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Conservation agriculture-based crop diversification options provide sustainable food and nutritional security in the Eastern Gangetic Plains of India

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The conventional rice-wheat system in eastern India faces serious challenges, including declining productivity, inefficient use of water and energy resources, and degradation of soil health. Despite being central to regional food security, the system's sustainability is increasingly under pressure. The hypothesis will boost productivity, conserve water, increase profits, and improve nutrition for resource-poor farmers. An on-farm study was conducted over three cropping cycles (2016–2019) in three villages in two districts (Vaishali and Samastipur) of Bihar. Five diversified cropping systems were tested under different establishment practices viz., conventionally established rice and wheat (CT–RW), conservation agriculture-based rice-wheat (CA–RW), conventional rice with conservation agriculture mustard and mungbean (partial CA–RMuMb), conservation agriculture maize and wheat (CA–MW), and conservation agriculture maize, mustard and mung bean (CA–MMuMb) systems. Systems productivity, irrigation water, energy use efficiency, and nutritional yields (protein, fat, iron, zinc) were assessed. The CA–MMuMb system achieved 52.6% higher system productivity (15.01 t ha⁻¹) and 63.2% higher net income (USD 2,046 ha⁻¹) compared to the CT–RW system (9.83 t ha⁻¹ and USD 1,253 ha⁻¹, respectively). The irrigation water productivity and energy productivity recorded 4.0 and 2.4 times higher (6.06 kg grain M⁻³ ha⁻¹ water and 0.68 kg grain MJ⁻¹) compared to CT–RW system (1.5 kg grain M⁻³ ha⁻¹ and 0.28 kg grain MJ⁻¹ respectively). Furthermore, this diversified cropping system resulted in 30.9, 1125, 119 and 26.5% higher protein, fat, iron and zinc yields, respectively, compared to the baseline CT–RW system. The CA–MW system achieved similar benefits in productivity and nutritional yields. These emerging systems can enhance sustainable food production and nutritional security. The CA–MMuMb system is a scalable

approach to enhance productivity, save natural resources (water and energy), and improve nutritional yields in eastern India, with implications for similar irrigated ecologies across South Asia.

KEYWORDS

conservation agriculture, crop diversification, input use efficiency, nutritional security, water productivity

1 Introduction

The Eastern Gangetic Plain (EGP), spanning across eastern Uttar Pradesh, Bihar, West Bengal, and Assam in India, extends into major portions of neighboring Nepal and Bangladesh. This densely populated region is home to over 450 million people, predominantly low-income agricultural communities (Gathala et al., 2021). The rice-wheat (RW) system is an important agricultural production system covering about 6.0 million hectares, significantly supporting food security in South Asia (Islam et al., 2019). However, conventional till (CT) practice in RW system, characterized by repetitive wet and dry tillage operations and faulty management of crop residues management, threatens its sustainability due to rapid groundwater depletion from continuous pumping, increased production costs, low resource-use efficiency (water and energy), and soil health degradation (Jat et al., 2021; Gathala et al., 2021; Sinha et al., 2021; Dutta et al., 2023).

Diversifying RW system has shown potential to improve productivity, profitability and nutritional security (Toorop et al., 2020; Bijarniya et al., 2020; Gathala et al., 2022). Furthermore, conservation agriculture (CA)-based crop diversification with sustainable intensification has been recognized as an effective strategy for achieving food and nutritional security, sustainable management of land and water resources, enhanced environmental sustainability and improved soil health in the IGP of India (Gathala et al., 2020b; Yadav et al., 2021; Dutta et al., 2023). However, potential benefits of CA-based management practices in different cropping systems have yet to be fully realized across most production systems in South Asia (Nayak et al., 2023).

To tackle the issues related to rice in RW system, maize (*Zea mays* L.) as an alternative crop holds promise due to its wide adaptability, low irrigation water requirement, high yield potential provides food and nutritional security and serving as animal and poultry feed (Choudhary and Dass, 2024). With the increase in demand for ethanol to reduce fossil-fuel dependency and reduce environmental impact, the price of maize has recently increased in the EGP and across South Asia (Kumar, 2024). In India, oilseed crops (e.g. mustard, *Brassica juncea*, L. Czern) hold the potential to replace *rabi* season cereals (e.g. wheat) due to their resilience and low irrigation demands and better remunerative prices apart from curtailing dependence on costly imports, thereby enhancing self-

sufficiency in edible oil (Ghosh et al., 2023; Krupnik et al., 2014). Maize serves as a versatile crop with relatively high productivity, shorter duration, and growing demand for food, feed, and biofuel industries (Hoque et al., 2023). Mustard is well adapted to winter conditions in the region, requires less irrigation compared to wheat, and provides a valuable cash crop with stable market demand for edible oil. Mungbean, as a short-duration legume, fits well into existing cropping sequences, enriches soil fertility through biological nitrogen fixation, and contributes significantly to household nutrition due to its high protein content (Gora et al., 2022). Together, these crops offer opportunities for enhancing resource-use efficiency, profitability, and dietary diversity for smallholder farmers.

Numerous studies from western IGP have shown that planting maize on permanent raised beds (a form of CA) while retaining residues as mulch led to marked reductions in irrigation water use and increases in water productivity compared to the CT flat system (Jat et al., 2020; Parihar et al., 2017). Incorporating short-duration pulse crops like mungbean *Vigna radiata* (L.) Wilczek into diversified cropping systems offers several benefits such as increasing system productivity with reduced inputs and environmental impacts and enhancing soil health (Kakraliya et al., 2024; Zhao et al., 2022). Additionally, legumes contribute to ensuring household nutritional security, as pulses are rich sources of protein and essential micronutrients, complementing the staple cereals in the diet (Gora et al., 2022).

The deficiencies of protein and micronutrients (e.g. iron and zinc) in cereals can hamper overall human health in South Asian countries (Gonmei and Toteja, 2018). According to FAO (2017), alone in India 190.7 million people suffered from nutritional problems. According to Sharma et al. (2020) 73-80% of India's population suffer from protein deficiency – mostly because traditional Indian diet tends to be rich in carbohydrates. Venkatesh et al. (2021) reported that iron (Fe) deficiency is most prevalence (54%) in Indian population due to intake of low Fe food. Zinc (Zn) deficiency is high among children, pregnant and lactating women in South Asian countries (Akhtar et al., 2013; Davis et al., 2018). Most of the previous studies on CA-based cropping systems in EGP in India focus on yield improvements and irrigation water savings without considering protein and calorie yields for food-insecure smallholder farming households and rural communities (DeFries et al., 2015; Damerau et al., 2020; Hoque et al., 2023).

There is thus, a strong need for identifying cropping systems which have higher potential for increased productivity, water and energy-efficient, cost-effective and provide nutritional benefits. However, limited information is available on the relative benefits of CA-based sustainable intensification of diversified cropping systems on productivity, water and energy use efficiencies and nutritional security in the EGP of India. Most available evidence on CA-based crop diversification comes from the western Indo-Gangetic Plains (IGP), with limited information for the eastern region. To address this gap, we conducted a three-year on-farm study in three villages of Bihar, India, to evaluate the performance of CA-based diversified cropping systems, particularly maize–mustard–mungbean, as alternatives to the conventional CT–RW system. The study aimed to assess crop and water productivity, energy-use efficiency, profitability, and nutritional yields, under the hypothesis that CA-based sustainable intensification can enhance food and nutritional security for smallholders in the EGP.

2 Materials and methods

2.1 Study site characteristics and weather conditions

A three-year (2016–2019) on-farm experiment was conducted in three villages in Bihar, India, specifically Repura (25.90014° N, 085.6742716° E) and Bazidpur (25.83772° N, 085.56644° E) in Samastipur, and Nirpur (25.84015° N, 085.55372° E) in Vaishali districts, located within the Eastern Gangetic Plains (EGP) region. Two farmers were selected from each village, yielding a total of six participating farmers. To account for field variability, the average values for two farmers in each village were considered as three replications. The distance between the three villages was approximately 12 km. The soil texture of all the experimental sites was clay loam in texture and tested medium in Walkley and Black (1934) soil carbon content (mean value of 0.57%), low in available nitrogen (mean value of 112 kg ha⁻¹) determined using the

method of Subbiah and Asija (1956) and medium in NaHCO₃-extractable available phosphorus (mean value of 17 kg P ha⁻¹) and low in NH₄OAc-extractable potassium (mean of 69 kg K ha⁻¹). The climate of the region is hot and humid in summer and cold winters with 1140 mm average annual rainfall, of which 70 per cent occurs during the months of June to September. The mean annual maximum and minimum temperatures of the region are 30 and 19 °C, respectively and the relative humidity during the cropping seasons ranged between 60–95%. All the weather parameters recorded during the study period are presented in Figure 1. Total rainfall received during the annual cropping season was 1077, 1067 and 787mm in 2016–17, 2017–18 and 2018–19, respectively. The distribution of rainfall was not distributed uniformly through the cropping season and the year. During first year, most of the rainfall during *kharif* season was received in July (442 mm) and August (387 mm). *Kharif* season rainfall during 2017–18 was 304, 111 and 319 mm, and in the 2018–19 it was 170, 188 and 119 mm in the months of July, August and September, respectively. During *Rabi* season, 45-, 109- and 51-mm rainfall was received in 2016–17, 2017–18 and 2018–19, respectively. The maximum and minimum temperatures and relative humidity were nearly similar during the three years of study.

2.2 Treatment details and experimental design

In this study, five diversified cropping systems were evaluated under conservation agriculture (CA)-based practices (zero tillage/permanent beds and residue retention) for three years (2016–2019). Rice and maize crops were grown during *kharif* season (June–October), while wheat and mustard were raised during *rabi* season (November–April), and mungbean was cultivated during summer season (April–June). The five cropping systems (CS) included in the study were: 1. CT–RW, conventional puddled transplanted rice followed by (fb) conventional tillage (CT) wheat, all residues removed; 2. CA–RW, zero till (ZT) direct seeded rice (DSR) fb ZT

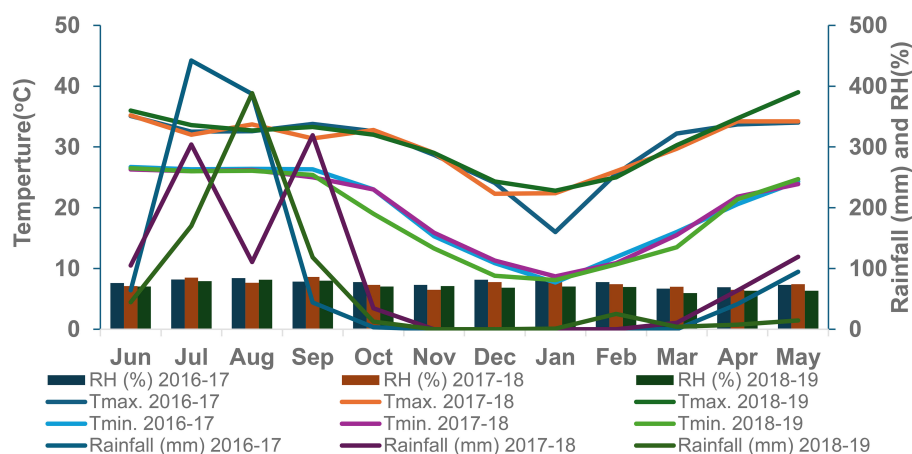


FIGURE 1

Monthly mean maximum and minimum temperatures (°C), average rainfall (mm) and relative humidity (%) during 2016–17, 2017–18 and 2018–19.

wheat with residue mulch; 3. Partial CA-RMuMb, CT-DSR fb ZT mustard (*Brassica juncea* (L.) Czern.) fb ZT mungbean (*Vigna radiata* (L.) Wilczek); 4. CA-MW system, permanent beds (PB/ZT) maize fb PB wheat with residue mulch; and 5. CA-MMuMb, PB maize-PB mustard-PB mungbean with residue mulch. Experiment was implemented on production-scale plots (1200 m²). Each year, six on-farm participatory research trials in three villages and two farmer fields in each village were conducted in the two districts of Bihar. The data from the two trials in each village were averaged and thus, three replications were considered for statistical analysis using a randomized complete block design (RCBD). The soil and crop management practices in CT-RW were adopted as per the farmers' practice in the region, whereas CA-based management practices were followed in the other improved diversified cropping systems. The description of different cropping systems and their management practices are presented in [Tables 1, 2](#). Crop production management practices were adopted in accordance with relevant guidelines and regulations for different crops of Dr Rajendra Prasad Central Agricultural University, Pusa, Bihar.

2.3 Crop management

2.3.1 Tillage, crop establishment, weed and residue management

Before the start of the experiment, the experimental fields were laser-leveled in May 2016. The conventional tillage involved ploughing with one pass of disc harrow followed by a spring-tine cultivator before sowing each crop. Maize was planted on freshly raised beds in the first year; however, in consequent seasons, they

were kept as permanent beds (PB). In PB systems, two rows (30 cm apart) of wheat and mustard and 1 row of maize were planted in the center of each raised bed (10–12 cm height), having a 37 cm wide top and configured 67 cm furrow to furrow spacing using a multi-crop raised bed-planter (National Agro, Ludhiana, Punjab, India). A bed shaper was used for reshaping the beds at the time of maize sowing in a single operation. Rice, wheat, mustard and mung bean crops were planted using multi-crop zero tillage happy seeder planter in flat system maintaining row to row spacing of 22.5 cm.

To manage existing annual weeds in permanent beds and zero-till plots, a pre-plant application of glyphosate (1.25 liters of active ingredient per hectare) was sprayed. Experimental plots utilized both pre-emergence and post-emergence herbicides as recommended to control the weeds. Weed control in DSR (CT/ZT) included pendimethalin (1000 grams active ingredient per hectare) as a pre-emergence herbicide, followed by Bispyribac Sodium + Pyrazosulfuronethyl (8–10 grams + 6 grams active ingredient per hectare, respectively) applied 20–25 days after sowing (DAS) to target grassy and broadleaf weeds, as well as sedges. In maize, atrazine (1000 grams active ingredient per hectare) was used as a pre-emergence herbicide, with Laudis (Tembotrione 42% SC; 90 grams active ingredient per hectare) applied as early post-emergence based on weed diversity and intensity. For mustard, weed removal was carried out manually. In wheat, a tank mix solution of Pinoxaden 5% EC (50 grams active ingredient per hectare) or Clodinafop ethyl + Metsulfuron (60 grams + 4 grams active ingredient per hectare) was applied 30–35 DAS to manage all weed types.

Crop residue management details for each cropping system is included in [Table 1](#). Approximately, 7.5–7.7 Mg ha⁻¹ of rice residue

TABLE 1 Treatment descriptions (tillage, residue, crop establishment methods and residue management practices).

Treatment abbreviation	Drivers of change	Cropping system	Tillage	Crop establishment method	Residue management
CT-RW	Business as usual (Farmer's practice)	Rice-wheat-fallow	CT-CT	Rice-Puddled transplanting Wheat-Broadcast seeding	All residues removed
CA-RW	Deal with rising scarcity of labor, water and energy	Rice-wheat-fallow	ZT-ZT	Direct seeded rice (DSR) drill seeding, Wheat-direct drill seeding	Rice- full (100%), Wheat-anchored residue (25-30%). Both residues retained on soil surface
Partial CA-RMuMb	Sustainable intensification to address the issues of labor, water, soil health and malnutrition	Rice-mustard-mung bean	CT-ZT-ZT	Rice-DSR drill seeding Mustard-ZT seeding Mungbean-ZT seeding on flat beds	Rice and mung bean -100%, Mustard anchored- (35-40%, ~50 cm height). All residues retained on soil surface
CA-MW	Sustainable diversification through maize-based cropping system to deal with labor and water scarcity, and declining economic profitability	Maize-wheat	ZT-ZT	Maize-Drill seeding Wheat-Drill seeding on permanent beds (PB)	Maize (65-70%) and wheat (25-30%) anchored residue. Both residues retained on soil surface
CA-MMuMb	Sustainable intensification for higher productivity, nutrition and soil health	Maize-mustard-mung bean	ZT-ZT-ZT	Maize-Drill seeding Mustard-Drill seeding Mung bean-Drill seeding on PB	Maize- (65-70%), Mustard-anchored (35-40%, ~50 cm height), Mung bean (100%). All residues retained on soil surface

TABLE 2 Crop management practices for different crops and cropping systems.

Cropping systems ^a / Management practices	CT-RW ^a	CA-RW	Partial CA-RMuMb	CA-MW	CA-MMuMb
Field preparation	Rice- 2 passes of harrow, 1 pass of rotavator, 2 passes of harrow in standing water followed by (fb) planking Wheat- 2 passes of harrow and rotavator each fb planking	Zero tillage (ZT) on flats in both rice and wheat	Rice-1 pass of harrow, 2 passes of cultivator fb planking (CT); mustard and mung bean- ZT on flats	Both maize and wheat on permanent beds (PB) and reshaping while maize planting	All crops on permanent beds (PB)
Seed rate (kg ha ⁻¹)	Rice- 12.5 Wheat- 100	Rice- 20 Wheat-100	Rice- 20 Mustard-05 Mung bean-20	Maize- 20 (80,000-83,000 plants) Wheat- 100	Maize- 20 Mustard- 05 Mung bean- 20
Sowing method	Manual transplanting of rice and broadcasting of wheat	Seeding with Happy Seeder machine	Rice and mustard seeding with multi-crop planter and mung bean seeding with ZT machine	Seeding with double disc planter on permanent beds	Seeding with double disc planter on permanent beds
Crop geometry (cm)	Random geometry	22.5—22.5	22.5—22.5	67.5 x 20—30 (2 rows/bed)	67.5 one row/bed) —30 (2 rows/bed) – 30 (2 rows/bed)
Fertilizers (N- P ₂ O ₅ - K ₂ O- ZnSO ₄), kg ha ⁻¹	Rice- 150:60:40:25 Wheat- 150:60:40:0	Rice- 150:60:40:25 Wheat- 150:60:40:0	Rice- 150:60:40: 25 Wheat- 150:60:40:0 Mung bean- 20:40:0:0	Maize- 150:60:40:0 Wheat- 150:60:40:0	Maize- 150:60:40:0 Mustard- 80:30:20:0 Mung bean- 20:40:0:0
Crop variety	Rice- Arize 6444 Wheat- HD 2967	Rice- Arize 6444 Wheat- HD 2967	Rice- Arize 6444 Mustard-RH749 Mung bean-IPM 2-3	Maize- DKC9081 Wheat- HD 2967	Maize- DKC9081 Mustard-RH749 Mung bean-IPM 2-3
Water Management	Continues flooding (5-cm depth) for 1 month, fb irrigation applied at hair-line cracks	Soil kept wet for first 20 days 'fb' irrigation at -20 to -30kPa soil metric potential (SMP)	Kept soil wet for first 20 days 'fb' irrigation at -20 to -30kPa SMP	In maize, wheat and mustard; tensiometer based irrigation at -40 to -50kPa SMP	

^aRefer Table 1 for description of cropping systems.

was recycled each year in CA- RW and partial CA- RMuMb. The amount of biomass of wheat and mustard ranged between 2.5–3.0 Mg and 1.8–2.4 Mg ha⁻¹ in partial CA-RMuMb and CA-MMuMb, respectively. In CA-MW and CA-MMuMb 6.5 to 7.0 Mg ha⁻¹ of maize stalks were recycled each year. The biomass of mungbean residue recycled ranged between 1.5 to 1.9 Mg ha⁻¹ each year in partial CA-RMuMb and CA-MMuMb cropping systems.

2.3.2 Irrigation water management

The source of irrigation was groundwater using one hp diesel pump for pumping groundwater to irrigate different crops in the system. Each plot was irrigated by using Polyvinyl chloride (PVC) delivery pipeline. For irrigation water measurement, on-line water meter (Woltman[®] helical turbine) was installed at the tube well PVC outlet. To monitor soil metric potential (SMP) a gauge-type tensiometer were installed with the 5 m distance from each bund to apply SMP-based for each crop (Table 2). To calculate the amount of irrigation water applied per plot, the initial and final readings on water meter were recorded. The amount of irrigation water applied was calculated as water depth (mm ha⁻¹) by using Equations 1, 2, while irrigation water productivity (WP₁) using Equation 3.

Volume of irrigation water (kiloliter ha⁻¹)

$$= \left(\frac{\text{Final water meter reading} - \text{Initial water meter reading}}{\text{Plot area in m}^2} \right) \times 1000 \quad (1)$$

Irrigation water (mm ha⁻¹)

$$= \text{Volume of irrigation water} \quad (2)$$

Where, 1 ha-mm irrigation depth = 10 kiloliters = 10,000 liters = 10 m³.

Irrigation water productivity (kg grain m⁻³)

$$= \frac{\text{Grain yield (kg ha}^{-1}\text{)}}{\text{Irrigation water used (m}^3 \text{ ha}^{-1}\text{)}} \quad (3)$$

2.3.3 Data recording

Crop management data (input-output) were recorded for each crop and cropping system using standard data recording protocols

for computation of production economics. All the crops were harvested manually from 20.1 m² randomly marked 3 quadrats from each treatment plot for computing the grain and straw yields. After threshing each plot, grains of different crops were air-dried and cleaned before weighing. Grain moisture content was determined gravimetrically by drying in a forced air oven at 65°C until constant weight. Yields reported were adjusted for grain moisture content: 140 g kg⁻¹ for rice and maize, 120 g kg⁻¹ for wheat, mustard and mung bean.

To explain the overall effect of treatments on crop productivity, the yield of non-rice crops (maize, wheat, mustard, mung bean) was converted into rice equivalent yield (REY) (Mg ha⁻¹) and calculated using the following Equation 4:

$$REY (t ha^{-1}) = \frac{\{Yield of non rice crop (t ha^{-1}) \times MSP of non rice crop (INR t^{-1})\}}{MSP of rice crop (INR t^{-1})} \quad (4)$$

Where, REY=Rice equivalent yield, MSP= Minimum support price, INR= Indian Rupees.

2.4 Economic analysis

The variable costs associated with production include factors such as human labor, machinery utilization, and inputs like tillage, planting, seeds, irrigation, fertilizers, pesticides, harvesting, and threshing. To calculate the labor cost per hectare for various operations (from seeding to harvesting and threshing), the time taken for each field operation was recorded. The time (h) was then expressed in person-days (8 hours) per hectare. Labor costs were calculated based on the minimum wage rates stipulated by Indian labor laws. Similarly, the total hours spent by tractors on field operations, including tillage, seeding, and harvesting, were documented and expressed as hours per hectare. The cost of using machinery or equipment for these operations was determined using the region's standard custom hiring rates. Irrigation costs were calculated by accounting for diesel consumption required for irrigation, multiplied by the current diesel market price, alongside labor costs for applying irrigation (Table 3). Total variable cost (TVC) of production was obtained by summing up all the input costs. The grain and straw yields of each crop multiplied by market prices of the product to calculate the gross returns (GR) (Table 3). The net returns (NR) were calculated by using the following Equation 5:

$$NR = GR - TVC \quad (5)$$

All the economic data were converted into US\$ using the average exchange rate for respective years (Table 3).

2.5 Input output energy analysis

The total energy input for each crop and cropping system was calculated from the total inputs like human labor, machinery, diesel, fertilizer, pesticides, seed, irrigation etc. and total energy output was

TABLE 3 Values of key inputs and outputs used for economic analysis in 2016–17 and 2017–18 and 2018–19.

Item/commodity	2016-17	2017-18	2018-19
Rice seed (US\$ kg ⁻¹)	3.79	3.69	3.65
Wheat seed (US\$ kg ⁻¹)	0.38	0.37	0.37
Maize seed (US\$ kg ⁻¹)	3.79	3.69	3.65
Mustard seed (US\$ kg ⁻¹)	0.38	0.37	0.37
Mung bean seed (US\$ kg ⁻¹)	1.52	1.47	1.46
Maize residue (US\$ ha ⁻¹)	0.02	0.02	0.02
Wheat residue (US\$ kg ⁻¹)	0.03	0.03	0.07
Rice residue (US\$ kg ⁻¹)	0.02	0.02	0.02
Urea (US\$ kg ⁻¹)	0.09	0.09	0.08
Di-ammonium-phosphate (US\$ kg ⁻¹)	0.35	0.34	0.34
Muriate of potash US\$ (kg ⁻¹)	0.25	0.24	0.24
Zinc sulphate;(US\$ kg ⁻¹)	0.61	0.59	0.58
Harrowing (US\$ ha ⁻¹)	22.73	22.12	21.93
Cultivator (US\$ ha ⁻¹)	15.15	14.75	14.62
Planking (US\$ ha ⁻¹)	6.82	6.64	6.58
Bed planter (US\$ ha ⁻¹)	12.88	12.54	12.43
Seed drill (US\$ ha ⁻¹)	15.15	14.75	14.62
Fuel cost (Diesel) (US\$ l ⁻¹)	0.92	1.0	1.0
Minimum support price (MSP) for maize (US\$ kg ⁻¹)	0.21	0.21	0.25
Minimum support price (MSP) for wheat (US\$ kg ⁻¹)	0.25	0.26	0.27
Minimum support price (MSP) for rice (US\$ kg ⁻¹)	0.22	0.23	0.26
Minimum support price (MSP) for mustard (US\$ kg ⁻¹)	0.56	0.59	0.61
Minimum support price (MSP) for mung bean (US\$ kg ⁻¹)	0.84	0.88	1.02
Wages rate (US\$ person ⁻¹ day ⁻¹)	2.92	3.11	4.50
USD (\$) to INR conversion rate	66.0	67.8	68.4

calculated from grain and straw yields and expressed as MJ ha⁻¹. The indirect energy use of agricultural machinery was calculated based on the total diesel consumption during various farm activities, including seedbed preparation, crop sowing, harvesting, threshing, and transportation. The total time required for these operations was also documented. The estimation of total fuel energy was carried out using diesel consumption for different farm operations, using the formula of Equation 6.

Energy equivalents used for estimation of energy efficiency from inputs and outputs, the energy equivalents used are given in Table 4. The direct and indirect energy coefficients, as shown in Table 4, were obtained from peer-reviewed literature. Based on the energy

equivalents of the inputs and outputs, energy use efficiency and energy productivity were calculated using Equations 7, 8.

$$ME = \frac{\beta \times \mu}{\gamma \times \alpha} \quad (6)$$

where ME—machinery energy (MJ ha⁻¹), β —energy conversion factor for machinery (MJ kg⁻¹), μ —machinery weight (kg), γ —effective field capacity (ha h⁻¹) and α —life of the machinery (h).

$$\text{Energy use efficiency} = \frac{\text{Total energy output (MJ ha}^{-1}\text{)}}{\text{Total energy input (MJ ha}^{-1}\text{)}} \quad (7)$$

TABLE 4 Energy equivalents used in the study for different agricultural operations.

Particulars	Unit	Energy equivalent (MJ unit ⁻¹)	References
A. Inputs			
a. Human labor			
1. Adult man	Man-hour	1.96	Mittal and Dhawan, 1988
2. Women	Woman-hour	1.57	Mittal and Dhawan, 1988
b. Diesel	Liter	56.31	Mittal and Dhawan, 1988; Parihar et al., 2013
c. Farm machinery	kg	62.70	Mittal and Dhawan, 1988; Parihar et al., 2013
d. Chemical fertilizers			
1. N	kg	60.60	Mittal and Dhawan, 1988; Parihar et al., 2013
2. P ₂ O ₅	kg	11.10	Mittal and Dhawan, 1988; Parihar et al., 2013
3. K ₂ O	kg	6.7	Mittal and Dhawan, 1988; Parihar et al., 2013
e. Chemicals			
1. Herbicides	kg	254.45	Mittal and Dhawan, 1988; Parihar et al., 2013
2. Insecticides	kg	184.63	Mittal and Dhawan, 1988; Parihar et al., 2013
f. Seed of crops	kg	14.70	Mittal and Dhawan, 1988; Singh et al., 1997
B. Outputs			
1. Grain/stover of crops	kg	14.70	Mittal and Dhawan, 1988; Singh et al., 1997

Energy productivity (kg MJ⁻¹)

$$= \frac{\text{Grain output (kg ha}^{-1}\text{)}}{\text{Total energy input (MJ ha}^{-1}\text{)}} \quad (8)$$

2.6 Analysis of nutritional quality parameters

Grain quality parameters, such as protein, fat, Fe, and Zn were computed using standardized content factors for each crop as specified in the Indian food composition (Longvah et al., 2017). These quality parameters were multiplied by the yield of a particular crop, to calculate the total amount of nutrients supplied through grains. The yield efficiency of protein, fat, Fe and Zn was calculated based on the average adult requirements of 58g protein, 30g fat, 17 mg Fe and 12 mg Zn person⁻¹ day⁻¹, respectively, as per the recommendations of the Indian council of medical research (ICMR, 2009).

2.7 Statistical analysis

The analysis of variance (ANOVA) technique was used for analysis of different parameters (Gomez and Gomez, 1984). Data analysis was done by using JMP 18 software (v18.2.1/11. March 2025) (SAS Institute, 2001). The pooled analysis was used to determine the effects of cropping systems (CS), year (Y) and their interactions (Y x CS) on crop and system productivity, irrigation water productivity, profitability, energy use efficiency and nutritional quality parameters. The Least Significant Difference (LSD) test was used as a *post hoc* mean separation test (P<0.05) to determine treatment effects.

3 Results

3.1 Crop yields and system productivity

Significant year by cropping system interactions were observed on REY of each crop and the system (Table 5). Therefore, simple effects of cropping systems for each year are discussed in the following section. In 2016-17, REY of rice/maize under the two maize-based cropping systems (CA- MW and CA-MMuMb) was significantly ($p \leq 0.05$) yielded more by 37.6% compared to that of the three rice-based systems (CT-RW, CA- RW and partial CA-RMuMb) (Table 5). In *rabi* season, REY of mustard was significantly lower under partial CA-RMuMb compared the other four cropping systems which showed similar REY. In *kharif* season of 2017-18, REY of rice/maize did not differ significantly under the five cropping systems (Table 5). In *Rabi*, REY of mustard was significantly higher under CA-MMuMb compared to that under the other cropping systems, which produced statistically similar REY (Table 5). In *kharif* season of 2018-19, maize (REY) in CA-MW system was significantly outyielded than the rest of the cropping

TABLE 5 Grain yield, total variable production cost and net return of different cropping systems during 2016–17, 2017–18 and 2018–19.

Treatment ^a		Rice equivalent yield (t ha ⁻¹)				Total variable production cost (USD ha ⁻¹)				Net returns (USD ha ⁻¹)			
		Rice/ maize	Wheat/ mustard	Mung bean	System	Rice/ maize	Wheat/ mustard	Mung bean	System	Rice/ maize	Wheat/ mustard	Mung bean	System
Cropping system (CS)													
	CT-RW	4.58c	5.25b	–	9.83d	743a	603a	–	1347b	495d	758b	–	1253d
	CA-RW	4.55c	5.84a	–	10.39d	672c	577ab	–	1248c	570c	942a	–	1512c
	Partial CA- RMuMb	4.60c	5.52ab	2.29	12.41b	685d	475c	240	1400a	571c	835ab	250	1657b
	CA- MW	5.64a	5.58ab	–	11.22c	594b	568b	–	1162d	738a	879a	–	1617bc
	CA- MMuMb	5.28b	5.72ab	4.01	15.01a	600d	483c	313	1395a	642b	866ab	538	2046a
Year (Y) by CS interaction													
2016-17	CT-RW	3.95e	6.02abc	–	9.97gh	700bc	633a	–	1333cde	343d	890bcd	–	1233gh
	CA-RW	4.14e	6.00abc	–	10.13gh	646de	579abc	–	1224ghi	457cd	963abc	–	1420efg
	Partial CA- RMuMb	4.21de	4.56d	2.47	11.23efg	660d	413g	254	1327ede	462cd	602f	281	1345fgh
	CA- MW	5.85ab	6.09abc	–	11.94def	592fg	569bcd	–	1161ij	710b	973abc	–	1684cde
	CA- MMuMb	5.43abc	5.00bcd	3.84	14.28bc	574g	432fg	315	1321de	636b	682def	518	1836abc
2017-18	CT-RW	5.40abc	4.95bcd	–	10.35fgh	820a	581abc	–	1401bc	570bc	650ef	–	1220h
	CA-RW	5.37abc	5.81bc	–	11.18fg	716b	565bcd	–	1280efg	673b	873cdef	–	1546def
	Partial CA- RMuMb	5.28abc	5.83bc	2.15	13.25bcd	721b	483ef	240	1445ab	643b	850cdef	246	1739bcd
	CA- MW	5.17bc	5.36bc	–	10.53fgh	568g	555bcd	–	1123j	613bc	773cdef	–	1386efg
	CA- MMuMb	5.50abc	6.45a	4.02	15.96a	655d	511cde	325	1491a	602bc	962abc	585	2149a
2018-19	CT-RW	4.39de	4.78cd	–	9.18h	710b	596ab	–	1305def	572bc	734cdef	–	1306fgh
	CA-RW	4.14e	5.71bc	–	9.86gh	654d	587ab	–	1241fgh	581bc	989ab	–	1569def
	Partial CA- RMuMb	4.32de	6.18ab	2.25	12.74cde	673cd	528cde	227	1428ab	609bc	1053a	224	1887ab
	CA- MW	5.91a	5.28bcd	–	11.19fg	622ef	578abc	–	1200hi	890a	890bcd	–	1780bc
	CA- MMuMb	4.93cd	5.70bc	4.16	14.79ab	573g	504de	298	1374bcd	687b	954bcd	511	2152a

(Continued)

TABLE 5 Continued

Treatment ^a	Rice equivalent yield (t ha ⁻¹)				Total variable production cost (USD ha ⁻¹)				Net returns (USD ha ⁻¹)			
	Rice/ maize	Wheat/ mustard	Mung bean	System	Rice/ maize	Wheat/ mustard	Mung bean	System	Rice/ maize	Wheat/ mustard	Mung bean	System
ANOVA (probability)												
CS	<0.001	0.038		<0.001	<0.001	<0.001		<0.001	<0.001	0.002		<0.001
Y x CS	<0.001	<0.001		<0.001	<0.001	0.001		<0.001	<0.001	<0.001		<0.001
CV (%)	4.23	7.00		5.00	2.00	5.00		2.00	8.00	10.00		6.00

^aRefer Table 1 for description of cropping systems.
^bGrain yield of crops is expressed as rice-equivalent yield (Mg ha⁻¹).
^cMeans followed by a similar lowercase letter within a column are not significantly different at 0.05 level of probability using Tukey's HSD test.

systems. The three-year pooled analysis demonstrated that REY of maize in Kharif season was highest in CA-MW, followed by CA-MMUMb and these were 12.3% higher than rice (CT-RW, CA-RW and partial-RMuMb). In rabi, the CA wheat (CA-RW) produced significantly higher REY than CT wheat (CT-RW), and the rest of treatments were at par with the former.

The total system REY (3-year average), CA-MMuMb system produced significantly ($p \leq 0.05$) higher, which was 5.18 t ha⁻¹ more REY than CT-RW. Partial CA-RMuMb system also proved superior on both CT-RW and CA-RW by 22.7%, but still, this was significantly lower yielded by 20.9% than CA-MMUMb (Table 5). Maize-based cropping systems (CA-MW and CA-MMuMb) recorded 20% higher mean system REY compared to rice-based systems (CTRW, CA-based RW and partial CA- RMuMb). Under CA-RW, 5.6% higher system yield was recorded as compared to CT-RW (Figure 2). In all the years (2016-19), significantly higher system REY was recorded with CA-MMuMb, CA- MW and partial CA-RMuMb systems compared to CA-RW and CT-RW systems (Table 5). Our study has the limitation of not evaluating sustainable intensification of CA-MW system with mungbean, which might have potential scope due to early harvesting of maize that allows advanced planting of wheat, which may create 10–15 days extra window than the RW system. The initial assumption was that mungbean sowing would be delayed after wheat harvest, resulting in late maturity and consequently postponing the planting of the subsequent kharif crop (rice or maize). In addition, socio-economic factors, such as limited access to conservation agriculture machinery, high input costs, and labor constraints, may hinder adoption by smallholders. Furthermore, climatic variability in the eastern IGP, including erratic rainfall and terminal heat stress, can adversely affect maize and wheat performance, thereby reducing the consistency of outcomes across seasons. However, studies from northwest India showed large benefits from sustainable intensification of CT-RW system with CA-MWMB system in terms of higher system productivity and profitability (Gora et al., 2022; Kumar et al., 2018).

3.2 Economic profitability

Like REY, significant year by cropping systems interaction effects were recorded on both variable cost and net profit (Table 5). In 2016-17, total variable cost of production was significantly lower (mean of 13%) for maize in CA- MW and CA-MMuMb cropping systems compared to the rice-based cropping systems (Table 5). Among rice-based cropping systems, the mean production cost was significantly higher (USD 47 ha⁻¹) for rice in CT-RW compared to CA-based RW and partial CA-RMuMb systems. In Rabi season, the cost of production for mustard was significantly lower than wheat, irrespective of cropping system. Among wheat-based cropping systems, the cost of production was significantly higher for CT-RW compared to CA- MW system. In 2017-18, the cost of production of maize was significantly lower in CA- MW and CA-MMuMb cropping systems. The highest cost of production was recorded for CT rice in CT-RW followed by CT-

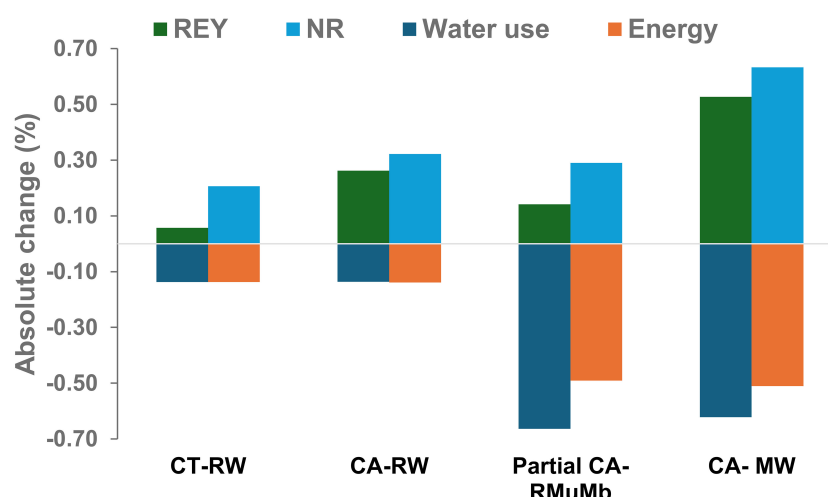


FIGURE 2

Absolute change in rice equivalent yields (REY), net returns (NR), water use and energy use under CA based systems over CTRW system. ^a Refer Table 1 for description of cropping systems.

DSR in partial CA-RMuMb and ZT rice in CA-RW. Like in 2016-17, cost of production was significantly lower for CA/ZT-based mustard compared to wheat in wheat-based cropping systems. In 2018-19, cost of production of maize was significantly lower in CA-MMuMb compared to maize in CA-MW system. In *Rabi* season, the cost of production in wheat-based systems, irrespective of tillage, was statistically similar but significantly higher than for mustard under CA-MMuMb and partial CA-RMuMb systems. The total variable cost differed significantly among the cropping systems. Mean cost of production (averaged over three years) was in the decreasing order; CA-MW < CA-RW < CT-RW < CA-based MMuMb < partial CA-RMuMb. The total cost of cultivation in CA-MW system was 13% lower compared to CT-RW system (Table 5).

In *kharif* season of 2016-17, net return from maize was significantly higher by 60% under maize-based (CA-MW and CA-MMuMb) systems compared to that from rice under three rice-based systems (Table 5). In *rabi* season, net returns from mustard in mustard-based systems were significantly lower by 32% than wheat in the wheat-based cropping systems (Table 5). In *kharif* season of 2017-18, net returns from both rice and maize were statistically similar, irrespective cropping systems. In the following *rabi* season, net returns from mustard in CA-MMuMb system were significantly higher than that from wheat under CT-RW systems, but net returns from this system was similar to the other cropping systems (CA-RW, partial CA-RMuMb and CA-MW). In 2018-2019, net returns from maize in CA-MW system were significantly higher compared with the rice in the rice-based cropping systems, but the net returns were on a par with CA-MMuMb system (Table 5). In *rabi* season, net returns from mustard were generally higher than that of wheat, irrespective of cropping system. Net returns from mungbean were higher in CA-MMuMb system compared to partial CA-RMuMb system in all three years of the study.

The CA-MMuMb system recorded significantly higher mean (averaged across three yrs) net returns compared to the other cropping systems (Table 5). The system net returns of different cropping systems varied from USD 1253 to 1836 ha⁻¹ in first year and USD 1220-2149 ha⁻¹ in the 2nd year, and USD 1306 to 2152 ha⁻¹ in the 3rd year (Table 5). Mean net returns increased by 63.2, 32.2, 29 and 20.6% under CA-MMuMb, partial CA-RMuMb, CA-based MW and CA-RW systems compared to CT-RW system (1253 USD ha⁻¹), respectively. The highest net return was reported during 2nd year with CA-MMuMb system, which was 76.1% higher compared to CT-RW system (USD 1220 USD ha⁻¹). Whereas 15-26% higher net returns were recorded in CA-RW system compared to CT-RW system across the three years of study (Table 5, Figure 2).

3.3 Irrigation water use and water productivity

The system irrigation water use varied significantly among the crops and cropping systems and was also influenced by amount and distribution of rainfall during the cropping seasons (Table 6). Like grain yields and net returns, significant year x cropping system interaction effects were observed on irrigation water use and irrigation water productivity (WP_i). In 2016-17, irrigation water use in rice was markedly higher by 3496 mm (mean of three rice-based systems) than maize (508 mm, mean of two maize-based systems) (Table 6). There was no significant difference in irrigation water use by rice under the three rice-based cropping systems. Nearly similar trends in irrigation water use were observed during 2017-18 and 2018-19, except water use was significantly higher in rice under CT-RW compared to rice under partial CA-RMuMb and

TABLE 6 Irrigation water use (mm ha⁻¹) and water productivity (kg grain m⁻³) as affected by different crops and cropping systems.

Treatment ^a		Water use (M ³ ha ⁻¹)				Water productivity (kg grain M ⁻³ water)			
		Rice/ maize	Wheat/ mustard	Mung bean	System	Rice/ maize	Wheat/ mustard	Mung bean	System
Cropping system (CS)									
	CT-RW	4447a	2140a	–	6587a	1.03b	2.25b	–	1.50d
	CA- RW	4062b	1619b	–	5682b	1.12b	3.30a	–	1.83cd
	Partial CA- RMuMb	4062b	1079e	545	5687b	1.13b	2.05b	1.01	2.18c
	CA- MW	625c	1592c	–	2217c	10.43a	3.21a	–	5.11b
	CA- MMuMb	652c	1294d	545	2491c	9.33a	1.77c	1.73	6.06a
Year (Y) by CS interaction									
2016-17	CT-RW	4377b	2140a	–	6517b	0.90d	2.55bc	–	1.53e
	CA- RW	3820b	1619a	–	5439d	1.08d	3.35a	–	1.86e
	Partial CA- RMuMb	3820b	1079a	545	5444d	1.10d	1.68d	1.19	2.06e
	CA- MW	512c	1592a	–	2104f	12.31a	3.46a	–	5.67abc
	CA- MMuMb	504c	1294a	545	2343ef	11.60ab	1.54d	1.86	6.09ab
2017-18	CT-RW	5003a	2140a	–	7143a	1.08d	2.07cd	–	1.45e
	CA- RW	4366b	1619a	–	5985bcd	1.23d	3.21a	–	1.87e
	Partial CA- RMuMb	4366b	1079a	545	5990bcd	1.21d	2.09cd	0.87	2.21e
	CA- MW	512c	1592a	–	2104f	10.98ab	3.01ab	–	5.00cd
	CA- MMuMb	611c	1294a	545	2450ef	9.79abc	1.93d	1.64	6.51a
2018-19	CT-RW	3960b	2140a	–	6100bc	1.12d	2.13cd	–	1.51e
	CA- RW	4002b	1619a	–	5621cd	1.04d	3.36a	–	1.76e
	Partial CA- RMuMb	4002b	1079a	545	5626cd	1.09d	2.39c	0.95	2.26e
	CA- MW	853c	1592a	–	2445ef	8.01bc	3.16a	–	4.64d
	CA- MMuMb	840c	1294a	545	2679e	6.62c	1.84d	1.70	5.57bc
ANOVA (probability)									
CS		<0.001	<0.001		<0.001	<0.001	<0.001		<0.001
Y x CS		0.002	1.00		0.002	0.003	0.001		0.011
CV (%)		8.00			5.00	24.0	7.00		9.00

^aRefer Table 1 for description of cropping systems.^bMeans followed by a similar lowercase letter within a column are not significantly different at 0.05 level of probability using Tukey's HSD test.

CA- RW systems in 2017-18. Irrigation water use in *Rabi* crops (wheat/mustard) was similar in all three years of study (Table 6). Significantly higher system irrigation water use was recorded in rice-based systems (CT-RW, CA- RW and partial CA-RMuMb) compared to CA-based MW and CA-based MMuMb systems. The mean system irrigation water use under CA- MW and CA-MMuMb systems was similar, that was 62.1-66.3% lower compared to CT-RW system. In partial CA- RMuMb system the

irrigation water use (5687 M³ ha⁻¹) which was about 13.6% lower compared to CT-RW system (Table 6).

The WP₁ was significantly higher for maize than for rice in all the three years of study (Table 6). In 2016-17, mean WP₁ of maize was nearly three times the WP₁ of rice (Table 6). Nearly similar trends in WP₁ in *kharif* season crops were also recorded for the other two years of the study. In *Rabi* season of 2017-18, WP₁ was significantly lower for mustard compared with wheat. Among

wheat-based cropping systems, WP_I for wheat in CA-based systems was significantly higher compared to CT wheat in CT-RW system. Similarly, in 2017–18, WP_I of wheat under CA-based systems was significantly higher than that of wheat in CT-RW system. Like, in 2016–17, the WP_I of mustard in two mustard-based systems in 2017–18 was significantly lower compared to wheat in wheat-based systems. A similar trend in WP_I was observed in wheat and mustard in 2018–19.

The rice-based systems reported lower WP_I (1.5 to 2.1 kg grains m^{-3}) compared to maize-based systems (5.1 to 6.0 kg grain m^{-3}) across the three years. On the basis of 3-year mean, the system WP_I was lowest with CT-RW system (1.5 kg grain m^{-3}), and it was maximum with CA-MMuMb system (6.06 kg grain m^{-3}). The CA-MW, partial CA-RMuMb and CA-RW systems recorded WP_I of 5.1, 2.1 and 1.83 kg grain m^{-3} , respectively (3-years mean). The WP_I of CA-MW and CA-based MMuMb systems was 204% higher compared with mean of rice-

based (CT-RW, CA-RW and partial CA-RMuMb) systems (Table 6, Figure 2). The mean system WP_I was nearly 304% higher for CA-MMuMb system (6.06 kg grain m^{-3}) compared with CT-RW system.

3.4 Energy utilization pattern and efficiency

3.4.1 Input and output energy

The system energy consumption varied from 36.10 to 73.78 $\times 10^3$ MJ ha^{-1} (average of 3-years) (Table 7). In all three years of study (2016–2019), the sum of all energy inputs was significantly ($p \leq 0.05$) higher under CT-RW system (farmer's practices), which was followed CA-RW, partial CA-RMuMb and CA-MMuMb systems. The CA-MW and CA-MMuMb systems involved 49.0 and 51.1% (3-yrs mean) less energy input compared to CT-RW system (73.78 $\times 10^3$ MJ ha^{-1}), respectively. CA-based RW and partial CA-based

TABLE 7 Energy input, energy output, use efficiency and energy productivity of different cropping systems during 2016–17, 2017–18 and 2018–19.

Year	Cropping system ^a	Total energy input (MJ $\times 10^3$ ha^{-1})	Total energy output (MJ $\times 10^3$ ha^{-1})	Energy use efficiency	Energy productivity (kg grain MJ ⁻¹)
Mean for three years	CT-RW	73.78a	330.46c	9.76c	0.28d
	CA-RW	63.66b	356.59b	12.08b	0.34c
	Partial CA-RMuMb	63.52b	281.33d	12.25b	0.34c
	CA-MW	37.61c	382.91a	21.04a	0.61b
	CA-MMuMb	36.10d	309.72c	21.70a	0.68a
2016-17	CT-RW	74.77a ^b	370.74bcde	11.28de	0.28ef
	CA-RW	64.52bc	402.10ab	13.87c	0.32def
	Partial CA-RMuMb	64.86b	277.49g	11.82cde	0.32def
	CA-MW	37.53ef	443.89a	24.07a	0.65ab
	CA-MMuMb	36.79efg	318.80efg	22.00a	0.68ab
2017-18	CT-RW	73.23a	312.74efg	9.04e	0.28ef
	CA-RW	63.28bcd	334.69def	11.17de	0.35d
	Partial CA-RMuMb	63.35bcd	287.07fg	12.58cd	0.36d
	CA-MW	37.88e	322.49defg	17.66b	0.57c
	CA-MMuMb	35.97fg	311.06efg	21.81a	0.71a
2018-19	CT-RW	73.35a	307.88efg	8.97e	0.26f
	CA-RW	63.18cd	332.97def	11.20de	0.33de
	Partial CA-RMuMb	62.34d	279.43fg	12.34cd	0.36d
	CA-MW	37.41ef	382.35bcd	21.38a	0.62bc
	CA-MMuMb	35.53g	299.30fg	21.30a	0.66ab
ANOVA (p value)					
Cropping systems		<0.001	<0.001	<0.001	<0.001
Year x Cropping system		0.021	<0.001	0.001	0.006
CV (%)		1.00	5.00	5.00	5.00

^aRefer Table 1 for description of cropping systems.

^bMeans followed by a similar lowercase letter(s) within a column are not significantly different at 0.05 level of probability using Tukey's HSD test.

RMuMb systems recorded almost 14% less energy input compared to CT-RW system. Same trends of energy consumption were observed across the three years (Table 7). CT-RW system recorded significantly higher energy input compared to the other cropping systems. Both CA-based MW and MMuMb systems involved lower energy input among the five cropping systems. The differences between the two systems were non-significant in 2016-17, however CA- MMuMb recorded significantly lower energy input compared to CA- MW system in the latter two yrs (Table 7).

The total output energy also differed significantly across the cropping systems in the three years of the study, and this variation primarily depended on system yield (Table 7). Significantly higher mean energy output was recorded under CA- MW system (382.91×10^3 MJ ha⁻¹) compared to all the other cropping systems, and it was followed by CA-RW system (356.59×10^3 MJ ha⁻¹). Partial CA-RMuMb recorded the lowest energy output (309.72×10^3 MJ ha⁻¹). Energy output from CT-RW and CA-MMuMb systems was similar. Under CA-MMuMb and partial CA-RMuMb systems, the mean total output energy recorded was 6.27 and 14.8% lower compared to CTRW system, respectively. In 2016-17, total energy output was significantly higher from CT-RW than partial CA-RMuMb, which was similar to CA-RW but was significantly higher compared with CA-MMuMb cropping systems. In 2017-18, however, no significant differences in the total energy output were observed among different cropping systems. In the 3rd year, total energy output from CA-MW was similar to CA-RW but significantly higher compared with the three other cropping systems (Table 7, Figure 2).

3.4.2 Energy efficiency and productivity

The lowest energy input requirement and highest energy output in CA-MW and CA-MMuMb resulted in higher system energy productivity (EP) as well as energy use efficiency (EUE) (Table 7). The EP and EUE in CA-MMuMb system were about 122–142% higher (3-yr's mean basis) compared to CT-RW system (EP of $9.76 \text{ MJ} \times 10^3 \text{ MJ ha}^{-1}$ and EUE of $0.28 \text{ kg grain MJ}^{-1}$). The EP was significantly higher under CA-MW and CA-MMuMb systems compared to the other cropping systems in all the three years of study. In 2016-17, EUE was significantly higher in CA-RW compared with CT-RW system, but both had similar EUE in the next two years of the study (Table 7). CA-RW and partial CA-RMuMb systems were intermediate in terms of EUE and EP across the study period. While partial CA-RMuMb and CA-RW systems showed similar values of EP in 2016-17, CT-RW recorded significantly lower EP compared to CA-RW system in the other two years of study (Table 7).

3.5 Nutrient productivity and efficiency

3.5.1 Protein yield

Different cropping systems significantly ($p \leq 0.05$) influenced the protein yields (Table 8A). CA-MMuMb and CA-MW systems improved the system protein yield by 25.8% and 24.7% in the first year, 33.3% and 7.7% in the second year, and 33.7% and 25.3% in

the third year, respectively, compared to the CT-RW system (0.89 , 0.9 and 0.83 Mg ha^{-1}). However, partial CA-RMuMb system produced lower protein yield in first year, but it was 7.7% and 16.8% higher in second and third year, respectively compared with CT-RW system. Based on 3-year mean, CA-MMuMb+R system recorded the highest protein yields of 1.04 Mg ha^{-1} , which was 30.9% higher than CT-RW system (0.87 Mg ha^{-1}) (Table 8A).

3.5.2 Fat yield

The fat yield under different systems varied from 0.09 to 1.24 Mg ha^{-1} over 3 years of the study (Table 8A). The mean system fat yield was higher by 1125% and 886% with CA-MMuMb and partial CA-RMuMb systems, respectively, compared to CT-RW system (0.093 Mg ha^{-1}). Fat yield was 221% and 7.10% higher with CA-MW and CA-RW systems, respectively, compared to CT-RW system. Compared to cereal-based systems (CT-RW, CA-RW and CA-MW), oilseed-based systems (CA-MMuMb and partial CA-RMuMb) produced significantly higher mean fat yield (>527%) during the study period (Table 8A).

3.5.3 Iron (Fe) and Zinc (Zn) yields

Fe and Zn yields were significantly influenced by different crops and cropping systems (Table 8B). The highest mean (averaged across three years) Fe yield was recorded under CA-MMuMb, which was followed in decreasing order: CA-MW partial CA-RMuMb, CA-RW, and CT-RW systems. CA-MMuMb system resulted in a 119.0% higher Fe yield compared to CT-RW system (220.6 g ha^{-1}). The increase in Fe yield CA-MW and partial CA-RMuMb systems was 59.5 and 57.5% over CT-RW system. The increase in Fe yield under CA-RW was relatively small (9.6%) compared to CT-RW system (Table 8B).

The highest mean Zn yield was reported under the CA-MW system, which was 46.2% higher than the CT-RW system (192.3 g ha^{-1}). CA-MMuMb and CA-RW systems recorded 26.5 and 7.9% higher Zn yield than the CT-RW system, respectively (3-year mean). On the other hand, partial CA-RMuMb system provided 17.5% lower Zn yield compared to CT-RW system (Table 8B).

3.5.4 System nutritional efficiency

Adult's protein and fat demands were significantly ($p \leq 0.05$) influenced by different crops and cropping systems over the years (Figure 3). The maize-based systems (CA-MW and CA-MMuMb+R) would meet the mean (3-year average) adult protein demand of equivalent to 53.8- and 49.0-persons ha⁻¹ year⁻¹ compared to 41.2 person's ha⁻¹ year⁻¹ with CT-RW system. The rice-based systems (partial CA-RMuMb and CA-RW) could meet out the protein demand of 43.8 more persons ha⁻¹ year⁻¹, which was almost similar to CT-RW system (Figure 3). Cropping systems integrated with mung bean (partial CA-RMuMb and CA-MMuMb) could meet out the adult protein demand of 2–12 more person's ha⁻¹ year⁻¹ compared to systems without mungbean.

The oilseed-based systems (CA-MMuMb and partial CA-RMuMb) can meet the fat demands of maximum adults (104- and 84-persons ha⁻¹ year⁻¹, respectively) compared to 8 persons ha⁻¹ year⁻¹ with CTRW system (3 year's mean). CA-MW and CA-

TABLE 8A Protein and fat yield of different crops and cropping systems during three years of study (2016–19).

Treatment ^a	Protein yield (mg ha ⁻¹)				Fat yield (mg ha ⁻¹)			
	Rice/maize	Wheat/mustard	Mung bean	System	Rice/maize	Wheat/mustard	Mung bean	System
2016-17								
CT-RW	0.31b ^b	0.58a	0.00a	0.89a	0.02a	0.08c	0.00a	0.10a
CA- RW	0.33b	0.58a	0.00a	0.90a	0.02a	0.08c	0.00a	0.10a
Partial CA-RMuMb	0.33b	0.35a	0.16a	0.84a	0.02a	0.73b	0.01a	0.76a
CA- MW	0.52a	0.58a	0.00a	1.11a	0.24a	0.08c	0.00a	0.32a
CA- MMuMb	0.49a	0.39a	0.24a	1.12a	0.22a	0.80a	0.01b	1.03a
2017-18								
CT-RW	0.43a	0.47a	0.00a	0.90a	0.03a	0.07a	0.00a	0.09a
CA- RW	0.43a	0.55a	0.00a	0.98a	0.03a	0.08a	0.00a	0.10a
Partial CA-RMuMb	0.42a	0.44a	0.11a	0.97a	0.03a	0.91a	0.01a	0.94a
CA- MW	0.47a	0.51a	0.00aa	0.97a	0.21a	0.07a	0.00a	0.28a
CA- MMuMb	0.50a	0.49a	0.21	1.20a	0.23a	1.00a	0.01a	1.24a
2018-19								
CT-RW	0.35a	0.48a	0.00c	0.83a	0.02a	0.07b	0.00a	0.09b
CA- RW	0.33a	0.58a	0.00c	0.90a	0.02a	0.08b	0.00a	0.10b
Partial CA-RMuMb	0.34a	0.50a	0.12b	0.97a	0.02a	1.03a	0.01a	1.06a
CA- MW	0.50a	0.53a	0.00c	1.04a	0.23a	0.07b	0.00a	0.30b
CA- MMuMb	0.42a	0.46a	0.22a	1.11a	0.19a	0.95a	0.01a	1.16a

^aRefer Table 1 for description of treatments/cropping systems.^bMeans followed by a similar lower case letter(s) within a column are not significantly different at 0.05 level of probability using Tukey's HSD test.

TABLE 8B Fe and Zn yield of different crops and cropping systems as affected by different management practices during the year 2016–19.

Year/cropping system ^a	Fe yield (g ha ⁻¹)				Zn yield (g ha ⁻¹)			
	Rice/ maize	Wheat/mustard	Mung bean	System	Rice/ maize	Wheat/mustard	Mung bean	System
2016-17								
CT-RW	25.65c ^b	216.4b	0.00b	242.0d	47.74c	155.3a	0.00c	203.1c
CA- RW	26.89c	215.4b	0.00b	242.3d	50.06c	154.6a	0.00c	204.7c
Partial CA-RMuMb	27.38c	242.6a	25.55a	295.53c	50.97c	73.0b	16.19b	140.1d
CA- MW	156.84a	218.6b	0.00b	375.4b	142.98a	156.9a	0.00c	299.9a
CA- MMuMb	145.61b	266.33a	39.82a	451.8a	132.74b	80.1b	25.23a	238.1b
2017-18								
CT-RW	35.07c	175.6c	0.00c	210.7c	65.29b	126.1b	0.00c	191.4c
CA- RW	34.88c	206.1b	0.00c	241.0c	64.93b	147.9a	0.00c	212.9b
Partial CA-RMuMb	34.29c	302.8a	18.73b	355.9b	63.84b	91.1d	11.87b	166.8d

(Continued)

TABLE 8B Continued

Year/cropping system ^a	Fe yield (g ha ⁻¹)				Zn yield (g ha ⁻¹)			
	Rice/ maize	Wheat/ mustard	Mung bean	System	Rice/ maize	Wheat/ mustard	Mung bean	System
2017-18								
CA- MW	139.94b	190.2b	0.00c	330.1b	127.58a	136.5a	0.00c	264.1a
CA-based MMuMb	148.90a	334.7a	35.07a	518.6a	135.74a	100.7c	22.22a	258.6a
2018-19								
CT-RW	28.55c	180.6c	0.00b	209.2c	53.14c	129.7b	0.00c	182.8d
CA- RW	26.92c	215.8b	0.00b	242.7c	50.11c	154.9a	0.00c	205.0c
Partial CA-RMuMb	28.06c	345.1a	20.31a	393.4b	52.23c	103.8c	12.87b	168.9d
CA- MW	151.46a	199.5b	0.00b	351.0b	138.08a	143.2a	0.00c	281.3a
CA- MMuMb	126.27b	318.3a	36.36a	480.9a	115.11b	95.7c	23.04a	233.9b

^aRefer Table 1 for description of treatments/cropping systems.

^bMeans followed by a similar lowercase letter (s) within a column are not significantly different at 0.05 level of probability using Tukey's HSD test.

RW systems will be able to meet fat demand of 27- and 9 more-persons persons ha⁻¹ year⁻¹, respectively compared with CT-RW. The highest Fe demand for 77 persons ha⁻¹ year⁻¹ could be met by adopting CA-MMuMb followed by CA-MW and partial CA-RMuMb (56-persons ha⁻¹ year⁻¹ for the both systems), and CA-RW system (38-persons ha⁻¹ year⁻¹) compared with CT-RW, which could meet the Fe demand of 35-persons ha⁻¹ year⁻¹. CA-MW and CA-MMuMb systems supplied the highest Zn demand of 64- and 55-persons ha⁻¹ year⁻¹ compared to CT-RW system (43 persons ha⁻¹ year⁻¹) (Figure 3).

4 Discussion

4.1 System productivity and economic profitability

Diversifying the conventional RW system with alternative resource-efficient CA-MW and CA- MMuMb systems significantly improved the system productivity, WP_B, profitability and nutritional security in the EGP of India (Table 5). The current study demonstrated that rice yield was unaffected by tillage

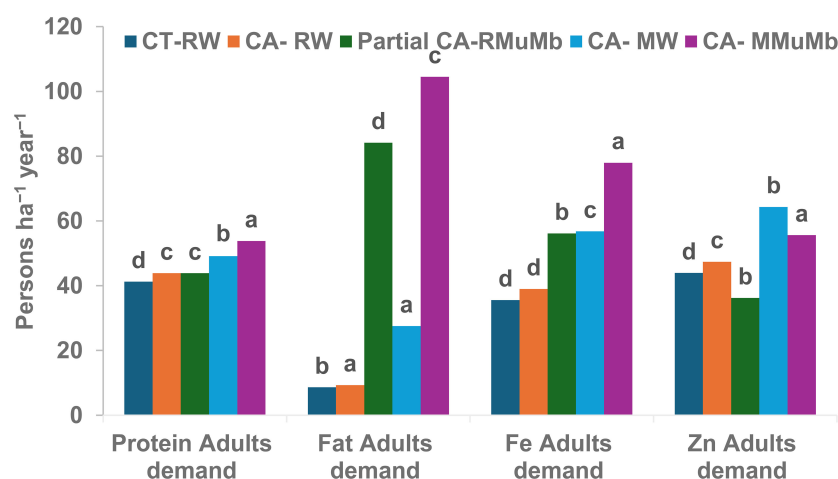


FIGURE 3

Effect of different cropping systems on yearly number of persons ha⁻¹ to meet demand of protein, fat, Fe and Zn demand based on 58, 30, 17 and 12 mg day⁻¹ adult⁻¹, respectively (3 year's mean). Refer Table 1 for description of cropping systems, Means followed by a similar lowercase letter on each bar not significantly different at 0.05 level of probability using Tukey's HSD test.

(conventional tillage *vs* zero tillage) and crop establishment techniques (transplanted *vs* direct seeded rice; DSR) during the three years of study, but ZT-DSR consumed 8% and 13% lesser irrigation water and input energy, respectively compared to CT transplanted rice. These findings are consistent with earlier reports from the region (Jat et al., 2020; Gathala et al., 2022; Dutta et al., 2020). The low productivity (REY) of CT-RW system was mainly due to poor performance of wheat after transplanted rice (Gathala et al., 2020a, b). The high crop yields (REY) observed in maize-based systems under CA (CA-MW and CA-MMuMb) may be attributed to the combined effects of high grain yields, improved soil moisture regimes due to residue mulch, improved soil health and enhanced nutrient use efficiency when compared to CT-RW system (Parihar et al., 2018; Islam et al., 2019). Furthermore, residue mulch in CA is reported to moderate soil temperature and increase nutrient use efficiencies (Singh et al., 2015; Singh et al., 2016; Jat et al., 2020, 2023). The higher economic value of mustard and additional pulse grains from mungbean contributed significantly higher system yields in partial CA-RMuMb and CA-MMuMb systems (Gathala et al., 2022).

The timely seeding of wheat or mustard in CA-based cropping systems and residue mulch moderated soil temperature reducing terminal heat stress and conserved soil moisture, improvement in soil health parameters, decreased the weed intensity resulted in significant increases in REY compared with CT-RW consistent with the earlier reports by researchers from northwestern India (Parihar et al., 2017; Bijarniya et al., 2020; Jat et al., 2018, 2019; Singh et al., 2016). The early maturity of mustard planted after maize followed by timely sowing of mungbean in CA-MMuMb resulted in higher yields of mung bean compared with that in partial CA-RMuMb system in all the study years. Furthermore, sowing crops on PB in CA-MMuMb provided an opportunity for drainage of excess water during the heavy rains, leading to higher productivity (Hoque et al., 2023). The high system productivity under CA-MMuMb compared with partial CA-RMuMb was mainly due to higher REY of maize on PB than CT-DSR.

Lower production costs in combination with higher crop yields (REY) recorded in CA-based systems compared with CT-RW system contributed towards the higher net returns during the study years (Table 5). The CA-based cropping system required less labor input for tillage and irrigation operations. Consistent with the results from our study, earlier studies in the EGP of South Asia have shown higher net returns due to 20–63% reduction in production costs (tillage and irrigation) in CA-based systems compared with CT-RW system (Haque et al., 2016; Gathala et al., 2020a; Islam et al., 2019; Jat et al., 2019). Integration of mungbean in CA-MMuMb and partial CA-RMuMb increased the net returns by ~ 47% compared with the other cropping systems. These mustard-based cropping sequences provided a better window for the integration of Mungbean due to the early maturity of mustard, which resulted in higher system net returns compared with the other cropping systems. In the present study, no attempt was made to include mungbean in CA-MW system. Generally, the late maturity of wheat compared with mustard delays the sowing of

mungbean due to which crop does not mature before/at the time of sowing next *kharif* crop (s).

In CA-based cropping systems, lower water and labor demand reduced the input costs to a greater extent compared with CT-RW system. Thus, sustainable intensification of the CA-MMuMb and partial CA-RMuMb systems through mung bean integration resulting in higher net returns equal to USD 598 ha⁻¹ compared with CT-RW system (Table 5). Our findings are consistent with the results from a study in EGP by Gathala et al. (2022), who reported that using CA-based system intensification options lowered the crop production costs by up to 22% and raised gross margins by 12–32% compared with traditional cultivation methods.

4.2 Irrigation water use and water productivity

Diversifying CT-RW system with lower water requiring crops such as rice with maize and wheat with mustard alongside adoption of CA practices and integration of short-duration legume crops such as mungbean resulted in reduced irrigation water requirement and thereby enhanced irrigation water productivity (Table 6). The reduced irrigation water usage observed in DSR (CT/ZT) based systems was primarily due to the elimination of puddling, which typically saves 25–30 cm of irrigation water. Additionally, retention of crop residues as mulch in CA-based systems has been reported to minimize the loss of soil moisture through evaporation (Yadvinder et al., 2014; Jat et al., 2023). In our study, replacing CT-puddled transplanted rice in the RW system with maize necessitated only 5–10% of the total irrigation water utilized by the RW system due to the lower water requirement of maize crop. These results are in close conformity with those of Pooniya et al. (2021), who reported significant reduction in irrigation water use in CA-based MW system compared to conventional RW system. Adoption of maize-based cropping systems on PBs (CA-MW and CA-MMuMb) reduced irrigation water use by about ~ 66% (3 years' mean) compared to CT-RW (Table 6). The reduction in irrigation water usage along with the increase in REY resulted in the 4-time increase in WP_I with CA-MMuMb (~ 6.06 kg grain m⁻³) followed by 3.41-time increase with CA-MW system (~ 5.11 kg grain m⁻³) compared to CT-RW (1.5 kg grain m⁻³). This could be attributed to the improvement in soil health and the promotion of robust root growth through CA-based practices, which exhibited significant increase in water productivity. Similarly, Gathala et al. (2022) while working in a similar ecology, reported that sustainable intensification practices under CA enhanced soil health and promoted root growth, which in turn improved the WP_I. Earlier studies from northwest IGP also reported that diversified crop rotations such as CA-MW and CA-MMuMb significantly reduced the quantity of irrigation water input compared with CT-RW system and was the lowest in CA-MMuMb system due to the lower water requirement of mustard crop compared with maize, which resulted in the highest system WP_I (Parihar et al., 2017; Gora et al., 2022).

4.3 Energy use and use efficiency

Total energy use was 51.1% and 49.0% lower under CA-MMuMb and CA-MW system compared with CT-RW ($73.784 \times 10^3 \text{ MJ ha}^{-1}$) system, respectively (Table 7). The large savings in energy use in CA-MMuMb and CA-MW systems were due to reduction in fuel consumption during land preparation, crop establishment and irrigation water pumping. The higher energy output in these CA-based diversified systems was related to increases in REY and lower energy inputs resulted in higher net energy returns than in CT-RW system. The greater energy demands in CT-RW are mainly due to intensive tillage operations, and manual transplanting of rice, along with high consumption of energy for pumping to meet the high irrigation water requirements (Gathala et al., 2020a). Consistent with the results from our study, previous studies conducted in EGP of Bangladesh have reported large savings in energy use in CA-based RW systems (Islam et al., 2019; Hossen et al., 2018; Gathala et al., 2020b). Similarly, Bijarniya et al. (2020) have reported that climate smart agriculture practices (such as ZT with residue retention) enhanced the EUE and EP by 43%–54% and 44%–61%, respectively, compared with CT-RW in the EGP of India.

4.4 Nutritional security

The cereal-based conventional rice-wheat (RW) system in the EGP of India faces challenges related to malnutrition, which exacerbates declines in input use efficiencies and degradation of soil and environmental quality (Gonmei and Toteja, 2018). The crop diversification and intensification strategy offer several advantages; like production of pulse and oilseed crops that are rich sources of proteins, essential vitamins, edible oils (fats), and minerals, often lacking in diets of millions of populations in South Asia (Kakraliya et al., 2018). This study demonstrated that adopting CA-based crop diversification and intensification will lead to ensuring food and nutritional security (e.g. protein, fats, and micronutrients) for a resource poor population of EGP in India (Table 8a). Higher protein and fat yields were recorded in the CA-MMuMb, which can supply 20–25% and 28–32% higher protein and fat yield, respectively. In another study from northwestern India, Gora et al. (2022) reported significantly higher protein yields in cropping systems that included pulse crops (soybean, pigeon pea, and mung bean). Similar increases in protein yield with mung bean integration in the RW and MW systems were reported by other researchers from northwestern India (Jat et al., 2019; Parihar et al., 2017). Similarly, diversifying wheat with mustard in a cropping system provides additional high fat yield and a window for the successful cultivation of short duration mungbean (Zohra et al., 2008). The CA-MMuMb system could meet the highest adult protein demand of 53 person's $\text{ha}^{-1} \text{ year}^{-1}$ compared to 41

person's $\text{ha}^{-1} \text{ year}^{-1}$ with CT-RW system. This system will also achieve the maximum requirement of fat for 96-person's $\text{ha}^{-1} \text{ year}^{-1}$, compared to 8 persons $\text{ha}^{-1} \text{ year}^{-1}$ with CT-RW system. Therefore, CA-MMuMb is considered to be an important food production system for reducing malnutrition in EGP of India (Samtiya et al., 2020). Dutta et al (2023) have demonstrated that diversifying the traditional RW system with maize-based systems in combination with CA increased system protein productivity by 18–68% and about 10-fold higher fat productivity in the EGP.

The Fe and Zn yield in a cropping system will depend upon both micronutrient content in the grains and the crop yields. CA based MMuMb and MW cropping systems provided 119% and 59% higher Fe yield than CT-RW system, respectively (Table 8b). The Zn yield was about 32% higher under CA-MMuMb and CA-MW system compared with CT-RW system (203 g ha^{-1}). These CA-based diversified cropping systems produced additional Fe and Zn yields that could meet the demand of 42- and 12 more-person's $\text{ha}^{-1} \text{ year}^{-1}$, respectively, compared CT-RW system. Yadav et al. (2021) demonstrated that CA-based management practices increased crop yields, resulting in higher nutrient production. Results from our study are in close conformity with the results of Rao et al. (2018) who reported that by replacing rice with alternative crops, it is possible to substantially reduce irrigation water demand (–21%), increase protein (+9%), iron (+43%), and zinc (+28%) supply. Limited farmer knowledge and awareness of conservation agriculture practices can hinder uptake, especially among smallholders who are more risk averse. Access to specialized machinery, such as Happy Seeder or zero-till planters, is often constrained by high costs and poor availability of custom hiring services. Moreover, market constraints particularly price volatility and weak procurement systems for maize and mustard can reduce farmer incentives to diversify away from rice wheat. Addressing these challenges through targeted extension programs, improved access to machinery, and stronger market linkages will be essential for scaling CA-based diversification in the region.

5 Conclusion

Conservation Agriculture-based sustainable intensification of diversified cropping systems offered promising solutions to address the farming challenges faced with large-scale adoption of conventional RW system in smallholder systems across the EGP of South Asia. The present study revealed that diversified CA-based MMuMb proved the most efficient production system, which resulted in 52.6% more grains, 63.2% higher economic profitability, 304% higher water productivity, 142% higher energy productivity along with 30.9, 1125%, 119% and 26.5% higher protein, fat, Fe and Zn yields, respectively, compared to farmers' business as usual practice (CT- RW system). Our study demonstrated that CA-MMuMb followed by CA-MW systems, showed promise as scalable alternatives to the CT-RW system.

These diversified cropping systems offer potential solutions to address the critical challenges of declining natural resources, food and nutritional security, contributing to the overall health and well-being of the smallholders of the EGP of Bihar and other regions with similar ecologies in South Asia. These findings could be highly valuable for the Government of India in directing interventions and prioritizing investments within the 4th Agricultural Road Map (2023-2028), which has an allocated budget of US\$ 20 billion. The present study has the drawback of lack of integration of mungbean in CA-MW system as one of the sustainable intensifications. Studies are needed to either develop a shorter duration of mungbean genotypes, which can fit well in the CA-MW system, or adoption of relay planting of mungbean in standing wheat. However, studies from western IGP have successfully integrated mungbean in CA-MW system. While the CA-MMuMb system offers clear benefits, its adoption entails trade-offs, including upfront investment in specialized machinery and the need for farmer training and technical support to ensure effective implementation. The impact of diversified cropping systems on soil health and environmental benefits needs to be investigated in future to strengthen the case for adoption potential of diversified cropping systems by smallholders of EGP.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

DB: Data curation, Formal Analysis, Methodology, Software, Writing – original draft. MG: Conceptualization, Funding acquisition, Investigation, Project administration, Writing – review & editing. KK: Data curation, Formal Analysis, Software, Writing – review & editing. RJ: Resources, Supervision, Writing – review & editing. YS: Investigation, Supervision, Validation, Visualization, Writing – review & editing.

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Conflict of interest

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