Energy Nexus 19 (2025) 100509

Contents lists available at ScienceDirect

Energy Nexus

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

Full Length Article

Achieving environmental stewardship through climate-smart agriculture practices in intensive cereal systems of North-western India: Effects on energy-water-carbon footprints

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ARTICLE INFO

Keywords:
Climate-smart agriculture
Environmental sustainability
Energy use efficiency
Energy-water-nitrogen footprints
Global warming potential
Subsurface drip irrigation

ABSTRACT

Intensive rice-based systems in the Indo-Gangetic Plain of India face critical sustainability challenges, including high energy use, excessive greenhouse gas (GHG) emissions, and unsustainable groundwater exploitation. This study evaluates productivity and environmental footprints (energy, water, and carbon) to foster environmental stewardship through conservation agriculture-based climate-smart agriculture practices (CSAPs). Six scenarios (*Sc*) were analyzed: conventional till (CT) rice-wheat (CT-RW, *Sc* 1); CT rice-zero till (ZT) wheat-ZT mungbean (CTR-ZTWM, *Sc* 2); ZT direct-seeded rice-ZTWM (ZTRWM, *Sc* 3); ZT maize-ZTWM (ZTMWM, *Sc* 4); *Sc* 3 with subsurface drip (SSD) irrigation (ZTRWM-SSD, *Sc* 5); and *Sc* 4 with SSD (ZTMWM-SSD, *Sc* 6). The CSAPs (*Sc* 3-*Sc* 6) outperformed *Sc* 1 with respect to key performance parameters. *Sc* 6 (ZTMWM-SSD) achieved the maximum rice equivalent yield (8.25 t ha^{-1}), a 22.2 % increase over *Sc* 1. Wheat yield in *Sc* 6 reached to 6.34 t ha^{-1}, corresponding to a 22.1 % enhancement compared to *Sc* 1, resulting in a total system yield of 16.73 t ha^{-1}, representing a 35.6 % increase over *Sc* 1. For system-wide partial factor productivity of N, *Sc* 5 showed 51.4 % improvement, while *Sc* 6 achieved the highest increase of 69.7 %, reflecting significant gains in nitrogen use efficiency. The CSAPs scenarios markedly improved system water productivity, resulting in a decreased water footprint, which was lowest in *Sc* 6 (189 L kg^{-1}) compared to *Sc* 1 (1642 L kg^{-1}). Energy dynamics revealed that *Sc* 6 was the most efficient among all the scenarios. With an energy input of 30,360 MJ ha^{-1}, it produced energy output of 471,633 MJ ha^{-1}, and recorded the highest energy use efficiency (15.69). In terms of environmental sustainability, CSAPs (*Sc* 3, *Sc* 4, *Sc* 5 and *Sc* 6) exhibited lower system net global warming potential (GWP$_n$), compared to CT-based scenarios (*Sc* 1 and *Sc* 2), reflecting a significantly reduced carbon footprint. These results highlight the potential of CSAPs to enhance productivity and profitability while minimizing environmental impacts, making CSAPs critical to the future of sustainable agriculture in North-western India.

Introduction

The Indo-Gangetic Plains (IGP) of South Asia support the rice-wheat cropping system (RWCS) across approximately 14 million hectares [1, 2]. The RWCS is being cultivated primarily using conventional tillage (CT)-based management practices throughout the region. However, these conventional agricultural practices contribute to resource degradation, including deterioration of soil, air, and water, while exacerbating global challenges such as climate change, biodiversity loss, and inefficient energy use [3]. The practice of puddling (ploughing in ponded fields) before transplanting rice deteriorates soil structure, while multiple tillage operations (5–6 times) required before sowing subsequent wheat crops accelerate oxidation–reduction cycles, leading to soil quality decline. These CT practices demand greater energy inputs and

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https://doi.org/10.1016/j.nexus.2025.100509
Received 18 December 2024; Received in revised form 9 June 2025; Accepted 19 August 2025

negatively impact farm profitability. Furthermore, the widespread practice of burning crop residues, particularly after rice harvest, significantly increases greenhouse gas (GHG) emissions and contributes to severe air pollution. Additionally, inefficient irrigation practices (such as open-border irrigation) place further strain on already limited water resources, resulting in accelerated groundwater depletion. Given these challenges, there is an urgent need to adopt resilient, eco-friendly and climate-resilient practices and alternative cropping systems in the RWCS belt of North-western (NW) India.

Climate-smart agriculture practices (CSAPs) integrate modern crop production techniques under the theme of 'more from less' - maximizing profitability through optimizing resource use tailored to local soil and ecological conditions. These practices aim to enhance sustainable farm productivity, boost system resilience, reduce GHG emissions, lower water and energy use, and promote carbon sequestration while ensuring food security in the region. Conservation agriculture (CA), a widely accepted concept in sustainable agriculture, operates on the principles of zero or minimum tillage, rational surface residue cover, and efficient crop rotations. CA primarily focuses on enhancing the sustainability of crop, soil and environment within agri-food systems. When these principles are layered with the sustainable management of agricultural resources and modern techniques, all components of the crop production system can be optimized for a specific region. Thus, adopting CA-based management systems to implement the CSAPs offers a sustainable path forward for enhancing productivity, resource use efficiency, and environmental sustainability in this productive but resource-fragile region of NW India.

Adopting CSAPs offers numerous benefits in the RWCS, including enhanced energy efficiency, water conservation, and increased soil organic carbon (SOC) sequestration [4]. For instance, zero tillage (ZT) and direct-seeded rice (DSR) can significantly reduce diesel consumption, which can save 50–60 L ha^{-1} of diesel and approximately 3000 MJ ha^{-1} of energy [5]. These energy savings are crucial as conventional systems, reliant on intensive tillage and inefficient irrigation methods, consume large amounts of energy for land preparation and water pumping. CSAPs such as precision irrigation, site-specific nutrient management (SSNM), and laser land levelling further enhance energy productivity by optimizing resource inputs, thereby reducing the carbon footprint of agricultural production [6]. In addition to improving energy efficiency, these practices lower GHG emissions from agriculture by reducing methane (CH_4) emissions from flooded rice fields and lowering nitrous oxide (N_2O) emissions through improved water and nutrient management [7]. Conventional RWCS have a high environmental footprint due to heavy fertilizer use, fossil fuel dependency, and residue burning, all of which contribute to CO_2 and particulate matter emissions [8]. CSAPs mitigates these impacts by promoting residue retention and minimizing soil disturbance, thereby improving nutrient cycling and soil structure. Studies show that adopting ZT with residue retention can lower the GWP by 12–33 %, enhance water productivity by 12.6 %, and increase crop yields by 5.8 % [7].

Conventional tillage-based RWCS often leads to inefficient water and energy use and soil health degradation. CSAPs such as ZT and DSR help conserve water by reducing evaporation and runoff, while micro-irrigation systems, particularly subsurface drip irrigation (SSD, further enhance water-use efficiency by delivering water directly to the root zone. Unlike surface drip systems, SSD requires less maintenance and is more compatible with CA systems [9]. In SSD, laterals are permanently installed in soil at certain depths, eliminating the need for frequent anchoring and offering a longer life span compared to surface drip systems, making SSD better suited for CA-based systems. SSD can further reduce water use, electricity consumption for irrigation and fertilizer inputs, thus contributing to overall water, energy, and fertilizer savings within CA systems.

Despite these advantages, the adoption of CA in the IGP remains limited due to several barriers, including the absence of a national CA policy, highly subsidized (nearly free) electricity, insufficient enabling policies, limited access to appropriate resources, and deeply entrenched traditional farming practices. Moreover, knowledge gaps regarding the long-term benefits of CA for farmers - such as energy savings, GHG mitigation, water conservation, sustainable yields, and improved soil health, hinder widespread adoption. Addressing these challenges through targeted research and robust extension services is essential to promote CSAPs and achieve sustainable intensification in cereal-based systems across South Asia.

This study evaluates the impact of CSAPs on system sustainability of cereal-based systems, considering indicators related to yield, soil, water, energy and GHG in the IGP. Long-term evidence has been generated on crop productivity, energy efficiency, water productivity, and GHG emissions and compared with conventional till systems. We hypothesize that CSAPs-based scenarios can enhance crop yields, improve net income, and increase resource-use efficiency while significantly reducing the global warming potential of cereal-based systems in South Asia. The findings provide valuable insights for policymakers and practitioners aiming to promote sustainable agricultural practices in the face of climate change, while also addressing food security challenges in the region.

Material and methods

Study site

A long-term study was initiated in 2009–10 at ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal (29° 70′ N, 76° 96′ E), India, aiming to investigate a suite of package of practices within cereal-based cropping systems, specifically focusing on climate-smart agriculture practices (CSAPs) (Plate 1). The CSAPs were implemented across varying scenarios throughout the years, and data on various parameters was recorded from 2016–17 to 2021–22. The experimental site represents the region characterized by a sub-tropical and semi-arid climate. Over the past 40 years, the average annual rainfall has been 765 mm, with a mean maximum temperature of 37.7 °C in June and a minimum temperature of 6.4 °C in January. The soil of the experimental field (0–15 cm) exhibited a silty loam texture (34 % sand, 46 % silt and 20 % clay), with low organic carbon (0.45 %), alkaline pH (8.0), 0.06 % total N, 5.74 mg kg^{-1} available P and 130 mg kg^{-1} exchangeable K. Before the commencement of this experiment, the area had been under the rice-wheat cropping system (RWCS), managed through conventional tillage for 30 years. Daily weather data, including rainfall, maximum temperature, and minimum temperature for all seasons during the experimental years, were sourced from the agro-meteorology observatory situated near the experimental site at ICAR-CSSRI, Karnal, India (Table S1).

Experimental details and scenario description

The experiment was initiated in 2009–10 by implementing four distinct CSAPs, designated as scenarios (*Sc*). Each scenario varied in tillage methods, crop establishment techniques, cropping systems, crop residue management strategies, and other related practices. These scenarios were developed under the CSISA (Cereal Systems Initiative for South Asia) project, aimed at addressing sustainability issues of the RWCS system in the western IGP. Initially (2009–10), the experiment comprised four cereal-based scenarios (*Sc* 1-*Sc* 4), each tailored with different ranges of indicators, implemented at a plot size of 20 m × 100 m, and designed in alignment with the principles of CSAPs. In May 2016, the plots of *Sc* 3 and *Sc* 4 were subdivided into two sections (plot size: 20 m × 50 m), with one plot in each scenario receiving precise water and N application through subsurface drip irrigation (SSD) across all the replications. These subdivided plots were then designated as *Sc* 5 and *Sc* 6, respectively. Briefly, the six scenarios (*Sc*) were: (1) conventional-till (CT) puddled transplanted rice-CT wheat (*Sc* 1; farmers' practice; CT-RW); (2) partial CA-based CT rice-zero tillage (ZT) wheat-ZT

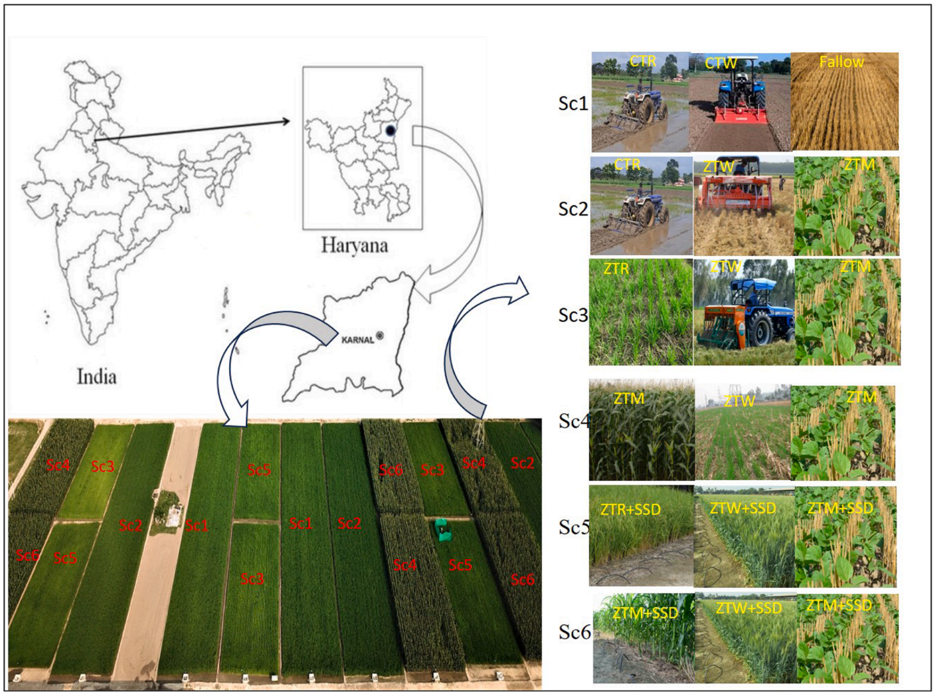

Plate 1. Overview of the experimental site and treatments.

mungbean with flood irrigation (*Sc* 2; CTR-ZTWM)); (3) ZT direct seeded rice-ZT wheat-ZT mungbean with flood irrigation (*Sc* 3; ZTRWM); (4) CA based alternative system ZT maize-ZT wheat-ZT mungbean with flood irrigation (*Sc* 4; ZTMWM); (5) ZT rice-ZT wheat-ZT mungbean with SSD (*Sc* 5; ZTRWM-SSD); and (6) ZT maize-ZT wheat-ZT mungbean with SSD (*Sc* 6; ZTMWM-SSD). The experiment employed a randomized block design, with three replicates for each scenario.

The SSD irrigation system consisted of 16 mm laterals fitted with in-line drippers (2 L h^{-1} discharge capacity) spaced 30 cm apart. The polyethylene laterals were laid at 20 cm depth using a tractor-operated drip laying trencher. The laterals were spaced 67.5 cm apart in both rice and maize-based scenarios, each serving three rows of rice, wheat and mungbean, and one row of maize crop. The operating pressure for drip irrigation was maintained between 1.5 to 2.0 kg cm^{-2}. For fertigation of N, a Venturi injector was installed in the drip system, with suction created by the pressure differences between upstream and downstream lines.

Detailed information on the different scenarios, including drivers of change, crop rotations, tillage, sowing techniques, and practices regarding residue and water management etc. is provided in Table 1. All the CSAPs scenarios were managed uniformly with respect to sowing window, tillage operations, residue management, weed management, etc. across the study years to ensure the uniformity in management practices. In the farmers' traditional approach (*Sc* 1), all crop residues were removed from ground level. In rice-based systems (*Sc* 2, *Sc* 3 and *Sc* 5), the entire rice residues were left on the soil surface for wheat cultivation. However, in maize-based systems (*Sc* 4 and *Sc* 6), 100 % of maize residues were initially retained for three years, followed by partial (65 %) residue retention in subsequent years. In *Sc* 1, both rice and wheat were conventionally established following farmers' practices. For rice in CT plots, dry-tillage (comprising two harrowing and two cultivators followed by wooden planking) and wet tillage (including puddling, with two harrowing passes and one planking) were done before transplanting. Similarly, for wheat in CT, two passes of harrowing and cultivator each, followed by planking were executed before sowing. In *Sc* 1, rice was manually transplanted into puddled field with 25–30 days-old seedlings, while wheat was manually broadcasted onto tilled soil. In *Sc* 2, following wet-tillage (comprising three passes of harrowing and one planking operations in standing mungbean crop after picking), rice was manually transplanted in a random geometry pattern (with a spacing of 20 × 15 cm). Under ZT conditions (*Sc* 3-*Sc* 6), rice, wheat, and mungbean crops were sown in rows (22.5 cm apart), using a Happy Seeder equipped with an inclined plate seed metering mechanism. However, maize was sown using a Happy Seeder with a row spacing set at 67.5 cm.

Rice (hybrid, Arize 6129) was seeded at a seed rate of 10 kg ha^{-1} in CT plots and 20 kg ha^{-1} in ZT plots. Wheat (cultivar, HD 2967) was seeded at a seed rate of 120 kg ha^{-1} in CT plots and 100 kg ha^{-1} in ZT plots. Both maize [hybrids, DKC 9125 (2016 to 2018) and CP858 (2019 to 2021)] and mungbean [cultivars, SML 668 (2016–2018), MH 421 (2019–2021)] were sown at a seed rate of 20 kg ha^{-1}. To enhance disease resistance, seeds of all crops except mungbean were treated with tabuconazole (Raxil 60 FS) (1 ml kg^{-1} seed) and imidacloprid (Gaucho 600 FS) (5 g kg^{-1} seed) before seeding. Rice and maize crops were cultivated during the Kharif (rainy) season, followed by wheat during Rabi (Winter), and short duration mungbean in spring season, following the CSAPs scenarios protocols. In rice, maize, and wheat, irrigation was applied according to pre-determined tensiometers (IRROMETER, Riverside, California) readings that measured soil moisture potential (SMP). The tensiometers were installed at a depth of 15 cm between the crop rows and drip laterals. Table 1 provides a detailed breakdown of the specific SMP values used for all crops under varying management scenarios. For rice cultivated with CT, the plots were kept continuously flooded during the first three weeks after transplantation to promote optimum growth of the seedlings. However, for DSR in *Sc* 3 and *Sc* 5, irrigations were given frequently from sowing until the emergence of 3–4 leaves to ensure successful germination and establishment of the crop. Thereafter, subsequent irrigations were scheduled based on pre-determined threshold values of SMP to maintain ideal soil moisture levels.

Grain yield and system productivity

All the crops were sampled at maturity by manual harvesting. Random samplings were carried out from two locations, each covering

Table 1

Details of the crop rotation, tillage, sowing methods, residue, and water management under different CSAPs scenarios.

Scenario	Issues to be addressed	Tillage and Crop sequences	Sowing Methods	Residue Management	Nutrient Management (NPK, kg/ha)	Water Management
Sc 1	Farmers' Practice	Rice-Wheat-Fallow under CT	Rice: Transplanting Wheat: Broadcast	All residue removed	Rice: 175+58+0 Wheat: 150+58+0	Rice: Continuous flooding of 5-cm depth for 1 month, followed by irrigation applied at hair-line crack Wheat: Need-based irrigation or at critical crop growth stages
Sc 2	Sustainable intensification with minimizing energy	Rice (CT) -Wheat (ZT)-Mungbean (ZT)	Rice: Transplanting Wheat: Drill seeding Mungbean: Drill/relay	Full (100 %) rice and anchored wheat residue retained on soil surface; full mungbean residue incorporated	Rice: 150+58+60 Wheat: 150+64+32 Mungbean: 0 + 0 + 0	Rice: Continuous flooding of 5-cm depth for first 15–20 days after transplanting 'fb' irrigation at −40 kPa matric potential at 15-cm depth till 1 week before flowering 'fb' irrigation at −15 to −20 kPa Wheat: Flood irrigation at −40 to-50 kPa matric potential
Sc 3	Sustainable intensification dealing with water, energy, soil health degradation and GHG emission	Rice (ZT) -Wheat (ZT)-Mungbean (ZT)	Rice: Drill seeding Wheat: Drill seeding Mungbean: Drill/relay	Full (100 %) rice and mungbean; anchored wheat residue retained on the soil surface	Rice: 160+64+62 Wheat: 150+64+32 Mungbean: 0 + 0 + 0	Rice: Kept soil wet for first 20 days 'fb' irrigation at −20 to −30 kPa matric potential Wheat: Flood irrigation at −40 to-50 kPa matric potential
Sc 4	Sustainable intensification dealing same issues (Sc3) with futuristic diversification	Maize (ZT) -Wheat (ZT)-Mungbean (ZT)	Maize: Drill seeding Wheat: Drill seeding Mungbean: Drill/relay	Maize (65 %) and full mungbean; anchored wheat residue retained on the soil surface	Maize: 175+64+62 Wheat: 150+64+32 Mungbean: 0 + 0 + 0	Flood Irrigation at −50 kPa in maize and −40 to-50 kPa matric potential
Sc 5	Sustainable intensification with same issues (Sc3) with precise water and N management	Rice (ZT) -Wheat (ZT)-Mungbean (ZT)	Same as in scenario 3	Same as in scenario 3	Rice: 130+64+62 Wheat: 120+64+32 Mungbean: 0 + 0 + 0 N in rice- 8 splits & wheat- 4 splits through SSD Fertigation	Subsurface drip (SSD) irrigation −20 to −30 kPa in rice and −40 to-50 kPa matric potential in wheat
Sc 6	Sustainable intensification dealing same issues (Sc3) with futuristic diversification and precise water and N management	Maize (ZT) -Wheat (ZT)-Mungbean (ZT)	Same as in scenario 4	Same as in scenario 4	Maize: 140+64+62 Wheat: 120+64+32 Mungbean: 0 + 0 + 0 N in maize- 3 splits & wheat- 4 splits through SSD Fertigation	Subsurface drip (SSD) irrigation at −50 kPa in maize and −40 to-50 kPa matric potential in wheat

Where: CSAPs: Climate Smart Agriculture Practices; CT- conventional tillage; ZT- zero tillage; CA- conservation agriculture; N-nitrogen; P-phosphorus; K-potassium.

of 25 m^2 area for rice, wheat and mungbean crops. For maize, samples were harvested from two random locations of 30 m^2 each, making a total area of 60 m^2 per plot. The grain yields of rice and maize crops were adjusted at a moisture content of 14 %, while wheat grain yields were adjusted to 12 % moisture level for uniformity across the samples and scenarios. For comparing the Kharif crops (rice and maize), the grain yield of maize (*Sc* 4 and *Sc* 6) was converted into rice equivalent yield (REY). While, for comparing the overall system productivity, the grain yields of maize, wheat, and mungbean were converted to rice-equivalent yield of system (REYS) by using Eq. (1).

$$Rice\ equivalent\ yield\ \left(Mg\ ha^{-1}\right) = \frac{Wheat\ or\ Maize\ or\ Mungbean\ yield\ \left(Mg\ ha^{-1}\right) \times MSP\ of\ respective\ crop\ \left(INR\ Mg^{-1}\right)}{MSP\ of\ rice\ \left(INR\ Mg^{-1}\right)} \tag{1}$$

MSP is the minimum support price of the Government of India, and INR is the Indian rupee.

Economic analysis

The economic analysis/profitability was worked out for all crops and cropping systems under the respective scenario. The total cost of cultivation (COC) includes all the inputs and related costs (field, labour, and electricity) that were involved in crop production from sowing to harvest. Net returns (NR) were calculated as the difference between the gross returns (GR) and the COC (Eq. 2). The system NR were calculated by adding the NR of crops harvested within an individual calendar year.

$$Net\ Returns = Gross\ returns\ - Total\ cost\ of\ Cultivation \tag{2}$$

Water productivity and water footprint

The amount of irrigation water applied to each plot was measured using a water meter (Dasmesh Co., India) fitted to the irrigation system of both flood and SSD. The amount of irrigation water that was applied was quantified (in mm ha^{-1}) by using Eqs. (3) and (4). The irrigation water productivity (WP$_I$) was then calculated by using Eq. (5), as given below:

$$\text{Volume of irrigation water}\ \left(kl\ ha^{-1}\right) = \frac{(\text{Final water meter reading} - \text{Initial water meter reading})}{\text{Plot area in } m^2} \times 10000 \tag{3}$$

$$\text{Irrigation water}\ (ha - mm) = \frac{\text{Volume of irrigation water}\ \left(kl\ ha^{-1}\right)}{10} \tag{4}$$

$$WP_I\ \left(kg\ grain\ m^{-3}\right) = \frac{\text{Grain yield}\ \left(kg\ ha^{-1}\right)}{\text{Irrigation water}\ \left(m^3\ ha^{-1}\right)} \tag{5}$$

Where, 1 ha–mm irrigation depth = 10 kl = 10 m^3; 1m^3 = 1000 L.

$$\text{Water footprint}\ \left(L\ kg^{-1}\right) = \frac{\text{Irrigation water}\ \left(m^3\ ha^{-1}\right) \times 1000}{\text{System productivity}\ \left(Mg\ ha^{-1}\right) \times 1000} \tag{6}$$

Partial factor productivity of nitrogen

The partial factor productivity of nitrogen (PFP$_N$) assesses the nitrogen utilization efficiency of the production system. It serves as an approach for evaluating the total economic gain relative to the utilization of any resource applied to the system, here N. Partial factor productivity of fertilizer nitrogen was estimated using the formula provided in Eq. (7).

$$\text{Partial factor productivity of } N\ (PFP_N) = \frac{\text{Grain yield}\ \left(kg\ ha^{-1}\right)}{\text{Fertilizer } N \text{ applied in } kg\ ha^{-1}} \tag{7}$$

Energy calculations

All the inputs used in crop production under different scenarios, as well as the outputs (grain and straw/stover), were considered to calculate the energy use indices. The direct (operational or renewable) and indirect (non-operational or non-renewable) energy input sources were used as energy inputs [10]. Direct energy involved human labour, fuel, and machineries, while indirect energy sources included crop biomass (grains and residues), and chemicals, viz., fertilizers and pesticides. We also assessed the utilization patterns of different energy inputs and operations across various CSAPs. The energy equivalents of various inputs and outputs were used for the computation of energy inputs and outputs expressed in MJ ha^{-1} (Table S2) for every item and crop production technologies by considering their primary data as recommended by Mittal and Dhawan [11], and Singh et al. [12]. The energy use indices were computed following the procedures described by Devasenapathy et al. [10] and Mittal and Dhawan [11] as per Eqs. (8)–11.

$$\text{Net energy}\ \left(MJ\ ha^{-1}\right) = \text{Energy output}\ \left(MJ\ ha^{-1}\right) - \text{Energy input}\ \left(MJ\ ha^{-1}\right) \tag{8}$$

$$\text{Energy use efficiency} = \frac{\text{Energy output}\ \left(MJ\ ha^{-1}\right)}{\text{Energy input}\ \left(MJ\ ha^{-1}\right)} \tag{9}$$

$$\text{Energy productivity}\ \left(kg\ MJ^{-1}\right) = \frac{\text{Biomass yield}\ \left(kg\ ha^{-1}\right)}{\text{Energy input}\ \left(MJ\ ha^{-1}\right)} \tag{10}$$

$$\text{Specific Energy}\ \left(MJ\ Mg^{-1}\right) = \frac{\text{Energy Input}\ \left(MJ\ ha^{-1}\right)}{\text{System productivity}\ \left(Mg\ ha^{-1}\right)} \tag{11}$$

Global warming potential (GWP) analysis

The Mitigation Options Tool created by Climate Change, Agriculture and Food Security (CCAFS-MOT) in collaboration with the University of Aberdeen was used to quantify GHG emissions [13]. Taking into account both land-use efficiency and efficiency per unit of product, this tool evaluates production systems from the standpoint of GHG emissions. Ammonia (NH_3) emissions were computed using the FAO/IFA model (2001), and nitrous oxide (N_2O) and nitric oxide (NO) emissions, including fertilizer-induced emissions, were estimated using a multivariate empirical model [14]. IPCC Tier 1 N_2O emission factors were used to calculate emissions from crop residues that were returned to fields.

Ecoinvent database [15] was used to derive fertilizer production and transportation emissions. The IPCC technique described by Ogle et al. [16] and Smith et al. [17] was used to assess changes in soil carbon (C) brought about by tillage and residue management strategies. Similarly, IPCC recommendations were used to estimate CO_2 emissions from urea application [18]. Total GHG emissions and total GWP were computed by converting all GHGs into CO_2 equivalents (CO_2 eq.) using 100-year global warming potentials as 34 for CH_4 and 298 for N_2O using IPCC (2013) (Eq. (12)). We did not consider methane emission due to the water regime in the scenarios where DSR was grown, as aerobic conditions were maintained in DSR and no flooding noticed during the rice growing period in all the years. The net global warming potential (GWPn) was then obtained by subtracting soil organic carbon (SOC) sequestration from the GWP, according to Eq. (13).

$$GWP\ \left(kg\ CO_2\ eq.\ ha^{-1}\right) = CO_2\left(kg\ ha^{-1}\right) + N_2O\left(kg\ ha^{-1}\right) \times 298 + CH_4\ \left(kg\ ha^{-1}\right) \times 34 \tag{12}$$

$$GWPn\ \left(kg\ CO_2\ eq.\ ha^{-1}\right) = GWP - \text{SOC sequesteation from tillage and residue retention}\ \left(kg\ CO_2\ eq.\ ha^{-1}\right) \tag{13}$$

Carbon footprint

The caron footprint, a reference boundary at the field level emissions, was calculated for different CSAPs scenarios using Eq. (14) given by Jiang et al. [19].

$$\text{Carbon footprint}\ \left(kg\ CO_2\ eq.\ ha^{-1}\right) = \frac{\text{GHG Emission}\ \left(kg\ CO_2\ eq.\ ha^{-1}\right) - \text{Annual change in SOC Stock}\ \left(kg\ CO_2\ eq\ ha^{-1}yr^{-1}\right)}{\text{System productivity}\ \left(Mg\ ha^{-1}\right)} \tag{14}$$

Table 2
Effect of climate-smart agriculture practices on grain yield, cost of cultivation and net returns (pooled from 2016–17 to 2021–22).

Scenarios	Grain yield (t ha^{-1})				Cost of cultivation (INR ha^{-1})				Net returns (INR ha^{-1})			
	Rice equivalent (Kharif crops)	Wheat	Mungbean	System	Rice/ Maize	Wheat	Mungbean	System	Rice/ Maize	Wheat	Mungbean	System
Sc 1	6.75 ± 0.20^{CB}	5.19 ± 0.17^{C}	-NA^{c}-	12.34 ± 0.67^{D}	$46{,}947 \pm 639^{A}$	$45{,}323 \pm 552^{A}$	–	$92{,}270 \pm 565^{C}$	$67{,}809 \pm 1307^{B}$	$66{,}339 \pm 1277^{C}$	–	$134{,}148 \pm 2444^{C}$
Sc 2	6.98 ± 0.20^{BC}	5.59 ± 0.06^{BC}	0.55 ± 0.01^{A}	14.95 ± 0.52^{B}	$44{,}897 \pm 136^{BC}$	$36{,}915 \pm 552^{C}$	$14{,}096 \pm 696^{A}$	$95{,}908 \pm 141^{B}$	$73{,}999 \pm 1614^{B}$	$79{,}498 \pm 1449^{B}$	$19{,}621 \pm 341^{A}$	$173{,}118 \pm 2569^{B}$
Sc 3	6.18 ± 0.12^{C}	6.03 ± 0.03^{AB}	0.16 ± 0.01^{D}	13.20 ± 0.17^{CD}	$40{,}635 \pm 542^{D}$	$36{,}696 \pm 542^{C}$	9561 ± 526^{B}	$86{,}892 \pm 309^{D}$	$65{,}123 \pm 750^{B}$	$88{,}415 \pm 729^{AB}$	2670 ± 147^{CD}	$156{,}208 \pm 2507^{B}$
Sc 4	7.74 ± 0.04^{AB} (8.10)*	6.09 ± 0.09^{AB}	0.19 ± 0.01^{D}	14.93 ± 0.22^{B}	$37{,}932 \pm 432^{E}$	$36{,}593 \pm 168^{C}$	9552 ± 140^{B}	$84{,}077 \pm 459^{E}$	$102{,}055 \pm 2093^{A}$	$89{,}618 \pm 830^{A}$	4629 ± 141^{C}	$196{,}302 \pm 1913^{A}$
Sc 5	6.48 ± 0.11^{C}	6.24 ± 0.03^{A}	0.32 ± 0.01^{C}	14.35 ± 0.21^{BC}	$43{,}863 \pm 120^{C}$	$42{,}860 \pm 340^{A}$	9268 ± 525^{C}	$95{,}991 \pm 423^{B}$	$66{,}790 \pm 1056$	$86{,}008 \pm 875^{AB}$	$10{,}793 \pm 385^{B}$	$163{,}591 \pm 2021^{B}$
Sc 6	8.25 ± 0.16^{A} (8.63)*	6.34 ± 0.04^{A}	0.45 ± 0.01^{B}	16.73 ± 0.40^{A}	$45{,}347 \pm 446^{B}$	$42{,}733 \pm 616^{B}$	9283 ± 436^{C}	$97{,}363 \pm 129^{A}$	$102{,}807 \pm 1571^{A}$	$88{,}553 \pm 867^{A}$	$19{,}752 \pm 426^{A}$	$210{,}880 \pm 2287^{A}$
P values												
Sc	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.02	<0.001	<0.001	<0.001	<0.001	<0.001
Year	0.03	0.002	<0.001	0.0001	<0.001	0.01	0.001	0.002	<0.001	<0.001	<0.001	0.03
Sc×Year	0.06	0.004	0.04	0.0001	0.09	0.08	0.12	0.02	0.01	0.03	0.1	0.01

[a] Refer Table 1 for scenario description.
[b] Means followed by a similar uppercase letter(s) within a column are not significantly different at 0.05 level of probability using Tukey's HSD test.
*Figures in parenthesis are the actual yield of maize.

Statistical analysis

The data obtained in the study were subjected to one-way analysis of variance (ANOVA), based on a randomized block design (RBD) framework, for each year separately, as outlined by Gomez and Gomez [20]. The General Linear Model (GLM) procedure was employed for statistical analysis using R software [21]. To assess the overall effect of CSAPs scenarios across years, pooled two-way ANOVA was performed considering CSAPs scenarios and year as factors. Prior to the pooled analysis, the homogeneity of error variances was tested using Bartlett's test. When significant differences were observed ($p < 0.05$), treatment means were compared and ranked using Tukey's Honest Significant Difference (HSD) test at a 5 % significance level. For visualization, bar plots were created using the ggplot2 package of R. The bars represent the mean values, with standard errors (SE) depicted as error bars. Tukey's HSD group letters were superimposed above the bars to indicate statistically homogeneous groups. Individual data points were visualized using jitter plots to show variability within each scenario. All data preprocessing and visualization were performed using R (version 2023), with additional packages including janitor, viridis, and extrafont used to enhance data cleaning and figure aesthetics.

Results

Yields and system productivity

Significant variability in grain yield was observed across different scenarios. A comparison of rice equivalent yield (REY) of Kharif season crops showed that the CA-based maize-wheat-mungbean system with SSD (*Sc* 6) exhibited the highest average rice equivalent yield (8.25 t ha^{-1}), followed by *Sc* 4 (ZTMWM; 7.74 t ha^{-1}) (Table 2). Partial CA-based *Sc* 2 (CTR-ZTWM) also demonstrated a high yield (6.98 t ha^{-1}). In contrast, *Sc* 3 (ZTRWM) recorded the lowest rice grain yield (6.18 t ha^{-1}). These variations underscore the substantial influence of different CSAPs scenarios on grain production, with the maize crop in *Sc* 6 presenting the most favourable conditions for higher REY yields.

Adoption of CA, either partially or fully, in Kharif rice/maize with summer mungbean and the integration of SSD positively influenced wheat yield. Wheat yield was highest under *Sc* 6 (ZTMWM-SSD), reaching 6.34 t ha^{-1}, indicating statistically superior performance compared to other scenarios. *Sc* 5 (ZTRWM-SSD) also recorded a high wheat yield of 6.24 t ha^{-1}. In contrast, the lowest wheat yield was observed in *Sc* 1 (5.19 t ha^{-1}). For mungbean, grain yield was significantly higher under *Sc* 2 (CTR-ZTWM) compared to the other scenarios.

Rice equivalent yield of the system (REYS), representing the overall productivity across the different crops, varied significantly among the scenarios. Scenario 6 (ZTMWM-SSD) achieved the highest system yield (16.73 t ha^{-1}) demonstrating an approximately 35 % yield advantage over *Sc* 1. *Sc* 2 emerged as the second-highest productive system (14.95 t ha^{-1}) followed closely by *Sc* 4 (14.93 t ha^{-1}). The fully CA-based scenario, *Sc* 3 (ZTRWM), also outperformed *Sc* 1, producing a 7 % higher REYS, which was further enhanced when SSD was integrated in *Sc* 5, achieving 14.35 t ha^{-1}, comparable to *Sc* 2. In contrast, *Sc* 1 exhibited the lowest system yield of 12.34 t ha^{-1}, which was significantly lower than the other scenarios (Table 2).

Profitability

The profitability analysis of CSAPs scenarios (*Sc* 3, *Sc* 5, and *Sc* 6), in comparison to the conventional system (*Sc* 1) and partial CA system (*Sc* 2), reveals a clear economic advantage in terms of both cost of cultivation and net returns (Table 2). *Sc* 6 (ZTMWM-SSD) achieved the highest system net returns of INR 210,880 ha^{-1}, despite incurring a slightly higher cost of cultivation (INR 97,363 ha^{-1}) than *Sc* 1 (INR 91,838 ha^{-1}), resulting in a 57 % increase in net returns over *Sc* 1 (INR 134,148 ha^{-1}). *Sc* 4 followed closely, with net returns of INR 196,302 ha^{-1} and the lowest cost of cultivation (INR 84,077 ha^{-1}) among the CSAPs. *Sc* 5, with a cost of cultivation of INR 95,991 ha^{-1}, provided net returns of INR 163,591 ha^{-1}, representing a 22 % improvement over *Sc* 1. Although *Sc* 3 exhibited the lowest profitability among the CA-based scenarios, it still outperformed the conventional farmers' practice (*Sc* 1), yielding 16 % higher net returns (INR 156,208 ha^{-1}) with a reduced cost of cultivation (INR 86,892 ha^{-1}) owing to lower input use. Overall, CA-based scenarios significantly outperformed the conventional system (*Sc* 1) by simultaneously reducing cultivation costs and enhancing net returns (Table 2).

Table 3

Effect of climate-smart agriculture practices on irrigation water use, water productivity and water footprint (pooled from 2016–17 to 2021–22).

Scenarios	Irrigation water use (mm ha^{-1})				WP$_I$ (kg grain m^{-3})				Water footprint (L kg^{-1})
	Rice/Maize	Wheat	Mungbean	System	Rice/Maize	Wheat	Mungbean	System	System
Sc 1	1671±33.2^{AB}	346±6.7^{A}	–	2017±40.8^{A}	0.41±0.01^{C}	1.6 ± 0.054^{B}	–	0.62±0.02^{D}	1642±35.2^{A}
Sc 2	1556±29.4^{A}	337±8.0^{A}	142±3.4^{A}	2035±45.3^{A}	0.46±0.03^{C}	1.74±0.06^{B}	0.41±0.01^{C}	0.74±0.03^{D}	1363±28.1^{B}
Sc 3	1416±27.5^{B}	337±9.2^{A}	137±3.2^{AB}	1889±41.6^{A}	0.46±0.02^{C}	1.83±.07^{B}	0.12±0.01^{D}	0.71±0.02^{D}	1431±32.5^{B}
Sc 4	111±2.8^{D}	327±7.9^{A}	134±3.3^{B}	572±13.4^{C}	8.47±0.26^{B}	1.92±0.08^{B}	0.15±0.01^{D}	2.71±0.09^{B}	383±12.4^{D}
Sc 5	816±17.0^{C}	192±5.0^{B}	59±2.0^{C}	1066±25.2^{B}	0.85±0.03^{C}	3.36±0.11^{A}	0.58±0.02^{B}	1.40±0.05^{C}	743±17.9^{C}
Sc 6	71±1.6^{D}	183±4.8^{B}	62±1.7^{C}	316±8.2^{D}	16.29±0.52^{A}	3.64±0.12^{A}	0.86±0.03^{A}	5.64±0.18^{A}	189±6.7^{E}
P values									
Sc	<0.001	<0.001	0.01	<0.001	<0.001	<0.001	0.03	<0.001	<0.001
Year	0.01	0.16	0.10	0.01	0.013	<0.001	0.15	0.02	0.01
Sc×Year	0.001	0.06	0.12	0.11	0.10	0.07	0.08	0.22	0.06

[a] Refer Table 1 for scenario description.

[b] Means followed by a similar uppercase letter(s) within a column are not significantly different at 0.05 level of probability using Tukey's HSD test. WP$_I$: irrigation water productivity.

Water productivity and water footprint

The average irrigation water applied in the CT-based rice crop (*Sc* 1; farmers' practice) was significantly higher by approximately 18 % and 51 % compared to CA-based rice (*Sc* 3/*Sc* 5) and maize (*Sc* 4/*Sc* 6), respectively (Table 3). The use of SSD in CA-based rice and maize systems (*Sc* 5 and *Sc* 6) further reduced irrigation water application compared to CA-based flood-irrigated rice (*Sc* 3). Over six years, the lowest irrigation water use (71 mm ha^{-1}) was recorded in *Sc* 6 (ZTMWM-SSD), while *Sc* 1 had the highest water use (1671 mm ha^{-1}). For wheat, irrigation water use ranged from 183 to 346 mm ha^{-1} across scenarios and remained relatively consistent. Mungbean integration increased irrigation water consumption by 19 %, irrespective of tillage and residue management compared to *Sc* 1 (Table 3).

Based on the six-year average, the system irrigation water input decreased in the order *Sc* 2 (2035 mm ha^{-1}) > *Sc* 1 (2017 mm ha^{-1}) > *Sc* 3 (1889 mm ha^{-1}) > *Sc* 5 (1066 mm ha^{-1}) > *Sc* 4 (572 mm ha^{-1}) > *Sc* 6 (316 mm ha^{-1}) (Table 3). Higher grain yield and reduced water usage resulted in significantly higher irrigation water productivity (WP$_I$) under CSAPs based management systems across all crops and cropping systems compared to the CT-based scenario (*Sc* 1). Specifically, the water productivity of wheat under the CA-based system increased by 122 % compared to CT (1.64 kg grain m^{-3} water). The water productivity under *Sc* 6 (ZTMWM-SSD), *Sc* 5 (ZTRWM-SSD), and *Sc* 4 (ZTMWM) were 20, 11 and 16 % higher, respectively, compared to *Sc* 1 (CT-RW) (Table 3).

System-level water footprint also varied substantially across scenarios. *Sc* 1 exhibited the highest water footprint (1642 L kg^{-1} system yield), reflecting the most water-intensive practice (Table 3). Adoption of partial CA (*Sc* 2) and full CA (*Sc* 3) in rice-based systems with flood irrigation reduced the water footprint by 20.5 % and 14.7 %, respectively, relative to *Sc* 1. The maize-based *Sc* 4 system was even more water-efficient (383 L kg^{-1}), exhibiting a 76.7 % lower water footprint compared to *Sc* 3. Integration of SSD in rice- and maize-based systems (*Sc* 5 and *Sc* 6) further improved water use efficiency, reducing water footprints to 743 L kg^{-1} and 189 L kg^{-1}, respectively, 48.1 and 50.7 % lower than their corresponding flood-irrigated systems (*Sc* 3 and *Sc* 4), and 55.6 and 88.5 % lower than the farmers' practice (*Sc* 1). These results clearly demonstrate that SSD integration combined with CA-based management offers the most water-efficient cropping systems (Table 3).

Table 4

Effect of climate-smart agriculture practices on partial factor productivity of nitrogen (pooled from 2016–17 to 2021–22).

Scenarios	PFP$_N$ (kg grain kg^{-1} N applied)		
	Rice/Maize	Wheat	System
Sc 1	38.54±0.35^{C}	34.60±0.26^{C}	37.92±0.23^{E}
Sc 2	46.52±0.22^{B}	37.29±0.21^{BC}	49.83±0.18^{C}
Sc 3	38.64±0.21^{C}	40.21±0.06^{B}	42.59±0.12^{D}
Sc 4	44.21±0.20^{BC}	40.63±0.17^{B}	45.93±0.26^{CD}
Sc 5	49.82±0.32^{B}	52.02±0.12^{A}	57.41±0.17^{B}
Sc 6	58.93±0.23^{A}	52.87±0.18^{A}	64.36±0.35^{A}
P values			
Sc	<0.001	<0.001	<0.001
Year	0.02	0.01	<0.001
Sc×Year	0.063	0.10	0.08

[a] Refer Table 1 for scenario description.

[b] Means followed by a similar uppercase letter(s) within a column are not significantly different at 0.05 level of probability using Tukey's HSD test.

Partial factor productivity of nitrogen

The results of partial factor productivity of nitrogen (PFP$_N$) for rice/maize, wheat, and the overall system across different scenarios (*Sc* 1 to *Sc* 6) demonstrated significant variation when compared to the baseline scenario (*Sc* 1) (Table 4). In the case of rice, the PFP$_N$ in *Sc* 1 was 38.54 kg grain kg^{-1} N, which rose to 46.52 kg grain kg^{-1} N applied under *Sc* 2, showing a 20.7 % improvement over *Sc* 1. Switching to direct-seeded zero-till rice under *Sc* 3 did not show any gain in PFP$_N$.

Energy input-output relationship

The analysis of energy input and output across various scenarios highlighted significant trends, particularly in the context of CSAPs (Table 5). The baseline scenario, *Sc* 1, demonstrated the highest energy input of 68,896 MJ ha^{-1}, yielding an energy output of 372,783 MJ ha^{-1} of the system. The CSAPs scenarios (*Sc* 3 to *Sc* 6) further illustrated the benefits of resource optimization. The scenario *Sc* 3 reduced the system energy input to 60,851 MJ ha^{-1} while maintaining a comparable output of 373,753 MJ ha^{-1}, suggesting that CSAPs can enhance energy efficiency even with reduced inputs. *Sc* 4 showcased a more pronounced effect, with energy inputs dropping to 36,118 MJ ha^{-1} and energy output rising to 451,641 MJ ha^{-1}. This represents a remarkable 21.1 % increase in energy output over *Sc* 1, highlighting the potential of CSAPs to significantly enhance productivity while minimizing energy use. Similarly, *Sc* 5 reflects a balanced approach with an energy input of 43,572 MJ ha^{-1} and an output of 387,459 MJ ha^{-1}, indicating positive results even with moderate input levels. *Sc* 6 stands out as the most efficient, with an energy input of just 30,360 MJ ha^{-1} and the highest output of 471,633 MJ ha^{-1}, underscoring the capacity of advanced CSAPs to maximize productivity while minimizing resource use (Table 5).

Energy use efficiency and energy productivity

Energy use efficiency (EUE) values for different cropping scenarios (*Sc* 1 to *Sc* 6) revealed significant variations across rice, wheat,

Table 5

Energy input-output relationship of different climate-smart agriculture practices (pooled from 2016–17 to 2021–22).

Scenarios	Energy input (MJ ha^{-1})				Energy output (MJ ha^{-1})			
	Rice	Wheat	Mungbean	System	Rice	Wheat	Mungbean	System
Sc 1	45,898±1123^{A}	22,978±93^{A}	–	68,876±1213^{A}	215,447±5126^{BC}	157,337±5156^{C}	–	372,783±10280^{B}
Sc 2	40,779±458^{B}	19,394±289^{B}	3704±10.49^{A}	63,877±700^{B}	226,681±7286^{B}	166,104±2301^{BC}	8020±161^{A}	400,806±9605^{B}
Sc 3	37,973±230^{B}	19,370±109^{B}	3507±6.67^{B}	60,851±257^{B}	195,458±3020^{C}	176,237±941^{AB}	2058±308^{D}	373,753±2177^{B}
Sc 4	13,528±305^{D}	19,121±178^{B}	3468±10.98^{C}	36,118±425^{D}	270,933±1257^{A}	177,973±1773^{AB}	2736±48^{D}	451,641±2920^{A}
Sc 5	25010^{c}±538^{C}	15,732±20^{C}	2830±76.93^{D}	43,572±617^{C}	202,136±943^{C}	180,578±1291^{AB}	4745±127^{C}	387,459±1971^{B}
Sc 6	12,046±252^{D}	15,545±38^{C}	2770±65.09^{D}	30,360±337^{E}	281,891±2792^{A}	183,641±925^{A}	6101±561^{B}	471,633±3173^{A}
P values								
Sc	0.01	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Year	0.03	0.04	0.01	0.04	0.01	0.07	0.04	0.01
Sc×Year	0.21	0.01	<0.001	<0.001	0.06	0.01	0.01	0.10

[a] Refer Table 1 for scenario description.

[b] Means followed by a similar uppercase letter(s) within a column are not significantly different at 0.05 level of probability using Tukey's HSD test.

Table 6

Effect of climate-smart agriculture practices on energy use efficiency and energy productivity (pooled of 2016–17 to 2021–22).

Scenarios	Energy use efficiency (EUE)				Energy productivity (EP) (kg MJ^{-1})			
	Rice	Wheat	Mungbean	System	Rice	Wheat	Mungbean	System
Sc 1	4.71±0.07^{D}	6.90±0.22^{D}	–	5.44±0.10^{E}	0.15±0.00^{D}	0.23±0.01^{C}	–	0.18±0.00^{E}
Sc 2	5.58±0.13^{D}	8.59±0.02^{C}	2.19±0.05^{A}	6.29±0.10^{D}	0.17±0.01^{D}	0.29±0.01^{B}	0.15±0.00^{B}	0.23±0.00^{D}
Sc 3	5.22±0.06^{D}	9.11±0.07^{BC}	0.56±0.09^{D}	6.17±0.03^{DE}	0.16±0.01^{D}	0.31±0.01^{B}	0.04±0.01^{D}	0.22±0.00^{D}
Sc 4	20.61±0.67^{B}	9.32±0.09^{B}	0.79±0.03^{C}	12.64±0.21^{B}	0.61±0.02^{B}	0.32±0.01^{B}	0.05±0.00^{D}	0.42±0.01^{B}
Sc 5	8.20±0.20^{C}	11.49±0.09^{A}	1.65±0.01^{B}	8.94±0.15^{C}	0.26±0.01^{C}	0.38±0.02^{A}	0.11±0.00^{C}	0.33±0.01^{C}
Sc 6	23.75±0.45^{A}	11.84±0.08^{A}	2.20±0.21^{A}	15.69±0.19^{A}	0.72±0.01^{A}	0.39±0.02^{A}	0.17±0.00^{A}	0.55±0.01^{A}
P values								
Sc	<0.001	0.02	0.01	<0.001	<0.001	<0.001	<0.001	<0.001
Year	0.01	0.04	0.01	0.02	0.01	0.02	0.04	0.001
Sc×Year	0.14	0.21	0.08	0.06	0.06	0.09	0.04	0.09

[b] Means followed by a similar uppercase letter(s) within a column are not significantly different at 0.05 level of probability using Tukey's HSD test.

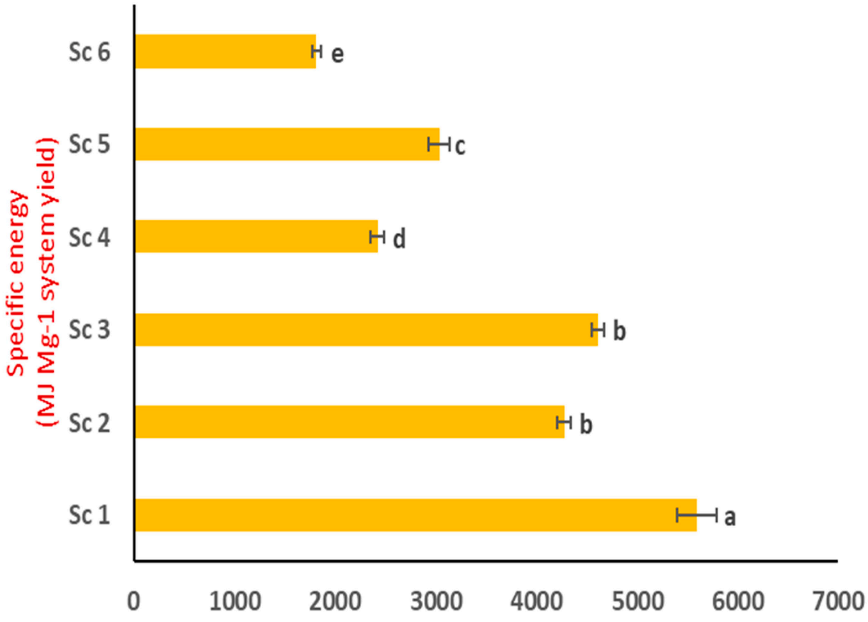

Fig. 1. Effect of climate-smart agriculture practices on energy footprint (specific energy). Bars followed by a similar letter(s) are not significantly different at 0.05 level of probability using Tukey's HSD test.

mungbean, and the overall system. These results highlighted *Sc* 6 as the most efficient scenario in converting energy inputs to outputs across all crops and the overall system, while conventional rice-wheat (*Sc* 1) was the least efficient (Table 6). In the baseline scenario (Sc1), EUE values were low with rice (4.71), wheat (6.90), and the system (5.44), indicating limited efficiency in energy conversion (Table 6). The CSAPs scenarios (*Sc* 3 to *Sc* 6) showed significant improvements, particularly in *Sc* 4 and *Sc* 6. In *Sc* 3, EUE values for rice, wheat, and mungbean were 5.22, 9.11, and 0.56, respectively, with a system efficiency of 6.17. Scenario 4 was significantly better with EUE of rice, wheat, mungbean and system reaching 20.61, 9.32, 0.79, and 12.64, respectively. The ZTMWM-SSD (*Sc* 6) consistently achieved the highest EUE with values of

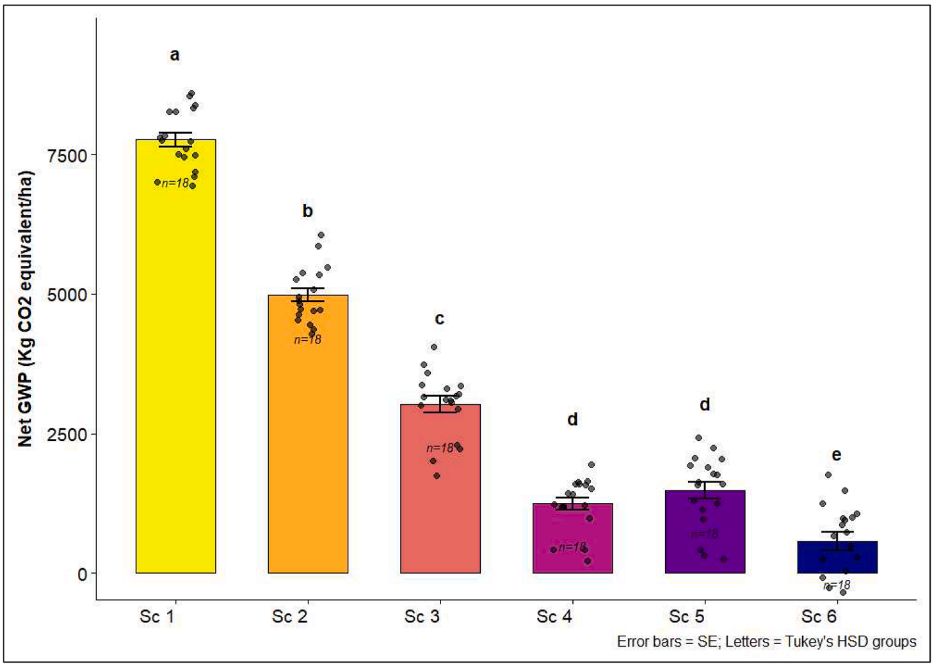

Fig. 2. Net global warming potential (GWPn) across the different climate-smart agriculture practices (pooled from 2016–17 to 2021–22). Bars followed by a similar letter(s) are not significantly different at 0.05 level of probability using Tukey's HSD test.

23.75 for rice, 11.84 for wheat, and 2.20 for mungbean, resulting in an overall system EUE of 15.69. In contrast, *Sc* 1 exhibited the lowest EUE (4.71 for rice, 6.90 for wheat) leading to an overall system EUE of 5.44 (Table 6).

Energy Productivity (EP) across different scenarios highlighted significant differences in the performance of rice, wheat, mungbean, and the overall system. In the baseline scenario (*Sc* 1), EP values were relatively low, with rice (0.15 kg MJ^{-1}), wheat (0.23 kg MJ^{-1}), and the overall system at (0.18 kg MJ^{-1}). The CSAPs scenarios (*Sc* 3 to *Sc* 6) demonstrated further improvements in EP, particularly in *Sc* 4 and *Sc* 6. In *Sc* 3, rice, wheat, and mungbean exhibit EP values of 0.16, 0.31, and 0.04 kg MJ^{-1}, respectively, while the overall system stands at 0.22 kg MJ^{-1}, suggesting an increase compared to *Sc* 1. *Sc* 4 showed a notable leap in EP for rice, achieving 0.61 kg MJ^{-1}, while wheat and mungbean report values of 0.32 and 0.05 kg MJ^{-1}, respectively. Finally, *Sc* 6 achieved the highest EP values among all scenarios, with rice (0.72 kg MJ^{-1}), wheat (0.39 kg MJ^{-1}), mungbean (0.17 kg MJ^{-1}), and the overall system efficiency (0.55 kg MJ^{-1}). This scenario exemplified the effectiveness of advanced CSAPs practices in optimizing energy productivity (Table 6).

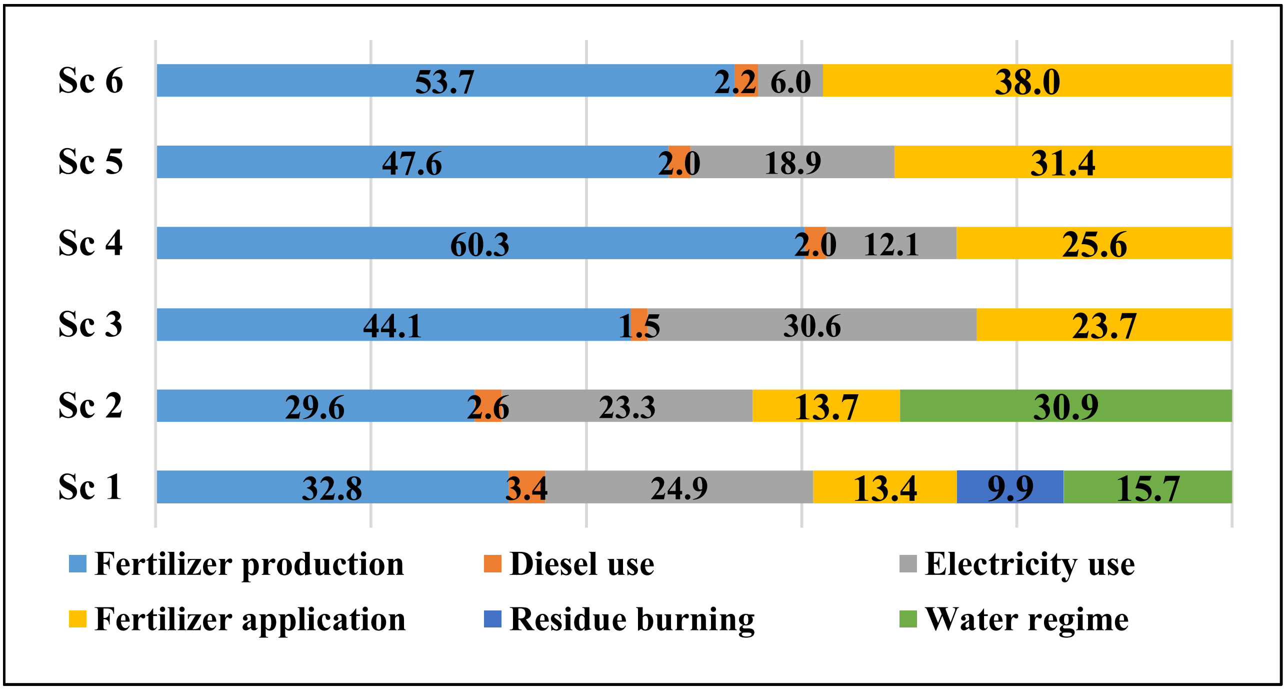

Fig. 3. Contribution of different factors towards total GWP in different scenarios.

Table 7

System average GHG emissions (kg CO_2 eq. ha^{-1}) and SOC sequestration from different sources/land use changes under different scenarios (Average of 2016–17 to 2021–22).

Emission forms/ Scenarios	CO_2 (kg CO_2 eq. ha^{-1})			N_2O (kg CO_2 eq. ha^{-1})		Methane (kg CO_2 eq. ha^{-1})		SOC sequestration (kg CO_2 eq. ha^{-1})		
	Fertilizer production	Diesel use	Electricity use	Fertilizer application in soil	Residue burning	Residue burning	Water regime	Residue retention	Conservation tillage	Total
Sc 1	2548.1	260.8	1934.8	1038.3	151.43	617.1	1215.5	–	–	–
Sc 2	2371.9	204.9	1867.1	1095.0	–	–	2473.6	2356	681	3037
Sc 3	2681.4	93.6	1857.4	1442.0	–	–	–	2158	891	3049
Sc 4	2801.2	93.6	562.4	1189.9	–	–	–	2262	1139	3402
Sc 5	2194.8	93.4	872.8	1446.3	–	–	–	2232	896	3129
Sc 6	2273.4	93.4	255.1	1607.8	–	–	–	2458	1201	3659

The Specific Energy (SE) values across different cropping scenarios reveal substantial differences in energy efficiency (Fig. 1). *Sc* 1 had the highest SE (5598 MJ Mg^{-1}), indicating the highest energy requirement per unit of output, while *Sc* 6 demonstrated the lowest SE (1815 MJ Mg^{-1}), reflecting the most efficient energy use. *Sc* 2 and *Sc* 3 had SE values of 4275 MJ Mg^{-1} and 4610 MJ Mg^{-1}, respectively, showing moderate efficiency compared to *Sc* 6. Overall, *Sc* 6 stood out as the most energy-efficient scenario, while *Sc* 1 is the least efficient.

GHG emission

Net global warming potential

The results of 6 years of pooled data revealed substantial differences in the system net global warming potential (GWPn) among the various scenarios evaluated (Fig. 2). *Sc* 1 recorded the highest system GWP at 7766 kg CO_2 eq. ha^{-1}, indicating the greatest potential contribution to global warming among all scenarios. In contrast, *Sc* 6 showed the lowest system GWPn, with a value of 571 kg CO_2 eq. ha^{-1}, reflecting a significantly reduced carbon footprint. Other scenarios, such as *Sc* 2, *Sc* 3, *Sc* 4 and *Sc* 5, displayed intermediate GWPn values of 4975, 3025, 1245, and 1479 kg CO_2 eq. ha^{-1}, respectively showing about 36, 61, 84 and 81 % lower GWPn compared to that of *Sc* 1.

Contribution of different factors to global warming potential

The contribution of different factors to total GWP across various scenarios revealed significant insights, particularly between rice-based (*Sc* 1, *Sc* 2, *Sc* 3, *Sc* 5) and maize-based systems (*Sc* 4, *Sc* 6) as well as between flood and SSD irrigation (Fig. 3 and Table 7). Fertilizer production emerged as the dominant contributor to total GWP emissions across all scenarios, with *Sc* 4 recording the highest at 60.3 % (2801.2 kg CO_2 eq. ha^{-1}), followed closely by *Sc* 6 (ZTMWM-SSD) at 53.7 % (2273.4 kg CO_2 eq. ha^{-1}). Rice-based systems, *Sc* 1 and *Sc* 2, showed relatively lower contributions from fertilizer production, at 32.8 % and 29.6 %, respectively. However, *Sc* 1 showed an additional 9.9 % (768.5 kg CO_2 eq. ha^{-1}) contributions from residue burning while *Sc* 2 had the highest contribution of 30.9 % (2473.6 kg CO_2 eq. ha^{-1}) due to CH_4

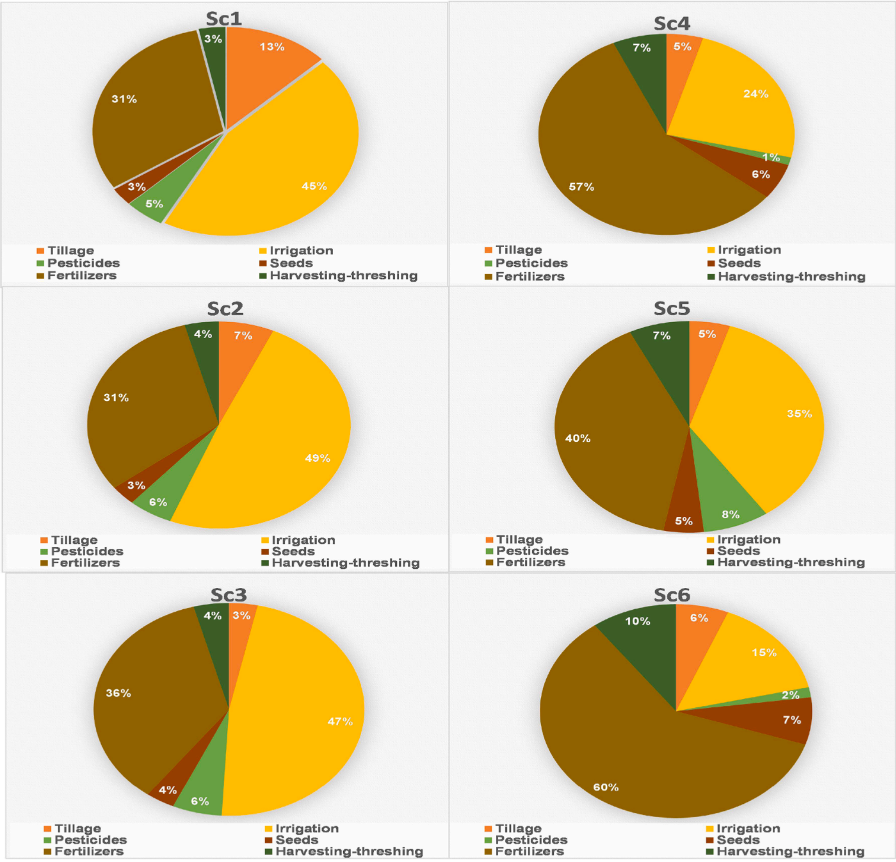

Fig. 4. Contribution of different factors in energy input under climate smart agriculture practices scenarios.

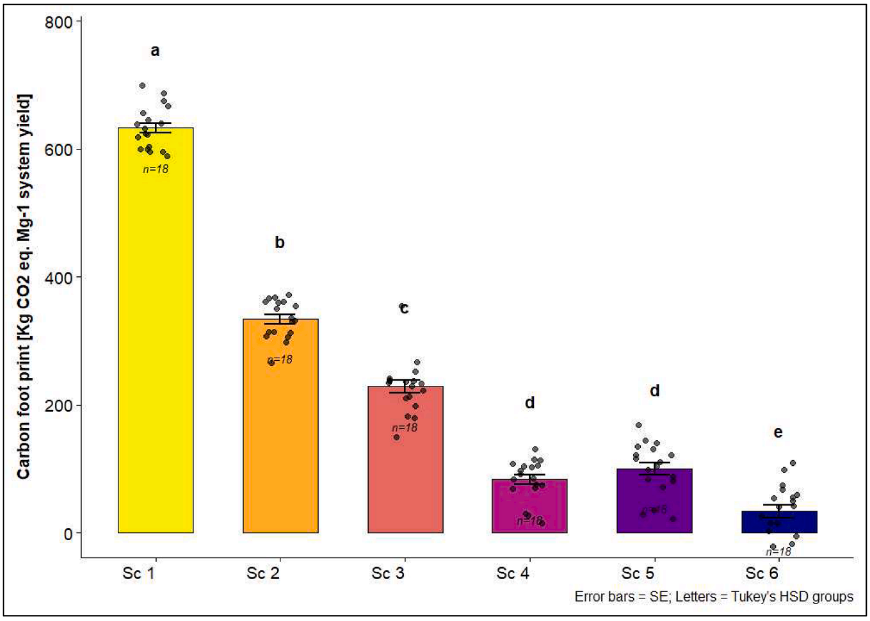

Fig. 5. Carbon footprint of different climate-smart agriculture practices (pooled from 2016–17 to 2021–22). Bars followed by a similar letter(s) are not significantly different at 0.05 level of probability using Tukey's HSD test.

emission. Fertilizer application also played a significant role in the GHG emission in the form of N_2O emission, with contributions ranging from 24.9 % (1038 kg CO_2 eq. ha^{-1}) in *Sc* 1 to 12.1 % (1189.9 kg CO_2 eq. ha⁻1) in *Sc* 4, indicating a marked reduction in maize-based systems compared to rice-based systems (Fig. 3 and Table 7). Diesel use, associated with field operations, is minimal across scenarios, contributing between 1.3 % and 3.4 %, with the lowest values seen in CA-based scenarios (*Sc* 3, *Sc* 5, *Sc* 6). The introduction of SSD in *Sc* 5 and *Sc* 6 significantly reduced GHG emissions due to electricity use, dropping to 14.9 % and 6.0 %, respectively. Overall, the results highlight that maize-based systems (*Sc* 4 and *Sc* 6) exhibit lower contributions from diesel, electricity, and residue burning, coupled with improved water-use efficiency compared to rice-based systems. Fig. 4.

Soil organic carbon sequestration

Residue retention and switching minimal or no-till substantially impacting the GWP by sequestering SOC, thus reducing the GWPn in all the CSAPs scenarios in contrast to farmers' practice where residue burning and intensive tillage contributed to emissions (Table 7). The CSAPs scenarios (*Sc* 2-*Sc* 6) sequestered 2158–2458 kg CO_2 eq. ha^{-1} $year^{-1}$ due residue retention. Similarly switching to minimal tillage (*Sc* 2) or ZT (*Sc* 3-*Sc* 6) resulted in sequestration of 891–1201 kg CO_2 eq. ha^{-1} $year^{-1}$. The total SOC sequestration was higher in maize-based scenarios, *Sc* 5 and *Sc* 6 (3402–3659 kg CO_2 eq. ha^{-1} $year^{-1}$) compared the rice-based scenarios (3037–3129 kg CO_2 eq. ha^{-1} $year^{-1}$).

Carbon footprint

The results demonstrate significant changes in the carbon footprint or yield-scaled GHG emission across the different CSAPs scenarios (Fig. 5). Conventional farmers' practice (*Sc* 1) had the highest CFP value of 633 kg CO_2 eq. Mg^{-1} system yield. Conversely, *Sc* 6 (ZTMWM-SSD) exhibited the lowest CFP (34 kg CO_2 eq. Mg^{-1} system yield), indicating a substantial reduction (95 %) in the environmental impact of this system. CSAPs scenarios *Sc* 2, *Sc* 3, *Sc* 4, and *Sc* 5 also showed intermediate values, with CFP of 334, 229, 83 and 100 kg CO_2 eq. Mg^{-1} system yield, respectively showing 47, 64, 87 and 84 % reduction in CFP compared to that of *Sc* 1.

Discussion

Climate-smart agricultural practices (CSAPs) are advocated as an essential component of agricultural production systems to address the threats of a changing climate while sustaining the resource base in the Indo-Gangetic Plains of Southeast Asia. Conservation agriculture (CA), owing to its positive influence on adaptability to adverse climatic conditions through greater resilience, mitigation of climate change effects via enhanced carbon sequestration in soils, reduction of greenhouse gas (GHG) emissions, and sustainable improvements in productivity and profitability, thus qualifies as a CSAP. The integration of micro-irrigation, particularly subsurface drip irrigation (SSD), further helps to overcome operational limitations of surface drip systems and addresses the growing water crisis. The findings of this study highlight the significant benefits of CSAPs, which encompass CA principles alongside precise water and nitrogen application, in enhancing productivity, profitability, and reducing environmental footprints within the rice/maize-wheat-mungbean cropping system in the northwestern Indo-Gangetic Plains (IGP) of South Asia. While much of the existing research has focused on the productivity gains of these practices, our study also emphasizes the often-overlooked impacts on energy utilization, water footprint, global warming potential, and soil organic carbon (SOC) sequestration

Crop productivity and profitability

The results from this study reveal significant variability in crop productivity, profitability, and system performance across different strategic CSAPs scenarios. The rice yields improved marginally when partial CA (CT-R-ZTWM) was adopted (*Sc* 2), indicating the benefits of residue retention and inclusion of a spring legume crop in the system. However, switching to ZT-DSR in *Sc* 3 (ZT-RWM) resulted in a yield penalty of 8.4 % in rice grain yield. The yield loss is a major concern in the adoption of ZT-DSR in the study region. However, the yield reduction in our study is smaller than the 12–16 % reported earlier (Singh et al. 2020; [22]) in similar agroecological situations. The weed infestation due to poor ground coverage initially by DSR and favourable moisture conditions; moisture and nitrogen loss through increased percolation rate, and increased spikelet sterility, etc., are attributed to yield penalty in DSR [23,24]. Thind et al. (2023) also reported a yield penalty in ZT-DSR in sandy loam soils of Punjab as compared to CT-DSR and CTR, owing to lesser panicle density under ZT-DSR. Studies also show that yield benefit accrues over time when CA is adopted, depending upon soil and climatic situations [25,26]. In India, based on the analysis of a large number of field studies, Kumar et al. [27] observed varying yield losses of 9.2–28.5 % under different types of DSR than that of TPR. Further, the yield loss is reported more in northwestern India owing to the low rainfall and medium-textured soils. While Singh et al. [28] observed a 22 % higher rice grain yield in the silty loam soil of the Eastern-IGP of India under lowland situations. Similarly, Jat et al. [29] also observed similar (after 3 years) or higher rice yield of ZT-DSR (after 6 years) in clay loam soil of Eastern-IGP. Thus, the yield levels of ZT-DSR depend on soil, climatic, management practices followed and duration of adoption, and location-specific strategies are needed to minimize the yield penalty. The transition from flood irrigation to SSD (*Sc* 5) further bridged the rice yield penalty of ZT-DSR in our study. Subsurface drip irrigation delivered water directly to the root zone, minimizing surface weed growth and ensuring precise nitrogen delivery to the plants. This approach effectively mitigated weed pressure, water stress, and issues related to nutrient and water percolation, resulting in improved rice yields. The delivery of water and nitrogen directly and frequently to the root zone promoted better root growth, nutrient absorption, favourable soil moisture throughout the growing period, which contributed to higher yield in drip as compared to the flood-irrigated rice across the different agro-ecological situations of India [9,30–33]. Furthermore, the rice equivalent yield of maize, both under *Sc* 4 (ZTMWM) and *Sc* 6 (ZTMWM-SSD), was significantly higher (14.6 and 22.2 %) than the rice grain yields, indicating a promising alternative to the water-guzzling rice crop in the medium textured soils of northwestern Indian IGP. Patra et al. [34] reported that continuous accumulation of N till the end of the vegetative stage improved biomass production, promoted proper filling, and led to higher maize yield under CA+SSD.

The wheat grain yield was significantly lower under farmers' practice (*Sc* 1). The adverse effects of puddling on the soil under rice crops, viz., destruction and dispersion of clay particles, that create a layer impermeable for root penetration, formation of sub-soil hardpan due to continuous tillage in wet soil, temporary water logging in wheat crops, etc., are underlying factors reducing the performance of wheat crop [35]. The average wheat grain yield improved significantly (7.7 to 22.1 %) under *Sc* 2-*Sc* 6, with marginal differences among *Sc* 3-*Sc* 6. Compared to flood irrigation and conventional fertilization methods, drip fertigation alters the patterns of water and nutrient movement within the soil, favouring uniform spatial and temporal distribution of moisture and nutrients, significantly influencing the root growth, development, and metabolic activity, which in turn impacts shoot development through root-shoot interactions leading to improved grain yield of wheat [36–38]. The improvement in wheat yield in these scenarios was due to the timely sowing of wheat (7–10 days before conventional transplanted rice) under ZT conditions with 100 % rice residue enabled by Happy Seeder, which led to more favourable temperature during grain filling and maturing period, thus minimizing the risk of terminal heat stress in April month coinciding grain filling period. The yield advantage was also due to improved soil physical properties (after ZT-DSR) compared to farmers' practice where intensive tillage and residue removal were followed. Numerous studies have shown a positive effect of ZT and residue retention on wheat yields [39–41]. Transition to CSAPs scenarios (*Sc* 2 - *Sc* 6) also provided the scope for the inclusion of summer mungbean in the system by advancing the wheat sowing to about 7–10 days. However, the mungbean yield varied depending upon the time window available under different scenarios. The mungbean yield was highest in *Sc* 2, owing to the availability of the longest growing window (April-June), as the rice was transplanted in July in this scenario and mungbean remained comparatively for longer time in the field. The scenarios with SSD (*Sc* 4 and *Sc* 6) also had higher mungbean yield as SSD enabled timely sowing of mungbean by about 7 days before flood irrigation systems.

Among the rice-based systems, *Sc* 2 (CTR-ZTWM) demonstrated notable improvements, yielding the highest system productivity (14.95 t ha^{-1} REYS), followed by *Sc* 5 (ZTRWM-SSD) (14.93 t ha^{-1} REYS). The higher rice, wheat and additional mungbean yield under these systems resulted in higher REYS compared to *Sc* 1 and *Sc* 3. However, maize-based systems, especially *Sc* 6 with SSD irrigation (ZTMWM-SSD), offered even greater benefits, achieving the highest rice equivalent yield of the system. The optimized supply of N and water throughout the crop growth period, along with reduced N losses and improved water availability, enhanced overall system productivity of CA+SSD maize-wheat-mungbean, as observed under similar soil and climatic conditions [42]. Economically, *Sc* 6 also generated the highest net returns over Sc1, underscoring the financial viability of CA+SSD practices. *Sc* 4 and *Sc* 5 also showed substantial net returns, reinforcing the benefits of CA and SSD. The superior performance of *Sc* 6 is linked to several key factors: the use of zero tillage (ZT) [43] for all crops, full residue retention [44], precise nutrient management [45] and reduced weed competition [46]. Improved soil health ([4,47]; Choudhary et al. 2022), and improved water management [33,48] led to greater resource and nutrient use efficiency compared to CT. Moreover, the enhanced root development observed in CA systems was a result of lower soil compaction, contributing to increased biomass production [49]. CA-based systems consistently outperformed *Sc* 1, driven by higher yields, better water-use efficiency, and reduced labour. This makes CA practices particularly viable in resource-limited regions, as they reduce input costs and enhance profitability [7,39,40,50].

Water and nitrogen use efficiency

The comparison between rice-based scenarios (*Sc* 1, *Sc* 2, *Sc* 3, and *Sc* 5) and maize-based scenarios (*Sc* 4 and *Sc* 6) reveals significant differences in irrigation water use, water productivity, and overall system performance, highlighting the advantages of maize-based cropping systems over rice-based systems. Rice-based systems, particularly under conventional tillage (*Sc* 1), recorded the highest irrigation water consumption (1671 mm ha^{-1}), which was significantly higher than rice-based systems (*Sc* 3 and *Sc* 5) by 18 % and maize-based systems (*Sc* 4 and *Sc* 6) by 51 %. Despite the improvements in water management in rice-based systems, such as *Sc* 5 (ZTRWM-SSD), which reduced irrigation water use to 1066 mm ha^{-1}, rice-based scenarios still consumed substantially more water than maize-based systems. The maize-based system with CA+SSD (*Sc* 6), had the lowest water use, only 316 mm ha^{-1}, indicating a dramatic reduction in water input compared to rice-based systems. The maize-based systems (*Sc* 4 and *Sc* 6) consistently outperformed rice-based systems in terms of irrigation water productivity. The precise application of water in rice-based (*Sc* 5) and maize-based (*Sc* 6) systems improved water productivity by 125 and 810 %, respectively over farmers' practice (*Sc* 1). This demonstrates the substantial gains in water use efficiency when maize is integrated into the cropping system, especially when paired with SSD. The results suggest that maize-based systems are inherently more water-efficient due to maize's lower water requirement compared to rice, making them a better option for regions facing water scarcity. From an environmental perspective, the integration of SSD in maize-based systems (*Sc* 6) substantially reduced irrigation water demand and improved water-use efficiency, leading to a significant reduction in the system's environmental footprint. The significant amount of water saving under SSD was further complemented by CA when compared with the flood irrigation system, which attributed to the uniform distribution of soil moisture in rhizosphere, thereby reducing losses from evaporation and deep percolation out of the soil profile [44,51]. Sandhu et al. (2019) observed that residue retention and drip irrigation increased irrigation water productivity for maize and wheat by 259 % and 66 %, respectively, over furrow irrigation. The findings of our study align with prior studies showing water savings under CA systems combined with advanced irrigation technologies [32,33,39,52,53].

As for water footprint, substantial differences were evident among the different CSAPs scenarios. The rice-based systems with flood irrigation (*Sc* 1-*Sc* 3) required 1431–1642 L of water kg^{-1} of system grain yield. Switching to water smart practices with SSD (*Sc* 5) reduced the water footprint of rice-based systems to 743 L kg^{-1}. The *Sc* 6 (ZTMWM-SSD) with the lowest water footprint, recorded an 88 % lower water footprint (189 L kg^{-1} system yield) owing to higher water and system productivity, highlighting it as a potential water-smart system. Flood irrigation in medium textured soils typically requires 6–8 cm of water per irrigation, with most parts lost through deep percolation, thereby increasing the total irrigation volume [9]. In contrast, the precise water application of 1.5–2.0 cm depth through SSD, applied directly to the crop root zone based on SMP and at increased frequency (2–5 days), conserved more water by reducing evaporation and percolation losses [54]. Additionally, surface residue cove further conserved soil moisture, moderated soil temperature, and improved water productivity [55].

The partial factor productivity of N, a function of crop yield and fertilizer N used, varied among the CSAPs scenarios. The CA systems combined with SSD (*Sc* 5 and *Sc* 6) had higher PFP_N in both rice and wheat crops. In these systems, 20 % less N was applied through SSD in multiple splits to suit the crop need with minimized losses through leaching. Thus, reduced N use with increased yields improved the PFP_N under the SSD system, which was notably higher in ZTMWM-SSD (*Sc* 6), mainly due to improved PFP_N in maize, indicating that maize-based systems are more N-efficient. The SSD system probably minimizes the leaching, volatilization and denitrification led losses of applied N, as small doses of N are applied each time in multiple splits directly to the root zone along with small amounts of irrigation water [42,56]. The reduction in nutrient losses led to greater N accumulation in crops, enhanced yields, and lower N inputs, ultimately improving PFP_N in both rice- and maize-based systems. Several previous authors also reported increased N use efficiency under SSD in rice [9,57,58], maize ([56,59,60]; Sandhu et al. 2019) and wheat [42,52,61,62]. Thus, precise water and nutrient management through micro-irrigation, particularly SSD, can help to address the emerging challenges of the inefficiency of water use in agriculture. These findings underscore the advantages of transitioning from water-intensive rice-based systems to more water-efficient maize-based cropping systems, particularly when SSD is utilized, making them a viable option for sustainable agriculture in water-scarce regions.

Energy efficiency and sustainability

The CSAPs scenarios demonstrated the highest overall performance across energy, carbon, and environmental metrics, reaffirming the critical role of integrated crop management for sustainable intensification. *Sc* 6 (ZTMWM-SSD) consistently demonstrated the highest energy efficiency across all crops (rice, wheat, mungbean) and the overall system. The energy input-output relationship showed a clear advantage for *Sc* 6, which required the lowest energy inputs while yielding the highest energy outputs. The higher EUE and EP observed in *Sc* 6 are mainly due to the integrated approach that reduces energy consumption in tillage, irrigation, and nutrient applications. The use of SSD in *Sc* 6 not only conserved water but also minimized energy inputs for pumping and irrigation from 45 % in Sc1 to 15 % in *Sc* 6, while full residue retention improved soil health, thereby enhancing energy conversion efficiency. The superior EUE in CSAPs scenarios further illustrates the capacity of CA systems to optimize resource use in an energy-constrained environment, compared to conventional systems, which recorded the lowest EUE. This finding is consistent with earlier studies, showing that CA can improve energy efficiency while improving crop yields [50,63,64]. A critical insight from our study is the importance of energy utilization in determining agricultural sustainability. Traditional practices, marked by the indiscriminate use of resources, have led to increased energy consumption and environmental degradation in the IGP [65].

Global warming potential

The net global warming potential (GWP_n) varied significantly across the scenarios, with CSAPs scenarios recording the lowest GWP_n, in stark contrast to *Sc* 1 (farmers' practice), which exhibited the highest GWP_n. The higher contribution of fertilizer at the production level in total GWP (up to 60 %) emphasizes the need for more efficient fertilizer use, particularly nitrogen, by reducing losses and thereby lowering the required application rate. The major factors contributing to the higher GWP_n in *Sc* 1 were fuel use in tillage operations, CH_4 due to puddled rice, residue burning of residue and soil organic carbon loss from tillage. In contrast, the reduction in GWP_n in CA-based systems is attributed to lower fossil fuel use in tillage, reduced methane emissions from rice fields, and enhanced carbon sequestration through conservation tillage and residue [66–70]. Furthermore, the maize-based systems (*Sc* 4 and *Sc* 6) exhibited significantly lower GWP_n than the rice-based systems (*Sc* 3 and *Sc* 5), highlighting their environmental sustainability. The savings in electricity and fertilizer use under SSD further reduced GWP_n in ZTRWM and ZTMWM systems compared to their flood irrigation counterparts.

Subsurface drip irrigation directly saved 20 % of fertilizer N. Thus, the lower use of N fertilizers, combined with enhanced N use efficiency under CA+SSD, led to a substantial reduction in N_2O emissions from both fertilizer production and field application. The reduction in water uses either by sifting to DSR or replacing rice with maize, a low water requiring crop, and through integration of SSD in rice and maize, all these lead to lower N_2O emissions in the order of reduction in water use. The decrease in water application in each case allowed comparatively more time for aeration (O_2) to reach the crop root zone during irrigation intervals, promoting greater nitrification and the overall reduction in N_2O emissions [60,71] as well as CH_4 emissions [72]. Moreover, zero methane emissions from maize, combined with its lower water requirement, reduced GWP_n compared to rice, irrespective of CA and SSD practices. The reduced GWP^n values suggest that adopting CA practices coupled with precise water and nitrogen management can play a crucial role in mitigating climate change by lowering agricultural emissions, a finding supported by previous research [40,73].

Carbon sequestration and carbon footprint

Soil organic carbon (SOC) sequestration is the process where CO_2 is captured for long-term storage in a stable form by natural or deliberate processes. The changes in tillage and residue retention over the years in different CSAPs (*Sc* 2-*Sc* 6) scenarios sequestered 3037–3659 kg CO_2 eq. ha^{-1} $year^{-1}$ SOC. Among rice-based CA systems (*Sc* 2, *Sc* 3 and *Sc* 5), the partial CA (*Sc* 2) had the highest SOC sequestration due to higher biomass production by all the crops of the system. Under these scenarios, about 12–16 t ha^{-1} of rice, wheat and mungbean residue was retained on the soil surface annually which is directly related residue retention is directly related to SOC sequestration [74]. As reported by several researchers, crop residues have a significant impact on improving soil quality by increasing SOC sequestration [6,75]. Minimizing the tillage intensity or zero tillage also favours SOC sequestration by avoiding the SOC mineralization loss compared to intensive tillage systems as in farmers' practice. Zero tillage serves as a physical barrier that protects SOC from microbial mineralization, effectively reducing the mineralization rate and enhancing SOC accumulation (Busari et al. 2015). The tillage practices and residue management in different CSAPs scenarios greatly influenced the carbon footprint (CFP). Excessive tillage intensity in *Sc* 1 (CT-RW) accelerated the decomposition of soil organic matter and residue burning, and released CO_2 and N_2O into the atmosphere, thereby recording the highest CFP. In contrast, scenarios with conservation tillage and residue retention, reduced CFP to the lowest value, indicating CO_2 sequestration per unit system output. This reinforces the role of residue retention and zero tillage in CA systems, which maintain soil organic matter, reduce carbon emissions, and improve soil health.

These results are consistent with previous research highlighting the long-term benefits of CSAPs in enhancing soil carbon stocks, which contribute to improved soil fertility and carbon mitigation [7,68,76].

Conclusion

This study demonstrates the transformative potential of Climate Smart Agriculture Practices (CSAPs) where Conservation Agriculture (CA) integrated with subsurface drip (SSD) to include off-season pulse for achieving the sustainable intensification in resource-degrading regions of South Asia. The CSAPs in these regions significantly improved system productivity, profitability, energy efficiency, and carbon sequestration while reducing agriculture's environmental footprint in rice/maize-wheat cropping systems. Among these, the zero-till maize-wheat-mungbean coupled with SSD (ZTMWM-SSD) proved as a sustainable CSAPs to dealt with water crisis, soil and environmental health. As it not only conserved water and energy but also achieved substantially lower global warming potential (−93 %) and nitrogen input (−20 %) with higher system yields compared to the conventional rice-wheat system. These results showed that CSAPs would play a critical role in aligning agricultural practices with climate mitigation efforts. Scaling up CSAPs in climate-vulnerable and resource-scarce regions of South Asia is essential for building resilient, sustainable farming systems. Despite its clear benefits, the adoption of CSAPs in the IGP faces some challenges also. The low grain yield of direct seeded rice (DSR), infestation of weeds in DSR and lack of suitable varieties with high yield potential are the major challenges in traditional rice growing areas for wider adaptation of this system despite numerous environmental advantages. Therefore, development of DSR compatible rice cultivars which has ability of exhibiting early vigour and rapid growth with a capacity to anaerobic germination is needed. High initial costs for SSD, specialized machinery requirement, technical know-how to farmers, availability of single molecule herbicide to kill all type of weeds, and the policy favoured towards traditional farming practices further limits adoption of CSAPs. Addressing these barriers requires comprehensive policy measures and targeted extension services including offering subsidies for CA and SSD implements, provision of assured procurement of maize at minimum support price, introducing carbon credit incentives, developing knowledge hubs to enhance local expertise, and promoting awareness initiatives to change farmer perceptions, etc. can encourage farmers to switch CSAPs. Additionally, long-term research on automation of SSD with fertigation with all essential nutrient elements across diverse agro-ecological situations can be explored to achieve high yield and nutrient use efficiency.

CRediT authorship contribution statement

Hanuman Sahay Jat: Writing – original draft, Formal analysis, Conceptualization. **Kailash Prajapat:** Writing – original draft, Formal analysis, Data curation. **Shivani Khokhar:** Writing – original draft, Formal analysis, Data curation. **Madhu Choudhary:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Manish Kakraliya:** Writing – original draft, Formal analysis, Data curation. **Tanuja Poonia:** Writing – original draft, Formal analysis, Data curation. **Kailash Chandra Kalwania:** Formal analysis, Data curation. **Prabodh Chander Sharma:** Writing – review & editing, Supervision. **Mangi Lal Jat:** Writing – review & editing, Supervision.

Declaration of competing interest

The author(s) have no competing interests.

Acknowledgements

Authors extend sincere thanks and gratitude to JK Ladha, MK Gathala, AJ McDonald, Virender Kumar, AK Yadav, SK Kakraliya, Ashim Datta, DK Sharma and Gurbachan Singh for their invaluable contributions to this research. Their insights, guidance, and support have been instrumental in shaping the direction and enhancing the quality of our study. We also acknowledge the technical support from CGIAR research program on Cereal Systems Initiative for South Asia (CSISA) and Climate Change, Agriculture and Food Security (CCAFS). This research was supported by the Indian Council of Agricultural Research (ICAR), Department of Agricultural Research and Education (DARE), Government of India. The basic infrastructure facilities for the experimentation and publication charges provided by ICAR-CSSRI (Central Soil Salinity Research Institute), Karnal are also thankfully acknowledged.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nexus.2025.100509.

Data availability

The data generated herein are not publicly available but can be made available from the corresponding author on reasonable request.

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