International Journal of Plant Production
https://doi.org/10.1007/s42106-024-00296-1

RESEARCH

Enhancing Sustainability and Productivity of Rice–Wheat-Green Gram Cropping System through Alternative Tillage and Crop Establishment Approaches in North-Bihar

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Received: 15 March 2024 / Accepted: 27 April 2024

Abstract
The conventional paddy-wheat-green gram cropping system in the North-Bihar, area experienced issues such as diminishing yield, water constraint, and uneven fertilizer usage. Researchers wanted to boost sustainability and productivity by testing alternative tillage and crop establishment (TCE) practices within this cropping pattern. The research was conducted out at the Climate Resilient Agriculture (CRA) the village in the Muzaffarpur region of Bihar. The purpose was to compare five distinct (TCE) utilization in the present rice–wheat-green gram cropping system. The study indicated that the TCE technique designated SN 5 (ZTDSR-HSZTW-HSG) resulted in the greatest yields across all crops, with 15–18% greater rice yield, 20–25% higher wheat yield, and 20–22% higher green gram yield compared to other TCE methods. Additionally, SN 5 produced 20.2% larger net returns employing a conservation agriculture (CA)-based system compared to the conventional technique. These results suggest that CA-based TCE outperformed conventional approaches in terms of net returns and overall efficiency.

Keywords Zero tillage operations · Conventional tillage · Cropping system · Tillage · Crop establishment

Introduction

Climate change is a critical global challenge with far-reaching implications for both present and future generations. The driving force behind this phenomenon is the buildup of greenhouse gases (GHGs) in the Earth's atmosphere. These gases act as a barrier, capturing heat from the sun and resulting in an increase in global temperatures. This temperature rise gives rise to effects that impact the environment, society, and the economy in various ways (Malla, 2008). Climate change has multifaceted impacts on various aspects of the environment and human societies, leading to a range of interconnected challenges *i.e.* disrupt water cycles, altered precipitation that affect freshwater ecosystems like lakes, rivers, and wetlands and shifts in water temperature (Malla, 2003). The interconnectedness approach needs for a comprehensive and integrated approach to safeguarding both the environment and human well-being. Conjunctive management involved optimizing surface water and groundwater for coordinating water allocation to various sectors (agriculture, industry, domestic use), considering the water availability and resources for proper management should be holistic and well-informed to ensure long-term sustainability and resilience (David, 2011). Strategic planning based on the principles of sustainable development is necessary for sustainability with existing irrigation and drainage networks (Lee, 2008). Shifting climate patterns leading to an increased variability of weather conditions, posing significant challenges to modern agriculture. Overall, the increased variability of weather variables increases both abiotic and biotic stresses, by shifting climatic patterns and adaptive approach to maintain rural livelihoods, and promote environmental sustainability in ongoing changes in the weather pattern (Ortiz et al., 2008). Weather vulnerability results pattern of shifting agriculture from conventional tillage management practices to zero tillage management practices. Zero tillage and residue retention have been popular methods

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Published online: 04 June 2024

for making intensive cropping systems sustainable over the past two to three decades (Sharma et al., 2012). Climate change can lead to changes in temperature, precipitation patterns, extreme weather events, and shifts in growing seasons, which significantly affect crop yields, potential environmental impacts like soil degradation, nutrient depletion, overuse of resources and overall food security. To mitigate the effect of climate, change a number of technologies has followed, such as the creation of drought-resistant crops and better water management. Growing more crops on a given piece of land each year resulted in increased agricultural productivity per unit area, which can either be achieved by raising the yield of a single crop or by increasing the cropping intensity (Pingali, 2012). Climate change and increasing food demands, ensuring the sustainability and resilience of the rice–wheat agricultural system is of paramount importance for the food security and livelihoods of millions of people in South Asia (Kumar et al., 2018). The North Indian Plain face significant challenges due to unsustainable agricultural practices that negatively impact natural resources and contribute to environmental issues like massive residue burning (Chaudhary et al., 2018). A combine harvester operation to harvest more over two thirds of the IGP's rice fields, results in loose rice residue that limits future field preparation and sowing. As a result, in-situ residue burning and regular ploughing is a popular practice throughout north India *i.e.* inexpensive and hassle-free. The states of Haryana and Punjab wasted 31.25million MJ of energy and 37 Mt of CO_2 emissions due to a practice of burning leftover rice and wheat residue (Singh et al., 2015). Residue burning causes a significant loss of biomass, organic C, surface water, and soil temperature, and it also negatively affects soil microorganisms. Residue burning accounts for around 0.05% of India's total GHG emissions. As a result, remaining management systems with high potential for resource efficiency are desperately needed (Gadde et al., 2009).

The development of resource-conserving technologies (RCTs) has made it possible to reduce cultivation costs while maintaining yield stability in intensive cropping systems. Crop residue management affects soil water movement, runoff, and infiltration as well as the quantity of nutrients incorporated into the soil for crop production. A resource conservation system cannot function well without effective crop residue management, and in-situ management. By lowering energy inputs and boosting biological activity and carbon storage in the soil, in-situ management promotes soil fertility (Bhan & Behera, 2014 and Behera & Sharma, 2011). Without ploughing a single tractor operation with a specially designed zero till seed drill cum fertilizer, the crop can be sown, ahead of schedule and without any field preparation (Meena et al., 2015). By maintaining a proper cropping system from planting through harvest, sustainability can be accomplished.

Crop diversification, which involves growing a variety of species or crop kinds in different seasons throughout the same year, is a crucial strategy for enhancing sustainability. According to research, it has variety of advantages, like higher productivity, improved nitrogen use efficiency, to improve other ecosystem services, there is need of reduction in carbon footprints (Tamburini et al., 2020; Gan et al. 2015; Yang et al., 2011). Cropping system changes that jeopardize economic viability or reduce labour, fertilizer, or energy efficiencies at the farm level are undesirable. The cropping system refers to maximizing crop output per unit of land within the appropriate time frame while minimizing the degradation of natural resources (Gangwar et al., 2012). Cropping systems are still dynamic to use traditional methods for mapping out their distribution across a larger area. Thirty significant cropping systems have been determined based on the justification for crop distribution in each district of the nation (Das, 2010). The cropping systems determined by the soils and climate, as it influence the overall agro-climatic condition for sustainability and suitability of crops for production (Gangwar et al. 2004b). About 10.5 million hectares of land in India were mostly used for the cereal based cropping system, to ensure global food security. To meet the increasing population's demands for nourishment, the North Indian Plain of Bihar must have high cropping intensity that is at least double its current level (140%) (Upadhaya et al., 2022). Therefore, research must be taken for variety of sustainability measures, as well as any potential synergies under ideal conditions that are typical for small land holders to compare alternate sequences of several cultivation practices to look at potential diversification strategies for cereal and pulse based cropping systems (Emran et al., 2021; Assefa et al., 2021; Hufnagel et al., 2020). The rice–wheat (R-W) cropping system is one of the most labour and resource-intensive land-use patterns used in South Asia. These activities are disturbing the ecological balance, depleting groundwater supplies, diminishing soil organic carbon (SOC), and adversely impacting the physicochemical qualities of the soil. (Bhatt & Singh, 2018, and Srinivasarao et al., 2019). This methodology employs the traditional method of cultivating rice, which includes manually transferring seedlings that are 25–30 days old into waterlogged conditions during the kharif season. This method uses a lot of water. It takes 200 to 250 mm of water to do puddling. The current land-use patterns in cropping system, need a lot of work, money, and resources. The ecological balance has thrown off, groundwater supplies have depleted, soil organic carbon (SOC) has drained, and labour-energy-intensive practices were used that have a deleterious effect on the soil physicochemical qualities (Islam et al., 2019 and Rashid et al., 2019). Additionally, the soil puddling for rice include greater weed control, faster seedling establishment, and increased nutrient availability, deteriorates the physico-chemical and biological properties of the soil, and adversely affects growth and productivity of crops Islam et al., 2019; Mondal et al., 2020 and Kumar et al., 2018). To ensure the food security of the nation, eastern India has been targeted for second Green Revolution. The Indo Gangetic Plains currently practice a rice wheat-based farming system with long-duration (150–160 day) paddy varieties and late transplanting followed by delayed wheat planting with decreased yield and quality due to terminal heat stress during grain filling stage due to late rice harvesting (Jain et al., 2017). Planting wheat after mid-November was reported average yield reduction of 27 kg ha (Tripathi et al., 2005). A significant amount of crop residue has been left in the fields as a result of the region's increased use of combine harvesters for harvesting rice and wheat.

The implementation of Conservation Agriculture (CA) by farmers involves minimal soil disturbance, maintaining coverage of crop residues on the soil surface, and incorporating a variety of crops in succession (Mishra et al., 2021). This strategy led to an investigation and resolution of several new difficulties (Ranaivoson et al., 2017). he agricultural systems and CA methods employed in the Muzaffarpur district differ from conventional practices. Zero-tillage (ZT) with or without keeping crop residues is implemented in forthcoming winter crops, showing a partial adoption of CA. Rice cultivation often requires puddling and transplanting.

The economic environment may move in favor of sustainable intensification of (RWCS) agriculture due to the implementation new crop establishment (CE) techniques. Various CE methods, including as mechanical rice transplanting, the System of Rice Intensification (SRI), zero-tillage with crop residue retention, and Direct Seeded Rice (DSR), come with their own advantages and disadvantages (Jat et al., 2019). Taking all these variables into account, the practice of triple zero-till cropping (ZT DSR—ZT wheat—ZT greengram) within the irrigated agro-ecosystem in the Indo-Gangetic plains of Bihar may emerge as a more sustainable choices for smallholder farmers.

Keeping above facts, the present study was focused to identify the suitable tillage and crop establishment method to improve the productivity and profitability of rice–wheat-green gram system. Apart from it some important parameters like energy use efficiency can also help to reduce the environmental hazards.

Materials and Methods

Field experiments involving kharif sowing Paddy (June/July–October/November) followed by Rabi sowing of wheat (October/November–April) and green-gram (April–June) were conducted during 2019–20 to 2021–22). On the farmer's field of village Bhagwatpur (29° 75′ N, 76° 86 E), Dawarikanatpur (29° 83′ N, 76° 88′ E) and Karja Ananth (29° 80′ N, 77° 10′ E) of Muzaffarpur district of Bihar *i.e.* north eastern part of North Indian Plain (Fig. 1). The experimental site was loamy and sandy loam in texture (International Pipette Method) with the history of paddy, rapeseed and mustard and fallow (summer) cropping mainly. The crops were sown in five different scenarios in RBD as per (Table 1) in farmer's field of all the three villages. All the recommended practices were adopted for rice, wheat as well as green gram (Table 2). Observations were recorded for yield and its attributing traits of 10 randomly selected plants. Cost of cultivation was calculated by taking into prevailing price of inputs like fertilizer, seed, herbicides, irrigations, tillage operations, transportation charges, management charges, and depreciation cost of implements. Returns were calculated by taking minimum support price and market price. The package and practices was mentioned in Table 2.

Weather parameter during cropping season were recorded at agrometeorological station installed at KVK, Saraiya *i.e.* the experimental field of village bhagwatpur, dwarkianathpur and kant karja under Madwan block of Muzaffarpur Bihar, India. Among the many meteorological factors, rainfall pattern (both intensity and distribution) was relatively diverse over the experimental years (2020–21 to 2021–22) (Fig. 2).

Crop Residue Management and Its Impact on Soil Organic Matter

The objective of the field study was to compare different crop residue management techniques in the context of wheat, rice, and green gram crops. In order to manage agricultural residues left behind after harvesting rice, wheat, and green gram crops, the study explored the amount of crop residue recycled under various tillage and crop establishment (TCE) methods like zero-tillage (ZT), conventional tillage (CT) and happy seeder (HS). The study's primary aimed to assess the effects of various TCE techniques on crop residue management, with an emphasis on the crop's wheat, rice, and green gram. The findings offer insightful information about sustainable agriculture methods and the significance of recycling leftover crop residue for ensuring soil health and productivity.

Soil organic matter (SOM) content is crucial for understanding soil health, fertility, and carbon matter. Soil samples were collected according to soil type and vegetation of experimental site. Diagonal sampling method was followed for collection of soil from each grid. Five random

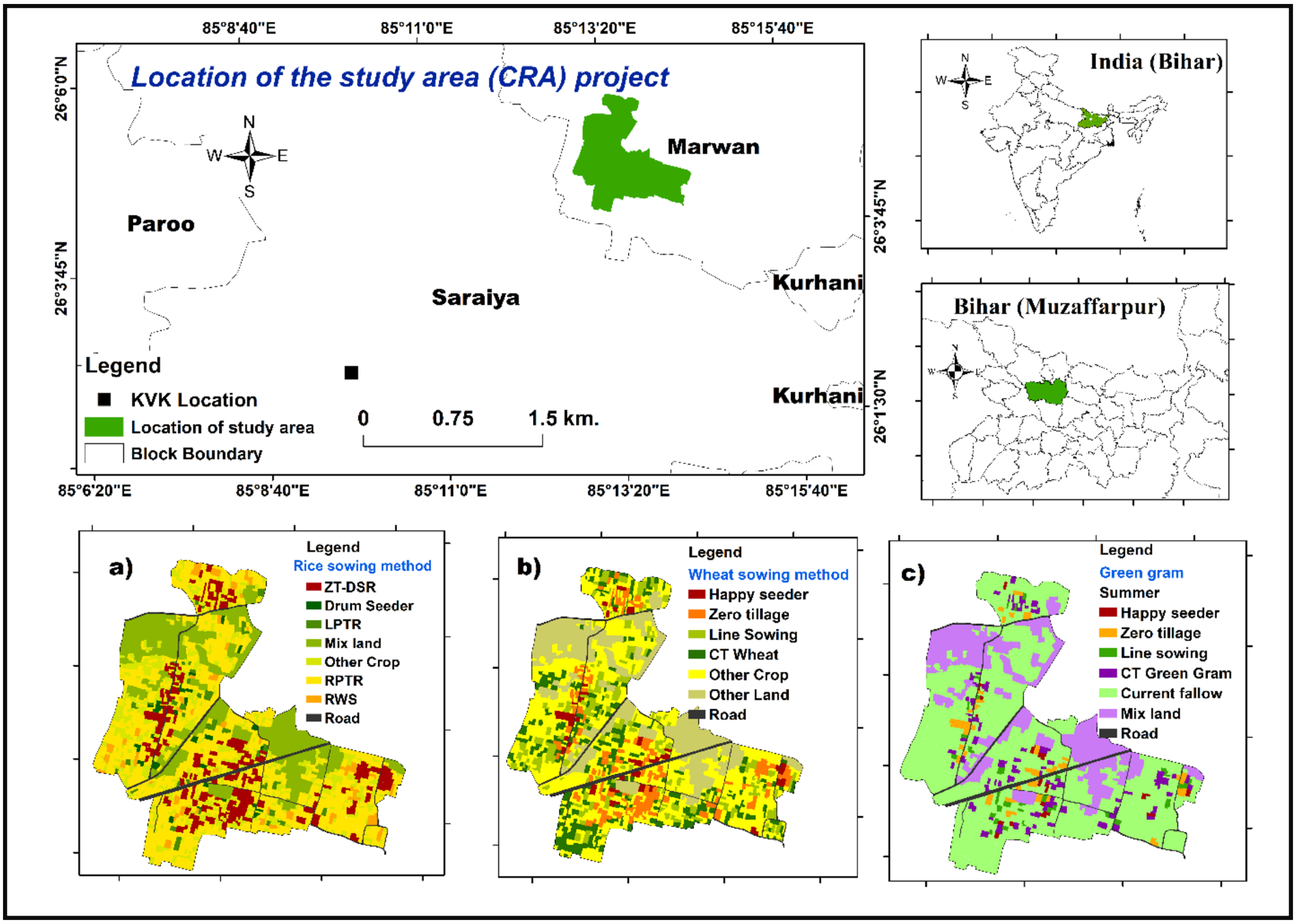

Fig. 1 Geospatial Cropping Pattern of the Study Area for (**a**) Kharif Season, (**b**) Rabi Season, and (**c**) Summer Season

sample were collected from selected farmers' fields of three different villages of Madwan block under Climate resilient agriculture. Samples were dried at room temperature after removing debris stone through an 80-mesh sieve with a hole-size of 2 mm, and then saved for testing the organic matter. The determination of organic matter was based on the Walkley and Black, 2019.

Rice Equivalent Yield, Relative production efficiency and Partial factor productivity

For comparing the results of different cropping sequences, the yields of Kharif, rabi and summer crops were converted into rice equivalent yields using the formula (Eq. 1) cited by Upadhaya et al., 2022 and Kumar et al., 2018:

$$\begin{aligned}\mathrm{REY}\left(\mathrm{tha}^{-1}\right) = &\left\{\text{Yield of first crop}\left(\mathrm{tha}^{-1}\right)\times \text{Price of first crop(Rs/t)/Price of paddy(Rs/t)}\right\}\\ &+\left\{\text{Yield of second crop}\left(\mathrm{tha}^{-1}\right)\times \text{Price of second crop(Rs/t)/Price of paddy(Rs/t)}\right\}\\ &+\left\{\text{Yield of third crop}\left(\mathrm{tha}^{-1}\right)\times \text{Price of third crop(Rs/t)/Price of paddy(Rs/t)}\right\}\end{aligned} \tag{1}$$

The rice equivalent yield (REY) was calculated to compare the system performance by converting the non-rice crop's yield into an equivalent paddy yield based on price.

The relative production efficiency was computed by (Eq. 2) the formula cited by Upadhaya et al., 2022.

$$\begin{aligned}\text{Relative Production Efficiency}\left(\%\right) = &\left\{\text{Total productivity }\left(\mathrm{TP}\right)\text{ of diversified cropping system}\right.\\ &\left.-\text{TP of existing cropping system/TP of existing cropping.System}\right\}\times 100\end{aligned} \tag{2}$$

Table 1 Details of tillage, crop establishment and residue management in different scenario

Treatment	Tillage			Crop establishment					Residue management		
	Paddy	Wheat	Green gram	Rice			Wheat	Greengram	Paddy	Wheat	Green gram
				Transplanting/ Seeding	Seedling age	Spacing (cm)					
T5: ZTDSRH-SZTWHSG	Zero-till direct seeded rice	Happy seeder wheat	Happy seeder greengram	DSR: Zero-till	Drill seeding	20 cm row spacing	Happyseeder	Happyseeder	30% Incorpo-rated	30% retained on soil surface	100% Incorpo-rated
T4: CTDSR-ZTW-ZTG	Rice–wheat seeder: Cultivator: 2 passes (dry tillage: DT) Rotavator: 1 pass Dry till-age: DT),	Zero till-agewheat	ZT greengram	DSR: Zero-till	Drill seeding	20 cm row spacing	Zerotill	Zerotill	30% Incorpo-rated	30% retained on soil surface	100% Incorpo-rated
T3: RWSR-WZTWZTG	Drum Seeder: Conven-tional till direct seeded rice\ (CTDSR)	Zero tillage wheat	ZT green gram	Rice–wheat seeder	-	20 cm row spacing	Ricewheat seeder	Zerotill	5% Incorpo-rated	5% Incorpo-rated	100% Incorpo-rated
T2: LPTRCTL-WLSG	Puddled line transplanted rice (LPTR)-	Conventional tillage line sown wheat (CTLW)	Conventional tillage line sown ZT: green gram	Line trans-planting (Manual)	21–25 days	20×20	Line sowing: 20 cm	Zerotill	5% Incorpo-rated	5% Incorpo-rated	100% Incorpo-rated
T1: RPTRB-CWBCG	Random Puddle transplanted rice (RPTR)	Broadcasted wheat: Cultivator: 2 passé, Rotavator: 1 pass	Broadcasted: 1 pass Rota-vator	Manual	21–25 days	Random	Broadcasting	Broadcasting	5% Incorpo-rated	5% Incorpo-rated	100% Incorpo-rated

Table 2 Package and practices of crop sown under cropping system

S.No	Crop	Sowing Time	Variety	Seed rate (ha)	Spacing (cm × cm)	Fertilizer Application (N/P/K/S in kg/ha)	Number of irrigation	Harvesting Time
01	Paddy	15th June (Nursery Raising) 06th July (Transplanting)	Rajshree	35 kg	20	120kg N (Two Spilt dose) 60 kg P (Basal dose) or 40 kg K (Basal dose)	03	03rd-07th November
		10 to 15th June DSR		25 kg				
02	Wheat	10th to 15th November	HD2967	100 kg	22.5	90 kg N (Two Spilt dose) 60 kg P (Basal dose) or 40 kg K (Basal dose)	02	20th—25th March
03	Green gram	25th – 30th March	IPM-2–3	30 kg	25 × 25	50 kg P (Basal dose)or 25 kg K (Basal dose)	01	29th April-25th May

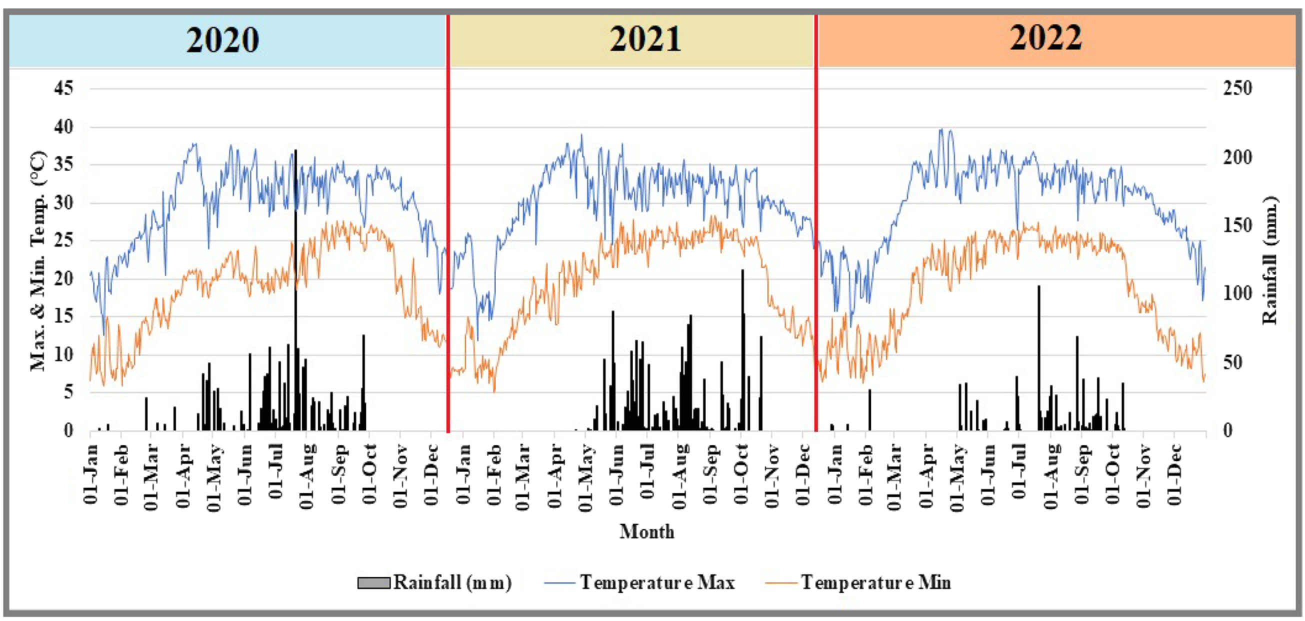

Fig. 2 The daily maximum (Tmax in °C), minimum temperature (Tmin in °C), and total rainfall (mm) were recorded for three crop years 2020 -2022

Partial factor productivity (PFPN) of applied N (kg grain kg N^{-1}) is calculated as grain yield (kg ha^{-1}) produced from the unit quantity of N applied (Gupta et al., 2022a, b).

Standard statistical methods of analysis were followed for the yield and yield attributing parameters according to ANOVA to determine the effects of the treatment of the cropping systems on the system productivity. At 5% probability level error mean square of the "F" test was used to determine the importance of the causes of variation. RBD test at the 5% level was used to compare the mean values of the various experimental parameters. Data analysis were performed by SPSS Software and MS Excel.

Earthworm Population Estimate

Geographical location, temperature, soil quality, and particular factors like how crop residues are managed in a rice–wheat-green gram cropping system can all have a significant impact on earthworm populations. The procedure used to assess the earthworm population required digging dirt trenches that were each 1 m long, 1 m wide and 0.30 m deep. On each side, these excavations were done. The topsoil was painstakingly collected after the soil trench was dug, and an earthworm count was done there. The method described by Schmidt and Curry in their papers from 2001 and 2009 was then used to separate the earthworms from the soil. Every soil pit's total number of earthworms was meticulously recorded. After that, the weight of the earthworms was measured using an electronic balance.

Statistical Analysis

Standard statistical methods of analysis were followed for the yield and yield attributing parameters according to ANOVA to determine the effects of the treatment of the cropping systems on the system productivity. At 5% probability level error mean square of the "F" test was used to determine the importance of the causes of variation. RBD test at the 5% level was used to compare the mean values of the various experimental parameters. Data analysis were performed by SPSS SOFTWARE and MS Excel. Principal Component Analysis (PCA) was carried out using R-Studio to reveal hidden correlations and trends present in the dataset. This methodical technique considerably improved our comprehension of the relevance of the data and clarified the experiment's results.

Results

Yield Attributing Traits

The analysis pooling two years of data revealed a significant impact of tillage and crop establishment methods on paddy spike length (Table 3) with a statistical significance level of $P < 0.05$. Additionally, both the number of panicles per square meter and the number of grains per panicle exhibited significant variations due to the different tillage and crop establishment methods. SN-5 (ZTDSR-HSZTW-HSG), comparable to SN-4 (CTDSR-ZTW-ZTG), demonstrated a significantly higher number of panicles per square meter (407), ranging from 9.7% to 25.6% ($P < 0.05$) compared to transplanted rice (324–365) and SRI (371) (Table 3). Similarly, SN-5, on par with ZTDSR-ZTW-ZTG and RPTR-BCW-ZTG, recorded a significantly higher number of grains per panicle (193), showing an increase of 17.7% to 36.9% compared to other crop establishment methods (141–164) Shown in Table 3.

Regarding 1000-grain weight, RPTR-BCW-ZTG exhibited a significantly higher value (23.38 g) compared to other crop establishment methods (22.18–22.75 g), showing an

Table 3 Morphological parameters of different crops

Paddy						Green gram					Wheat				
Scenario	AET	No of filled grain panicle	Spike length	Number of panicles/m2	Grain Yield (q/ha)	Plantheight	Number of pods/plant	Number of seeds/pod	Pod length	Grain Yield	AET	No of filled grain/panicle	Spikelength	Number of panicles/m2	Grain Yield (q/ha)
SN-1	24.09	181.12	19.2	270.30	41.26	71.25	11.6	7.3	8.94	9.59	86.4	48.36	9.71	386.6	37.46
SN-2	18.10	190.50	19.5	272.70	42.13	68.65	13.2	7.9	8.80	11.14	96.6	60	10.35	463.5	44.26
SN-3	14.50	183.50	19.5	268.65	40.60	56.65	18.9	8.55	9.24	12.64	96	64.6	10.90	476.6	57.41
SN-4	28.40	203.00	19.8	282.95	47.80	61.25	19.2	8.95	9.29	12.4	98.1	66.8	10.06	462.4	41.69
SN-5	32.00	228.00	19.8	302.55	57.74	63.35	19.8	9.6	9.29	13.55	100.9	69	10.85	488.6	59.57

increase of 2.8% to 5.4%. In contrast, the lowest value was observed with CTDSR-ZTW-ZTG (22.1 g).

Yield and Yield Attributing Traits

The result shows that yield and yield attributing traits of paddy, wheat and green gram sown under cropping system in both the year significantly influence all yield attributing traits like average effective tillers, number of filled grain/panicle, number of panicle, 1000 grain weight, grain yield (kg/ha). The yield of crop was observed best in SN 5 (57.74 q) and all the traits were significantly at par with SN3. The economics of crop (right from cost of cultivation to B: C ratio) was found best in SN5 apart from all other scenario. Wheat sown after paddy harvest without ploughing by happy seeder machine was found to be significant for all parameters except spike length. Wheat yield was found to be highest under SN5 and significantly higher than SN3. Green gram is a key crop of the Zaid season, and it was seeded shortly after wheat harvest. All yield and yield contributing characteristics were found to be significant in SN5 (Fig. 3).

Conservation agriculture (CA) based cropping pattern aims to promote sustainable and eco-friendly agriculture practices *i.e.* based on three main principles: minimum soil disturbance, permanent soil cover, and crop rotation. It reduces soil disturbance during tillage, planting operations, maintain soil structure and reduce soil erosion, and improve soil fertility and water retention. Farmers can achieve this by using minimum tillage, zero tillage, or no-till planting methods. Overall, conservation agriculture is a sustainable farming system based approach to promote the long-term productivity and environmental health for sustainable agriculture.

Rice Equivalent Yield in Different Scenario

Crop diversification is an agricultural strategy to improve soil health, reduce pest and disease pressure, increase resilience to weather extremes, and improve the overall sustainability of farming systems and help farmers to adapt changing weather patterns and reduce the risks associated with relying on a single crop. It can help farmers to adapt changing weather patterns and reduce the risks associated with relying on a single crop. Rice–wheat cropping system significantly influenced the system productivity in different scenario (Fig. 3). The highest Rice Equivalent Yield were observed highest in SN5 and were found significantly superior to all other

Table 4 Equivalent yield and production efficiency of diversified cropping system

Scenario	Rice Equivalent Yield (t/ha)	Relative Production Efficiency (%)	Partial factor productivity(PFP)		
			Paddy	Wheat	Green gram
SN-1	10.15	11.73	1.29	0.10	0.96
SN-2	9.46	12.13	1.80	0.11	1.13
SN-3	9.95	14.37	4.00	0.11	1.30
SN-4	9.28	11.25	1.34	0.00	1.16
SN-5	12.73	17.01	1.84	0.10	1.14
SEM	0.14	0.05	0.01	0.18	1.43
CV	1.86	0.48	0.81	0.01	0.13

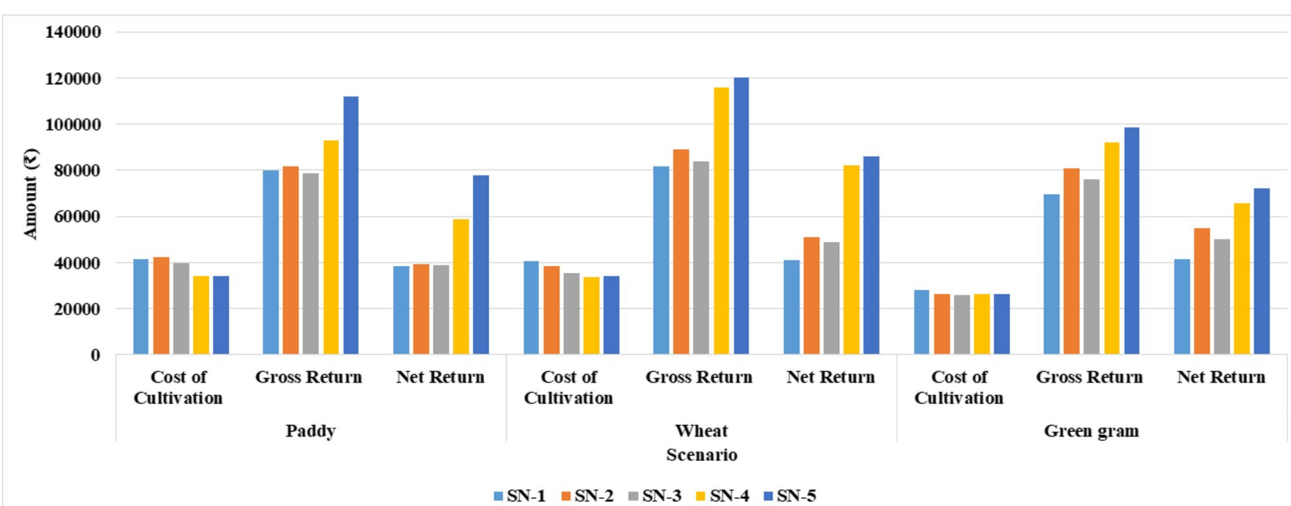

Fig. 3 Economics of Different scenario of cropping system

scenario as per Table 4. However, all other scenario were significantly at par with other.

Relative Production Efficiency, Partial Factor Productivity, System Production Efficiency and System Profitability

Utilization of improved agricultural implements (Happy Seeder, Zero tillage machine etc.) for sowing of different crops without ploughing in the prevailing cropping system varied greatly in different scenario and caused large variation in relative production, system production efficiency and partial factor productivity. SN-5 demonstrated the highest relative production efficiency among the various cropping systems, significantly outperforming the others. The utilization of different implements in cropping systems had a notable impact on both system production efficiency and partial factor productivity. Likewise, the maximum value of partial factor productivity varied across different scenarios, with SN-3 recording the highest value (Table 3). SN-5 exhibited significantly superior system production efficiency (SPE) and system profitability compared to other scenarios, surpassing the rest of the cropping system patterns. The choice of tillage and crop establishment methods exerted significant effects on system profitability in both study years.

The pooled average data from two years indicated a substantial impact on system productivity. In North Indian Plain (NIPs), traditional rice cultivation involves puddling and intensive tillage. Transitioning to Direct Seeded Rice (DSR) from traditional puddling necessitates changes in agronomic management practices, particularly in handling weeds and crop residues (Gathala et al., 2011). Consequently, zero-tillage initially results in yield declines in humid climatic conditions but catches up with conventional tillage practices in subsequent years. This pattern was evident in our experiment, where system productivity was 12–15% lower in the initial two years. Similarly, Jat et al. (2014) observed that in rice–wheat rotation, no-till with residue retention exhibited lower yields than conventional tillage initially, but after 4–5 years, yields were equivalent in both conservation and conventional tillage.

Earthworm Population and Soil Organic Matter

Different crop establishment tillage methods have a major impact on earthworm population and soil organic matter. Earthworm population was varied in several scenarios and found to be significantly higher in SN-5 (750–760/m^3) and comparable to SN-4 (700–710/m^3), although it ranged from 350–680/cubic metre in other crop establishment methods. The fresh weight of earthworm changed according to crop setup method as well. In compared to other tillage techniques, it was significantly higher in SN-5 (7.7–7.8 g/m^3) and comparable to SN-4 (7.2–7.3 g/m^3) (Fig. 4 and Figs. 5 and 6).

Principal Component Analysis (PCA)

The principal component analysis visualizes the similarities and dissimilarities between the methodologies, and further shows the impact of each attribute on each of the principal components. Different methods of sowing paddy have two dimensions. It has sown in the Fig. 3 that RPTR and LPTR has negative correlation or lower PC2 scores but both the technology was close association with each other whereas ZTDSR has positive correlation and higher PC1 scores. PCA biplot for green gram in Fig. 7 shown that green gram sown by happy seeder has highest positive correlation having highest PC1 scores and has closer association with green gram sown by zero tillage. Broadcasted green gram (Fig. 7) has highest negative correlation having highest PC2 scores. PCA biplot for wheat (Fig. 8) shown that green gram sown by happy

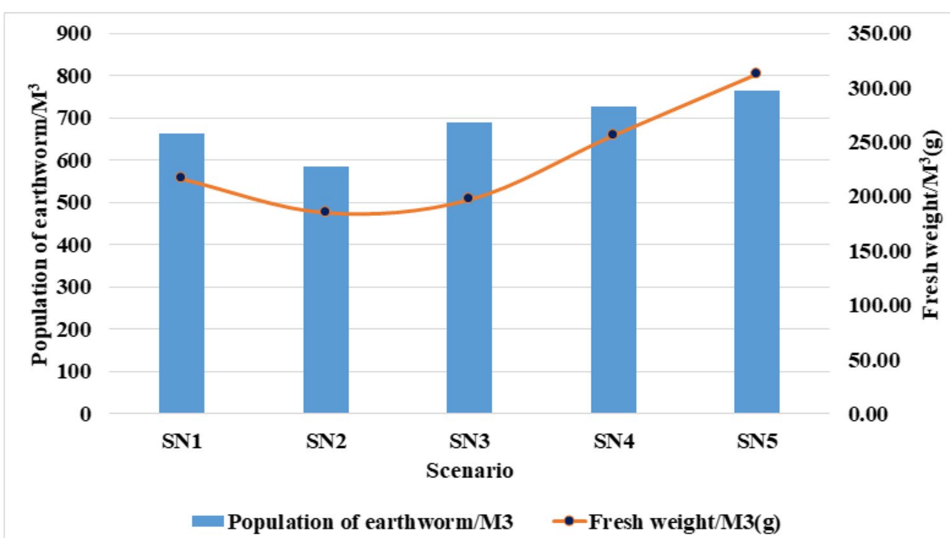

Fig. 4 Earthworm Population as per scenario

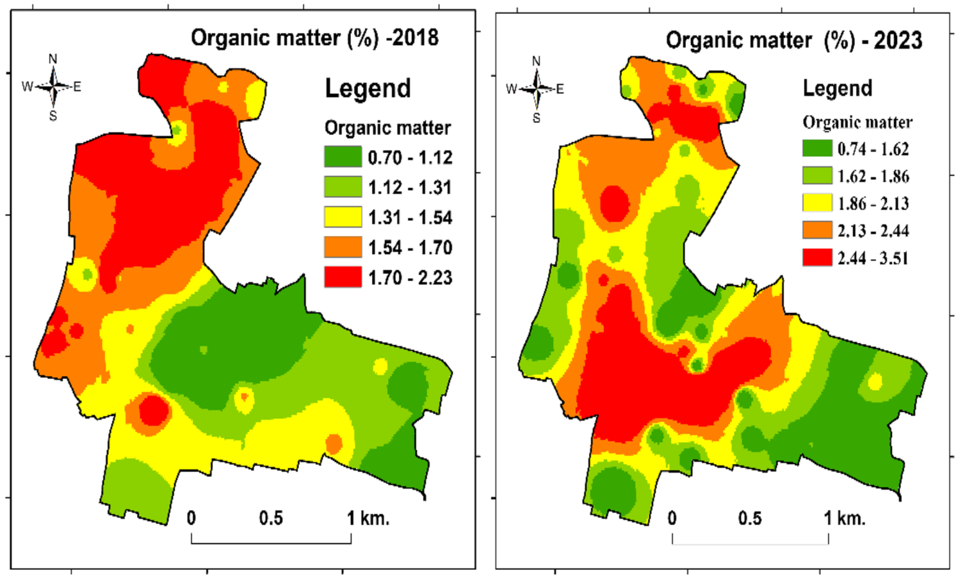

Fig. 5 Organic Matter % before and after practice of crop establishment method

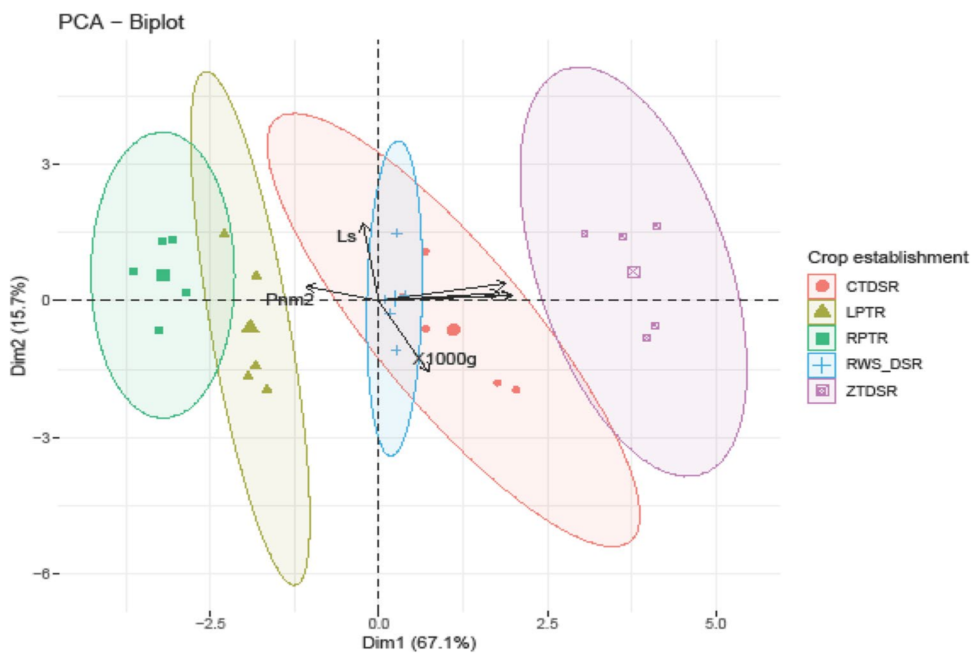

Fig. 6 Principal Component Analysis (PCA) of paddy

seeder has highest positive correlation having highest PC1 scores and has closer association with wheat sown by zero tillage. Broadcasted wheat has highest negative correlation having highest PC2 scores.

Discussion

The meteorological parameters recorded during the cropping seasons at the Krishi Vigyan Kendra, Saraiya meteorological observatory in Muzaffarpur, Bihar, India, over a span of two years (2020–2021 to 2021–2022). The maximum amount of rainfall observed in July suggests that the region might have experienced a monsoon climate, where heavy rainfall is typical during the monsoon season and is influenced by monsoon winds, topography, and sea surface temperatures. The variability of rainfall patterns and the consistency in mean monthly maximum and minimum temperatures during the kharif season (June-October) (Mishra et al., 2021). In both years, the irregularities in rainfall and other weather parameters leads to El Niño/La Niña events, climate change, local topography, and change in atmospheric conditions.

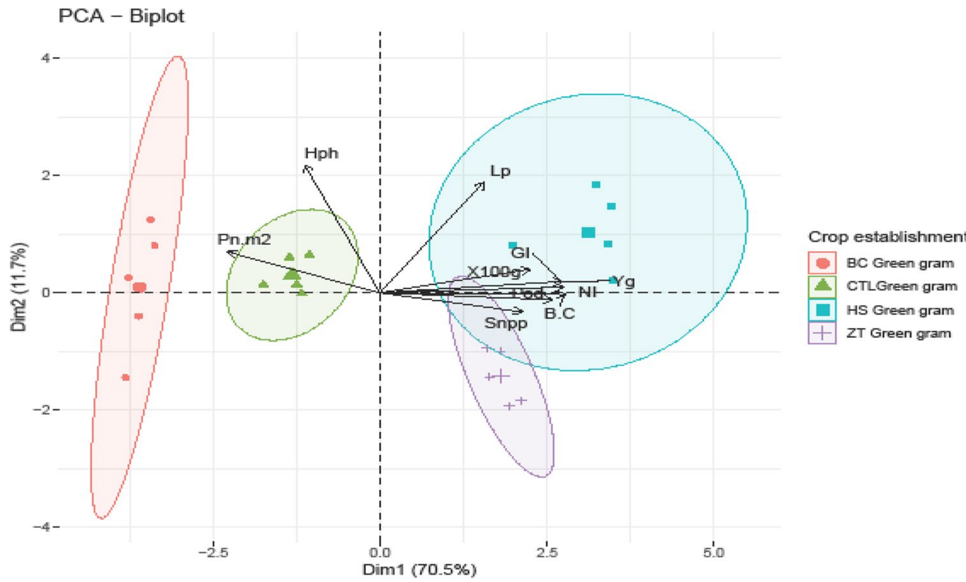

Fig. 7 Principal Component Analysis (PCA) of green gram

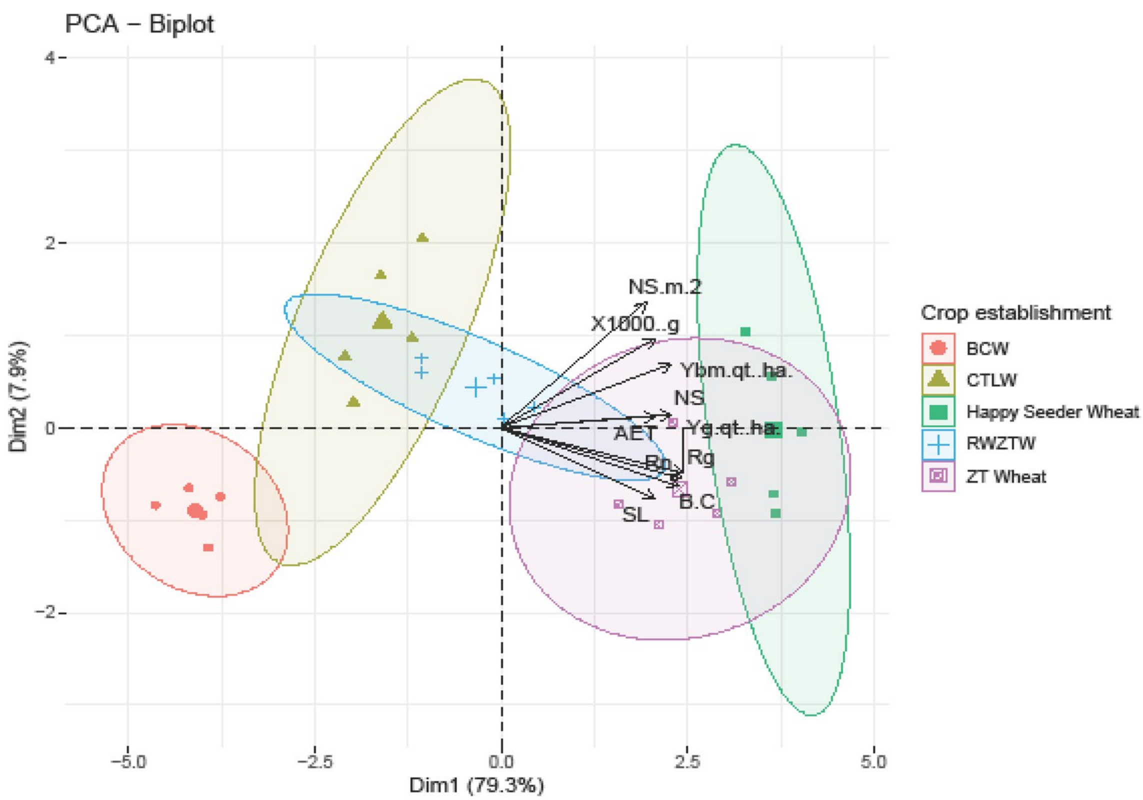

Fig. 8 Principal Component Analysis (PCA) of Wheat

These variations highlight the earth's climate system, where changes in one aspect can trigger a cascade effects across different components of the environment. The consequences of these variations may be significant. It can impact agriculture, water resources, and mitigate potential risks to adapt changing climatic conditions. The climatic pattern is common in many regions, particularly in arid and tropical zones. The changes in temperature and precipitation influence the local ecosystems, agriculture, and overall climatic scenario and cropping condition in the region (Gupta et al., 2022a, 2022b). The wet monsoon season is crucial for replenishing water sources and supporting vegetation growth, while the dry and hot summers and winters have their own impacts on various aspects of the environment and local activities.

The study demonstrates that both tillage and crop establishment methods have a significant impact on various rice yield parameters. Different methods can lead to variations in panicle density, grain count per panicle, and grain weight, all of which contribute to the overall yield of paddy. According to Singh et al., 2020 and Xu et al., 2019 there was yield loss of 12 to 15% in DSR over PTR whereas CTDSR yielded at par to MTR, PTR and SRI. DSR plot production was lower than other plots due to soil sickness, faster weed growth because of favorable conditions due to alternate wetting and drying and moisture stress due higher percolation rate. The pooled data indicated that the grain yield and morphological traits of paddy was significantly higher by 15–18% in SN-5(Zero-till direct seeded rice) as compared to another scenario. The present study indicates that Zero-till direct seeded rice has observed higher yield by following proper management practices like timely sowing, timely fertilizers and pesticides application and mitigates the problem of higher spikelet sterility and other abiotic stresses to optimize paddy growth and yield outcomes. The above finding has an agreement of Sharma et al. 2022. In wheat pooled data indicated that the SN-5 (Happy Seeder wheat) have a significant effect on average number of effective tillers, spike length, number of panicles/m^2, grain yield and has observed 20–25% higher for all traits under study in comparison to all other scenario. The current study was also contrasted with previous studies (Kumar et al., 2018; Singh et al., 2020). The adoption of zero-tillage for wheat cultivation has proven advantageous in terms of grain yield. This practice involves leaving crop residues on the soil surface, providing protection against erosion, crusting, and moisture loss through evaporation, thereby contributing to improved carbon sequestration (Mondal et al., 2020) and soil moisture conservation (Jat et al., 2019). Additionally, zero tillage promotes enhanced rooting (Chaki et al., 2022) and effectively reduces weed infestation (Mishra et al., 2021). By minimizing tillage operations, it results in time savings during crop establishment. The method also contributes to better soil aeration and structure, creating a conducive environment for optimal plant growth and increased yield (Singh et al., 2020). These benefits contribute to sustainable and efficient agricultural practices. It's important to observe effectiveness of zero tillage that depends on local climate, soil type, crop choice, and management practices. Researchers often study these factors to understand the broader implications of adopting zero tillage techniques in different agricultural contexts.

Sowing green grams using a happy seeder machine was a new approach of sowing crops without tilling or ploughing the soil, hence minimizing soil disturbance and preserving natural structure. It was sown in an embedded wheat residual field by zero tillage methods and a happy seeder machine. Diverse crop establishment methods in different scenarios influenced grain yield in both years. All the yield and yield attributing traits were significantly at par with each other and was significantly higher in SN-5. However, during 2020–21 and 2021–22, it was significantly higher (20%) in SN-5. As green gram was sown in zero-tilled uniformly anchored wheat residue under all the treatments, differences in yield among the treatments were marginal. Zero-tilled green gram proved its superiority over conventional system. The above finding agreed by Mishra et al., 2021 and Upadhaya et al., 2022.

In the context of the comparison between different crop establishment techniques in a rice–wheat-green gram cropping system, the statement "Gross returns and net returns proportional to the economic yield of crops and the variable cost of cultivation" means that when the economic yield of crops (in this case, rice, wheat, and green gram) increases, both gross returns and net returns are likely to increase, assuming that other factors remain constant. The highest net return and B: C ratio were recorded in SN-5 (Paddy-80625.40, 2.35; Wheat-88429.96, 2.60 and Green gram-71693.26, 2.72) which was significantly higher over the rest of the crop establishment methods. In this scenario, if the yield of crops like rice, wheat, and green gram increases, it would generally lead to higher total revenue (gross returns) generated from the sale of these crops. Additionally, if the variable cost of cultivation remains consistent, the increase in yield would contribute positively to the net returns as well. Net returns are calculated by subtracting costs (including variable costs) from gross returns. Therefore, a higher economic yield and constant variable costs would result in greater net returns. Similar results were also corroborated by Kumar et al., 2008, Sharma et al., 2004 and Olekar et al., 2000a, b. The observance of higher net return in SN-5 was due to reduction in cost of tillage operation, reduction in irrigation cost over conventional system as reported by Jat et al., 2019; Gathala et al. 2015 and Erenstein, 2002.

The system production efficiency, rice equivalent yield (T/Ha), Relative Production Efficiency (%), Partial Factor Productivity and System profitability (Rs ha^{-1} day^{-1}) varied significantly due to diversified crop establishment methods. These parameters "varied significantly due to diversified crop establishment methods" indicates that different ways of establishing crops within the rice–wheat-green gram cropping system had a notable impact on the overall efficiency, productivity, and profitability of the system. These variations could be attributed to factors such as differences in input management, plant spacing, planting techniques, nutrient application, and more. The results of this analysis can provide valuable insights into which methods are more efficient, productive, and profitable for the given cropping system. Similar results were also corroborated by Samant, 2015 and Gangwar and Ram, 2005.

The impact of different tillage methods on both earthworm populations and soil organic matter is a crucial aspect of sustainable agricultural practices. The researchers assessed the effects of various crop establishment methods on earthworm populations and presence of earthworm has significant relationship between tillage practices, and enhancement of soil organic matter content. The results revealed that different tillage methods have a significant influence on earthworm populations. Specifically, the earthworm populations and fresh weight were notably higher in zero tillage practice method. The higher earthworm populations in the SN-5 and SN-4 suggests that these might create conditions i.e. favorable for earthworm habitat and activity. Earthworms are known to play a crucial role in soil health and fertility by enhancing soil structure through their burrowing activities and by promoting the breakdown of organic materials. The higher earthworm populations in could contribute to improved soil structure and organic matter decomposition, ultimately benefiting overall soil health and agricultural productivity. The implications of these findings contribute to the attraction of earthworm in zero tillage system due to better soil aggregation, carbon cycling (Ashworth et al., 2017) and the enhancement of soil nutrient availability, and increased soil organic matter content over time (Mishra et al., 2021).

Principal Component Analysis (PCA) performed on different methodologies used in sowing paddy, green gram, and wheat within a cropping system. It is based on new coordinate system (principal components) where the first component captures the maximum variance in the data, the second component captures the second maximum variance. Positive correlation means that when one methodology increases, the other tends to increase as well, and vice versa. Negative correlation indicates an inverse relationship. The PC1 and PC2 scores indicate the importance of each principal component. Sowing by happy seeder machine seems to have a positive correlation and closer association with certain methods for different crops, indicating that these methods might have similar effects or characteristics. The information provided seems to be findings of the PCA analysis, highlighting different sowing methods for paddy, green gram, and wheat and their contribution to the variation in the dataset. The results were in agreement of Bera et al., 2017.

Conclusion

The study underscores multiple challenges in agriculture, particularly in North Bihar, such as decreasing productivity, water scarcity, labor shortages, and effects of climate change. In response, Conservation Agriculture (CA) emerges as a promising strategy, to enhance sustainability and environmental health while maintaining or even improving agricultural yields. Transitioning from traditional farming to CA, particularly in the Rice–Wheat Green gram-based Cropping System (RWCS), yields notable benefits like cost savings, efficient water use, increased profitability, and soil structure preservation. Notably, shifting to Direct Seeded Rice (DSR) from traditional puddling involves adjustments in agronomic practices, with zero-tillage initially showing yield decreases under humid conditions but later catching up with traditional methods. The study emphasizes the significant influence of tillage and crop establishment methods on rice production characteristics, affecting panicle density, grain count per panicle, and grain weight, all crucial for overall paddy yield. Ultimately, Conservation Agriculture, anchored on principles of low soil disturbance, permanent soil cover, and crop rotation, emerges as a beacon for sustainable and eco-friendly agricultural practices in the region.

Acknowledgements We sincerely appreciate the generous financial support from the Government of Bihar through the Climate Resilient Agricultural (CRA) initiative. Our sincere gratitude goes out to Dr. RPCAU Bihar for their invaluable collaboration in facilitating our research. We greatly appreciate their unwavering support and provision of necessary facilities, which have been instrumental in the successful execution of our study. This study owes its success to the invaluable contributions made by them. Their involvement has been pivotal in ensuring its feasibility and progress.

Data Availability The data supporting the earthworm population estimate in this study and Tillage crop establishment method.

Declarations

Competing of Interest Dr. Tarun Kumar, declare that they have no conflicts of interest linked to this research work named "Enhancing Sustainability and Productivity of Rice–Wheat-Green Gram Cropping System through Alternative Tillage and Crop Establishment Approaches in North-Bihar " There are no financial that may be interpreted as impacting the impartiality, integrity, or validity of the study. This research was conducted with the sole objective of enhancing scientific knowledge in the field of the International Journal of Plant Production. The conclusions presented in the publication are based on an impartial analysis and interpretation of the data.

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