher yield with greater nutrient use efficiency. The PFP of total NPK applied increased due to PNM in wheat under zero-tillage and PB. Crop residue retention resulted in soil organic matter build-up, which improved soil fertility and nutrient supply capacity and ultimately better soil moisture led to improved root system and nutrient uptake. Similarly, Mohanty et al. (2015) and Parihar et al. (2017) reported that the PNM offers the potential to reduce fertilizer dose to increase the PFP of applied nutrients with optimal wheat yield. Mitra et al. (2023) indicated that high yields associated with high nitrogen use efficiency (NUE) can be achieved in wheat when blanket fertilizer recommendations are replaced with GS. In our study, the PFP of total applied NPK was increased by 19 % with the inclusion of soybean (ZTSWMb) compared to CT wheat with farmers' fertilizer practices (Table 3). The inclusion of soybean instead of rice in the RW system reduced the dose of N fertilizers and increased the PFP of N in soybean as well as in succeeding wheat crops by providing residual N as a legume effect. The inclusion of double legumes in the cropping system (ZTSWMb: soybean-wheat-mungbean) increased N supply through their biological N fixation and reduced the dose of N fertilizers. Moreover, the crop residues from legumes have low C: N ratios, which help in early decomposition and mineralization to increase the bio-availability of nutrients for the crop plant. The crop mulch improves soil P fertility and reduces P fertilizer dose which increases PFP of P in wheat (Malhi et al., 2011). Similarly, Ram et al. (2013) reported that the soybean as a legume leaves 45–60 kg residual N/ha for subsequent crops.

4.6. Environmental footprints

Wheat under conventional management practices (CTRW) emitted more greenhouse gasses due to higher consumption of non-renewable energy in tillage and fertilizer applications. Intensive tillage accelerates the oxidation of organic matter and converts it to CO_2, which is released into the atmosphere and contributes to the greenhouse effect and global warming (Kakraliya et al., 2022). Jat et al. (2019a) reported that the CA-based SOP of better crop establishment, legume inclusion and precision nutrient management helps to reduce the use of non-renewable energy such as fuel, fertilizer, herbicides, and electricity use for pumping irrigation water, resulting in decreases in cultivation cost and environmental footprints for economic and ecological benefits. Moreover, the SOP in wheat as ZT/PB, residue retention and diversified systems reduced the release of non-mineralized organic matter, resulting in a slowdown of microbial decomposition processes that contribute to carbon sequestration by reducing CO_2 emissions. The rice residue retention in ZT wheat eliminates the need to burn residues to clear fields for tillage, thus helping to improve environmental quality (Shyamsundar et al., 2019). Erenstein and Laxmi (2008) reported that ZT in wheat could save diesel about 36 l/ha, equivalent to 93 kg of CO_2 emissions/ha/year. Kakraliya et al. (2018) and Jat et al. (2020b) reported 34–40 % lower GHG emissions under CA-based improved management practices compared to CT. Mishra et al. (2021) reported that the CA-based rice-wheat system also led to 8–10 % lower global warming potential (GWP) than conventional methods in Eastern Indo-Gangetic plains.Kakraliya et al. (2022) reported that the GWP was reduced by 44–47 % under the CA-based rice-wheat system without significant yield loss compared to the conventional system. Similarly, Parihar et al. (2018) and Jat et al. (2019b) found lower carbon footprints under CA and advocated maize-wheat systems as efficient and clean. The double legume system (soybean-wheat-mungbean) significantly decreased CO_2 emissions and GWP in our study. Earlier studies have also shown that the crop after legume reduces carbon footprint by 17 % than the cereal-cereal system (Gan et al., 2011).

The increased eco-efficiency in SOP wheat over the CTRW was due to lower use of non-renewable energy resulting in reduced cost and increased net returns. Kakraliya et al. (2022) reported that climate-smart agricultural practices reduce environmental footprint while increasing farm profitability, thus enhancing eco-efficiency. Similar reports were also made by Heidenreich et al., (2022). The total CO_2 emission, emission intensity and eco-efficiency were significantly influenced by the effect of year. It could be due to increased total CO_2 emission associated with the oxidation of CO_2 from decomposing crop residue and higher electricity consumption for pumping irrigation water in the second year owing to lesser rainfall. Thus, changing rainfall patterns were also found to have an effect on GHG emissions in irrigated agriculture.

4.7. Weed dynamics

The significantly reduced weed density with system SOP of ZT/PB wheat with residue retention was associated with better crop establishment.The zero-tillage in rice-wheat system reduces the weed flora density and soil weed seed bankby least soil disturbance and residue retention (Mishra et al., 2022).However, the higher infestation of grassy and BLWs with CTRW might be due to greater aeration by intensive tillage as well as flood irrigation practices led better weed growth environment (Baghel al., 2020). The burning of rice straw increases the germination of *Phalaris minor* and reduces the efficacy of soil-active herbicides (Chhokar al., 2021).Additionally, herbicides play an important role in facilitating the adoption of ZT practices for effective and economical weed control. The inhibitory effect of rice residue on weeds was more pronounced with early wheat sowing compared to mid or late-Novemberplanting and thus reduces weed infestation severity in ZT wheat. Many researchers studied that the early wheat planting combined with rice residue mulch significantly reducesgrassy weed density especially *Phalaris minor* than the normal and late planting (Kumar et al., 2013; Chhokar et al., 2021).

Moreover, ZT with residuemulchenhancesmechanical impedance for seedling emergence, and higher weed seed predation and delays the germination and emergence of weedsby providingmoderate soil temperaturewhich provides favorable conditions to the crop for early vigour over weeds.Also, the residues mulch prevents light availability and releases allelochemicals, thusthe annual weed seeds may not germinate and grow.Our study recorded that the grassy weed density was significantly decreased in the second year of the experimentation at 90 and 120 days. Also, it was significantly decreased in the second year at 60 days. The level of weed infestation reduced with weed flora shift in wheat could be associated with different cropping systems, residue retention, tillage and crop establishment practices.Such observations were alsoreported by Chhokar et al. (2021) in similar agroecology. Kumar et al. (2013) and Mtambanengwe et al.(2015) reported that the crop residues as mulch reduced the weed density by 70 %, thus it offsetsthe concern about the use of herbicides in CA.

Similarly, the residue mulch of maize or soybean (up to 4–6 t/ha) appliedin a diversified scenario of wheaton PBreduced weed density by 3.0–31.0 % over the CTRW. However, the higher infestation of BLWs in ZT wheat was observed due to the lower amount of residue (4–6 t/ha) retained and more row spacing resulted in limiting the potential benefits of mulch for suppressing weeds. This could also be possible due to the shift of the weed flora from grassy to BLWs. Similarly, Chhokaret al. (2021) reported a higher density of BLWs(*Rumex dentatus*)in ZT compared to CT while a higher infestation of *Phalaris minor* in CTcompared to ZT wheat. The type and amount of residue retention influences weed infestation as earlier reported by Kumar et al.(2013).Chhokaret al.

(2021) reported that the 2.5 t/harice residue mulch was not effective in suppressing weeds, but 5.0–7.5 t/ha residue mulch significantly reduced weed infestation.In this study,we found that the BLWs density was significantly influenced by year (cropping system × year interaction) at different stages of observation due to the seasonal addition of crop residues leading to decreased weed density in the second year of the study by suppressing the weed seed emergence with over the year residue accumulation.

Many researchers reportedthat the wheat under CA-based management had a lesser infestation of *Phalaris minor,Ipomoea sp.* and *Chenopodium album* over conventional wheat(Singh et al., 2017; Chhokar al., 2021).Similarly, the ZT wheat under maize residue mulch resulted in better weed suppression, more seed bank depletion, delay in weed resistance, and higher productivity and profitability in the maize-wheat system (Susha al., 2018; Chhokar al., 2021; Ghosh et al.,2022).Additionally, the periodic nitrogen application using PNM practices helps in weed suppression by synchronized N application according to crop demand thus resulting in vigorous crop growth than weeds. Oyeogbe et al. (2018) reported that weed interference and N immobilization can be reduced by periodic N fertilizer application.Similarly, the PB with residue using 75 % N resulted in 34 % lesser weed density over the CT-basedflatbedwheat (Ghosh et al.,2022).

4.7.1. *Integrated assessment of SOP in wheat*

We have calculated the effect of the adoption of system optimization practices (SOP) on a 1 million ha (m ha) area over CTRW (Table 5). As per our study, the adoption of CA-based diversified in wheat with ZTSWMb (double legume system) on 1 m ha can increase 1.05 million tonnes (m t) of wheat production with saving of irrigation water use by 118 ha-mm/ha over the CT-wheat (CTRW). Moreover, it generates an additional profit of 362 US$/ha with a significant reduction of GWP and grassy weeds density (60 days) by 861 kg CO_2 eq/ha and 32 %, respectively over the CTRW. However, the SOP in wheat with ZTMWMb can increase 0.86 m t of wheat production by saving irrigation water by 129 ha-mm/ha over the CTRW. Additionally, the farmers can enhance the profit of 283 US$/ha while significantly lowering GWP and grassy weeds density by 783 kg CO_2 eq/ha and 46 %, respectively over the CTRW. Furthermore, the saving of non-renewable energy by 6700 MJ/ha by the adoption of diversified SOP (ZTSWMb and ZTMWMb) in wheat over CTRW.

Similarly, the adoption of DSR-ZTWMb and CTR-ZTWMb on 1.0 m ha can increase wheat production by 0.59 and 0.37 m t, respectively over the CTRW. The 85–86 ha-mm/ha irrigation water saving with additional income of 169 and 99 US$/ha can be generated in DSR-ZTWMb and CTR-ZTWMb, respectively over CTRW. Moreover, it can reduce GWP by 802 and 798 kg CO_2 eq/ha with a reduction in the grassy weed density by 67 and 46 % with DSR-ZTWMb and CTR-ZTWMb, respectively over the CTRW.

5. Conclusions

The on-farm study suggests that the system optimization practices (SOP)of zero tillage/permanent raised bed; summer legume inclusion and diversified cropping system with maize and soybean haveshown potential to increase wheat crop productivity with improved net returns. The integration of multiple tactics, including crop residue mulch, crop diversification, and manipulation of sowing time with better crop establishment was effective in suppressing weeds and can be included for sustainable weed management in wheat along with judicious use of herbicides.Moreover, the adoption of SOP reduced the environmental footprint (decreased waterand non-renewable energy use with lesser GWP), deceased weed infestation and improved nutrient productivity in conventional tilled rice-wheat systems in Indo-Gangetic Plains. Thus, puddled transplanted rice-ZT wheat-ZT mungbean (CTR–ZTWMb) and direct seeded rice-ZT wheat-ZT mungbean (DSR–ZTWMb) in the rice-wheat system and ZT raised bed-based futuristic diversified system of maize-wheat-mungbean(ZTMWMb)as well assoybean-wheat-mungbean (ZTSWMb, a double legume system)are better alternative to the conventional wheat cultivation (CTRW) for sustainable wheat production with lesser environmental footprints. In the present and future climate change scenario, the water availability and crop productivity are predicted to be adversely affected and hence, adoption of these SOP will be helpful in mitigation as well as adoption of climate change for sustainablewheat production in Indo-Gangetic Plains and similar agroecologies.

Table 5
The potential benefit of system optimization practices (SOP) in wheat in Western Indo-Gangetic Plains by adoption on one million ha acreage over conventional CTRW system.

Parameters	ZTSWMb	ZTMWMb	DSR-ZTWMb	CSR-ZTWMb
Wheat production increased (m t)	1.05	0.86	0.59	0.37
Saving of irrigation water (ha-mm)	118	129	85	86
Saving of non-renewable energy (MJ/ha)	6700	6700	5700	5700
Net returns enhanced (US $/ha)	362	283	169	99
Reduction in GWP (kg CO_2 eq/ha)	861	783	802	798
Reduced grassy weeds density (%) at 60 days	32	46	67	46

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

The author thankfully acknowledges the CIMMYT Academy and its Karnal staff for providing all logistic support and funding in this study. Also, thanks to farmers for participating in crop management and providing fields for this study.

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