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Designing an ecofriendly and carbon-cum-energy efficient production system for the diverse agroecosystem of South Asia

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ABSTRACT

There is an urgent need for identification of the eco-friendly/cleaner production system that is more productive and profitable; efficient user of energy, water, and carbon-based inputs, and also environmentally safer. The four years study was conducted from 2016 to 2019, where the dominant rice-wheat cropping system is practiced extensively after 'Green Revolution'. The objectives of the experiment were to evaluate: (1) energy budgeting, (2) carbon auditing, (3) production and economic efficiency of diverse cropping systems for upland rainfed as well as irrigated ecosystems of eastern India. Tillage and cropping system treatments were laid out according to a completely randomized block design and replicated thrice. Ten cropping sequences were comprised of: T1) a farmers' practice of transplanted rice-wheat-mungbean, T2) conventional till-direct seeded rice (CTDSR)-wheat-mungbean, T3) soybean-maize, T4) CTDSR-mustard-urdbean, T5) foxtail millet-lentil-fallow, T6) pearl millet-chickpea-fallow, T7) finger millet-*toria*-fallow, T8) sorghum (grain)-chickpea-fallow, T9) maize cob—pigeon pea, and T10) sorghum (fodder)-mustard-urdbean. Energy contributions of different inputs were 42—55, 12—21, 8—18, and 4—12% for fertilizers, diesel, labour, and electricity, respectively. The amount of indirect (fertilizer, chemicals, and machinery) and direct (diesel and electricity) non-renewable energy inputs were 40—60 and 18—26%, respectively. Indirect renewable energy input (seed and crop residues) was 1—7% as compared to 15—24% of direct-renewable energy (human labour and irrigation water). The maximum energy input was recorded for T1 (53511 MJ ha^{-1}). The maximum biomass production (40.2 Mg ha^{-1}) was recorded with T9, while the maximum benefit: cost ratio (3.64) was noted for T10 and T8. The highest specific energy (33.5 MJ kg^{-1}) and energy productivity (0.92 kg MJ^{-1}) were recorded in T8 treatment. Irrespective of cropping systems, retention of crop residues accounted for 28.6—58.5% of total carbon input. The carbon sustainability index was 5—7 times higher for the millet-based production system [T6 (9.32) and T8 (10.27)] compared to cereal-based systems [T1 (1.66) and T2 (1.21)]. Diversification of the rice-wheat system through climate-resilient millets-based production system reduced 84% energy consumption and 87% carbon footprint. The millet-based production system also helps in reducing the carbon input by 172% and improves the energy use efficiency by 61% compared to the cereal-based cropping system. Therefore, the study has an innovative idea to support the crop modelling, policymakers, government planners, researchers, and producers to achieve the sustainable development goals in Indo-Gangetic Plains and similar agro-climatic conditions of South Asia.

1. Introduction

The continent of Asia is vulnerable to the anthropogenic climate

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change because of its more reliance on agriculture [1]. Small landholdings and poor natural resource management are among the major issues for lower crop productivity of the agricultural production systems of South Asia [2]. Rice (*Oryza sativa*), a major staple food crop, is cultivated on ~163 M ha of 114 countries with a total production of ~742.4 MT during 2016 [3]. In India, ~12.5 M ha area is under rice-wheat cropping system (RWCS) [4], which is less remunerative due to more labour, water, capital, and energy requirements. The erratic and unpredictable rainfall patterns prevailing during the rainy season, declining ground-water level, and severe soil degradation, further aggravate the total factor productivity, and sustainability of the system [5]. Also, the widespread practice of in-field burning of crop residues before the planting of wheat is exacerbating the emission of greenhouse gases (GHG. The emission from global RWCS is estimated at ~523 MT CO_2-e year^{-1} and contributes ~10% of the total agricultural emission globally [6].

Achieving the food and nutritional security by increasing crop productivity and diminishing the inter-annual variations in crop yields in South Asia has become a major challenge. There is strong evidence of the negative impacts of climatic change on the productivity of wheat and rice by variable magnitude under diverse climates of the region [7]. Composite exposure using different indicators (i.e., maximum and minimum temperatures, the intensity of low and high rainfall during rainy and winter seasons) has revealed that RWCS in eastern India is highly vulnerable to climatic change. The yield of wheat and rice is predicted to decline from 10 to 40% by 2050 [8]. With each degree centigrade rise in temperature, the demand for irrigation water is expected to rise by 10% [9]. In India, freshwater withdrawals are ~761 billion cubic m (2008–12) and ~90% of this is linked with the agricultural production system. In order to meet the demands of food for the ever-increasing population, India has to produce 37% extra rice and wheat by 2025 using 10% less irrigation water [4].

As farmers of South Asia practice different crop rotations, it is imperative to assess the energy budgeting and C-auditing of annual crop rotations. For developing cleaner and safer production systems, energetics steadiness must be assessed for diverse cropping systems of upland rainfed as well as irrigated agro-ecosystem of eastern India [10]. Diversification of the existing cropping system with non-cereal crops are reported to have a lower emission of greenhouse gasses (GHGs) [11]. The leguminous crop has a lower C- and water footprint as compared to cereals due to the lesser release of GHG [12]. Intensive tillage operations, which are an integral component of modern agriculture, require higher inorganic fertilizers, fossil fuels, and electricity, leading to increased C-footprints and declined energy use efficiency [13].

Designing of the productive and environmentally sustainable production systems, with lower emission of GHGs and energy use, is the need of the hour for a cleaner/safer environment and higher profitability of the farmers [14]. Zero tillage (ZT), a key component of conservation agriculture (CA), improves soil health, crop productivity, and curtails the fuel requirement leading to a significant decline in CO_2 emission [15]. Thus, it could be an appropriate technology for reducing energy input and C -footprint [16].

Most of the climate-resilient cropping systems include millets, oilseeds, and grain legumes due to their low input requirement, better resilience to adverse climatic conditions and superiority in productivity under sub-optimal resources. Choudhary et al. [13] also highlighted the importance of millets and grain legumes for the sustainability of the existing production systems in developing countries like India. Direct seeding of rice and other climate-resilient crops in cereal-based cropping can further reduce the GHGs emission [17].

Energy is an important input in the modern agricultural production system and, therefore, the inter-dependence of energetics, and crop production needs to be evaluated for designing an energy and C- efficient cropping system [18]. The input-output relationship of diverse production systems varies with total biomass productivity, soil type, and diverse tillage practices. The extreme dependence on fossil fuels (diesel) and other non-renewable energy sources, and increasing awareness of the emission of GHGs have shifted the focus on the judicious use of renewable energy such as biofuels [19]. Thus, there is a need to assess the energy use efficiency (EUE) and C-auditing of the diverse production systems in the Indo-Gangetic Plain (IGP) of South Asia. The rice-based cropping system, which is critical to food and nutritional security of the IGP of eastern India, warrants additional research in the context of moderating C- and energy uses. The available scientific information on C-footprint of climate-resilient cropping systems is scanty for designing and developing the strategies of sustainable production systems. At the same time, GHG emission and yield penalty from the identified cropping systems must be minimized for a cleaner environment [12]. We hypothesized that the diversified crop rotations result in a reduction in energy consumption and carbon footprints and provide more yields and income under the climate changing scenario. Thus, the present investigation was aimed to evaluate the energy use patterns, C-footprints, and economics of 10-diverse cropping systems in eastern India. The present study aimed to quantify the energy-cum-carbon budgeting for an eco-friendly low C-emissive and economically-efficient sustainable production systems in Indo-Gangetic Plains and similar agro-climatic conditions of South Asia.

2. Materials and methods

2.1. Experiment site and climate

The present investigation was conducted for four consecutive years from 2016 to 17 to 2019-20 in the region where the rice-wheat cropping system is widely practiced. The experimental site is located at the ICAR-Research Complex for Eastern Region, Patna, India, at 25°30′N, 85°15′E, 52 m above mean sea levels (MSL) (Fig. 1). This region has an annual precipitation of 1168 mm, of which 88% is received between July and September. The mean annual evaporation is 1573 mm. The data on precipitation and temperature for the study site are presented in Fig. 2. The soil of the experimental site was loamy in texture (50.4, 35.0 and 14.6% sand, silt, and clay, respectively) (Typic Haplustept, Fluvisol), with pH of 7.5, EC of 0.12 dS m^{-1}, soil organic carbon (SOC) content of 6.0 g kg^{-1}, $KMnO_4$ oxidizable N of 64.6 mg kg^{-1}, Olsen phosphorus of 23.9 mg kg^{-1}, NH_4OAc exchangeable potassium of 78.3 mg kg^{-1}, and DTPA-extractable zinc of 0.66 mg kg^{-1} (0–15 cm soil).

2.2. Experimental treatments and layout

Treatments were laid out according to the completely randomized block design (CRBD) and replicated thrice. Ten cropping sequences included T1: transplanted rice (*Oryza sativa)*-wheat (*Triticum aestivum)*-mungbean (*Vigna radiata)* (CT) (Farmers practices, FP), T2: conventional till-direct seeded rice (CTDSR)-wheat-mungbean (ZT), T3: soybean (*Glycine max)*-maize (*Zea mays)* (ZT), T4: CTDSR-mustard (*Brassica juncea)*-urdbean (*Vigna mungo)* (ZT), T5: foxtail millet (*Seataria italica)*-lentil (*Lens culanaris*) (ZT)-fallow, T6: pearl millet (*Pennisetum glaucum)*-chickpea (*Cicer arietinum*) (ZT)-fallow T7: finger millet (*Eleusine coracana)-toria* (*Brassica rapa)* (ZT)-fallow, T8: sorghum (grain) (*Sorghum bicolor*)-chickpea (ZT)-fallow, T9: maize cob (*Zea mays*)-pigeonpea (*Cajanus cajan)* (ZT), and T10: sorghum (fodder)-mustard-urdbean (ZT). All crops raised during the rainy season were grown under CT, while all winter and

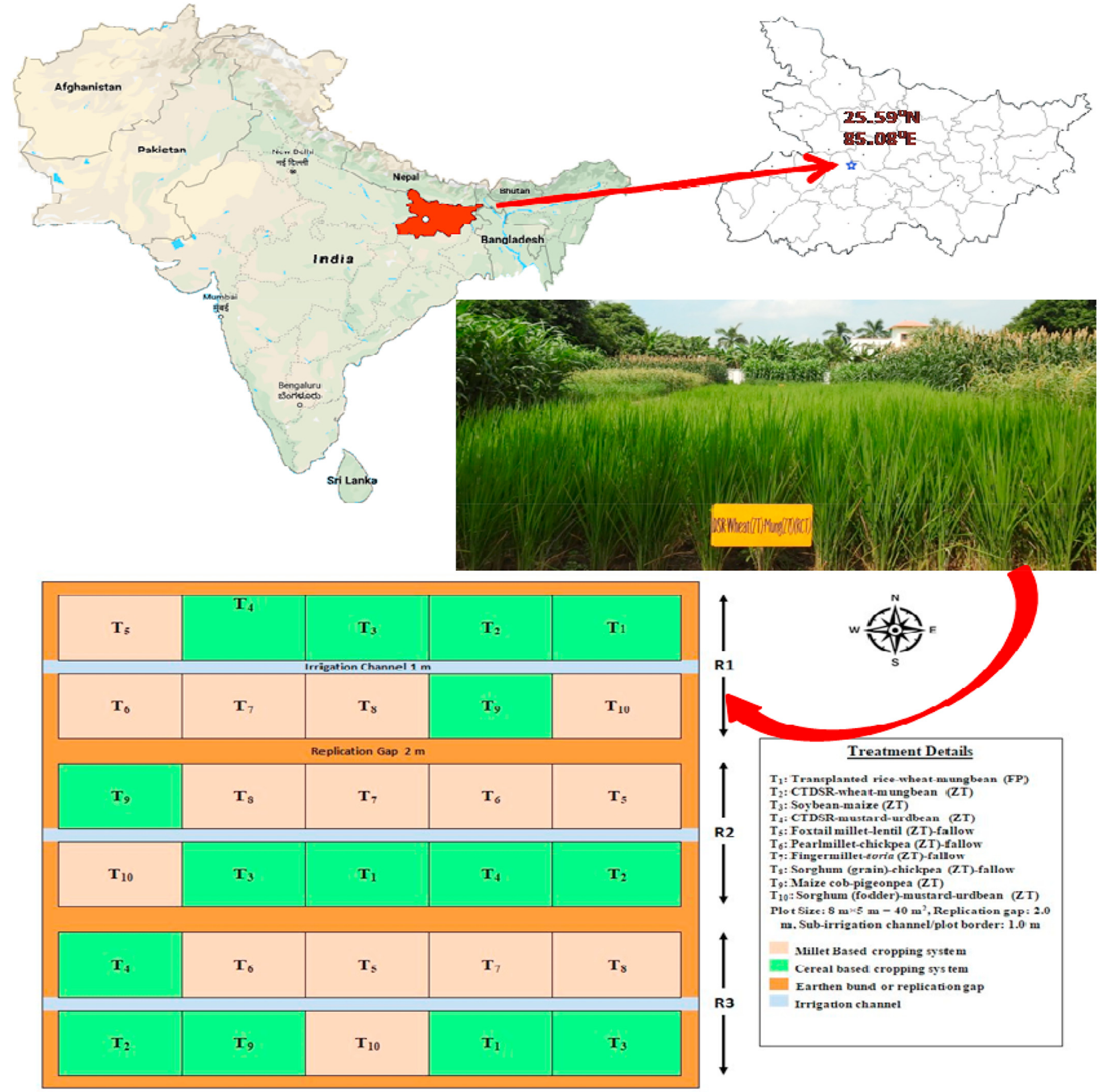

Fig. 1. Location of the experimental site, layout and experimental view.

summer crops were grown under ZT, except in farmers' practice (T1). In T2 treatment, ~30% residues of rice and wheat were retained, whereas for other treatments crops were harvested at the ground level and removed. Two to three manual harvestings were done for summer crops (mungbean/urdbean) and then entire crop biomass was incorporated into the soil. The size of the individual experimental unit was 8.0 × 5.0 m (Fig. 1).

2.3. Crop establishment and management

All the component crops were grown as per the standard crop calendar (Table 1). Before initiating the experiment, the land was chisel ploughed to 30 cm depth and levelled. The weed control was achieved by glyphosate (41% EC) at 1.5 l ha^{-1} a week before crop seeding/planting. Selective pre-and post-emergence (PE/POE) herbicides were used to manage the weeds. Atrazine (PE) for maize, pretilachlor (PE) for transplanted rice [2–3 days after transplanting (DAT)], pendimethalin (PE) followed by bispyribac-sodium (POE) for CTDSR [20 days after sowing (DAS)], pendimethalin (PE) for mungbean/urdbean and mustard (2–3 DAS), and clodinafop propagyl (POE) for wheat (30 DAS) were used for effective weed management. All crops of the rainy season were planted during the third week of June and harvested by the second week of October except for maize and fodder sorghum in T9 and T10 treatments. The

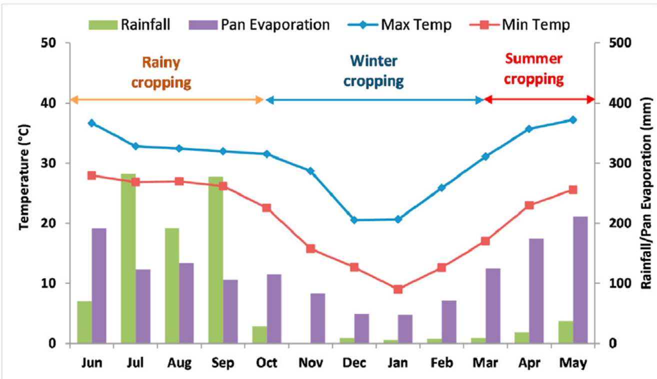

Fig. 2. Monthly four years average of rainfall, minimum and maximum temperatures during the crop growing seasons. [Source: Agromet Observatory, ICAR-Research Complex for Eastern Region, Patna, Bihar, India].

quality protein maize (QPM), which was grown for dual-purpose (green cob as well as fodder), was seeded on 20th June and harvested by the end of September in each year. All winter crops (e.g., wheat, oilseed, and pulses) were sown during the third week of October and harvested in March and April. Summer crops (mungbean/urdbean) were sown and harvested during the first week of April and June, respectively.

2.4. Energetics input-output relationships

Energy budgeting was computed to compare the energy use pattern and energy ratio of diverse cropping systems. The primary information of energy inputs for specific crop management practices under the different treatments was used for calculation of energetics. All the inputs used in a cropping system were recorded. Energy inputs associated with different cropping systems and their coefficients collected from published peer-reviewed literature are presented in Table 2. Energy inputs include both the operational (direct) and non-operational (indirect) energy. The operational inputs energy includes human labour, fuels, and machine; and non-operational energy includes seed, chemical fertilizers, and pesticides. Energy output (grains, fodder, stover, roots) was computed by multiplying the quantity of crop production with their respective energy coefficients [23]. In the present study, only the energy inputs used in crop production were included, but the renewable/built-in sources of energy (solar radiation, wind, inbuilt soil fertility) were not considered, since it has no opportunity cost [24]. Moreover, these inputs are independent of management practices during the experimentation. The flow chart of the methodology is presented in Fig. 3.

Energy input: Energy equivalent for all inputs were totalled for computing cumulative energy input.

Energy output: Energy outputs for a product (grain) and byproducts (straw/stalk/roots) were computed by multiplying the quantity with its corresponding energy equivalents.

Net energy returns: Difference between energy output and input involved for crop production.

The following formulae were used for calculating the energy use efficiency indices [23]:

$$Energy\ ratio = \frac{Gross\ energy\ output}{Energy\ input} \tag{1}$$

$$Energy\ profitability = \frac{Net\ energy\ output}{Energy\ input} \tag{2}$$

$$\text{Energy productivity}\ \left(\text{kg MJ}^{-1}\right) = \frac{\text{System rice equivalent yield}}{\text{Energy input}} \tag{3}$$

$$\text{Energy intensiveness}\ \left(\text{MJ US\$}^{-1}\right) = \frac{\text{Energy input}}{\text{Cost of cultivation}} \tag{4}$$

$$\text{Human energy profitability} = \frac{\text{Gross energy output}}{\text{Labour input energy}} \tag{5}$$

$$\text{Specific energy}\ \left(\text{MJ kg}^{-1}\right) = \frac{\text{Gross energy output}}{\text{System rice equivalent yield}} \tag{6}$$

Table 1
Crops, varieties, seed rate and fertilization used in experimentation.

Crops	Varieties	Seeding rate (kg ha^{-1})	Spacing (cm)	Fertilization (kg NPK-ha^{-1})
Rainy season				
Transplanted rice	Swarna Shreya	20	20 × 15	120-60-40
Direct seeded rice	Swarna Shreya	30	20 × 5	120-60-40
Soybean	Pusa 9712	80	45 × 15	20-80-40
Foxtail millet	Rajendra Kauni	10	25 × 10	60-40-25
Pearl millet	Proagro 9001	5	45 × 15	80-40-40
Finger millet	RAU 8	5	20 × 10	60-40-25
Sorghum grain	CSH 25	10	45 × 15	80-40-40
QPM maize	Shaktiman 5	20	60 × 20	100-60-40
Sorghum fodder	CSH 13	30	25 × 5	80-40-40
Winter season				
Wheat	HD 2967	125	22.5 × 5	150-60-40
Pigeonpea	Pusa 9	50	30 × 15	20-50-0
Lentil	HUL 57	35	30 × 10	20-50-0
Chickpea	Pusa 256	80	30 × 10	20-50-0
Toria	TS 38	5	30 × 10	60-40-40
Mustard	Proagro 5222	5	30 × 10	80-40-40
Maize	S2-945	20	50 × 20	120-75-50
Summer season				
Mungbean	Samrat	25	30 × 10	20-50-0
Urdbean	Uttara	25	25 × 10	20-50-0

Table 2
Energy equivalent of inputs and outputs used under present study.

Particulars	Unit	Energy equivalent (MJ unit^{-1})	References
Input			
Human power			
a. Adult man	man-hour	1.96	[18]
b. Women	man-hour	1.57	[18]
Diesel	litre	56.31	[18]
Electricity	kWh	11.93	[18]
Irrigation water	m^3	1.02	[16]
Farm machinery			
a. Electric motor	kg	64.8	[16]
b. Farm machinery	kg	62.7	[16]
Chemical fertilizers			
a. Nitrogen (N)	kg	60.6	[20]
b. Phosphate (P_2O_5)	kg	11.1	[20]
c. Potash (K_2O)	kg	6.70	[20]
Herbicides	kg/litre	254.5	[21]
Insecticides	kg/litre	184.6	[21]
Output			
Seed/grain/green cob/green fodder			
a. Rice/sorghum/pearl millet/foxtail millet/finger millet/pigeonpea/lentil/chickpea/mungbean/urdbean	kg	14.7	[22]
b. Maize cob/sorghum fodder	kg	12.5	[14]
c. Mustard/*toria*	kg	22.72	[22]
d.Straw/stover of cereal/pulses/oilseeds	kg	12.5	[22]

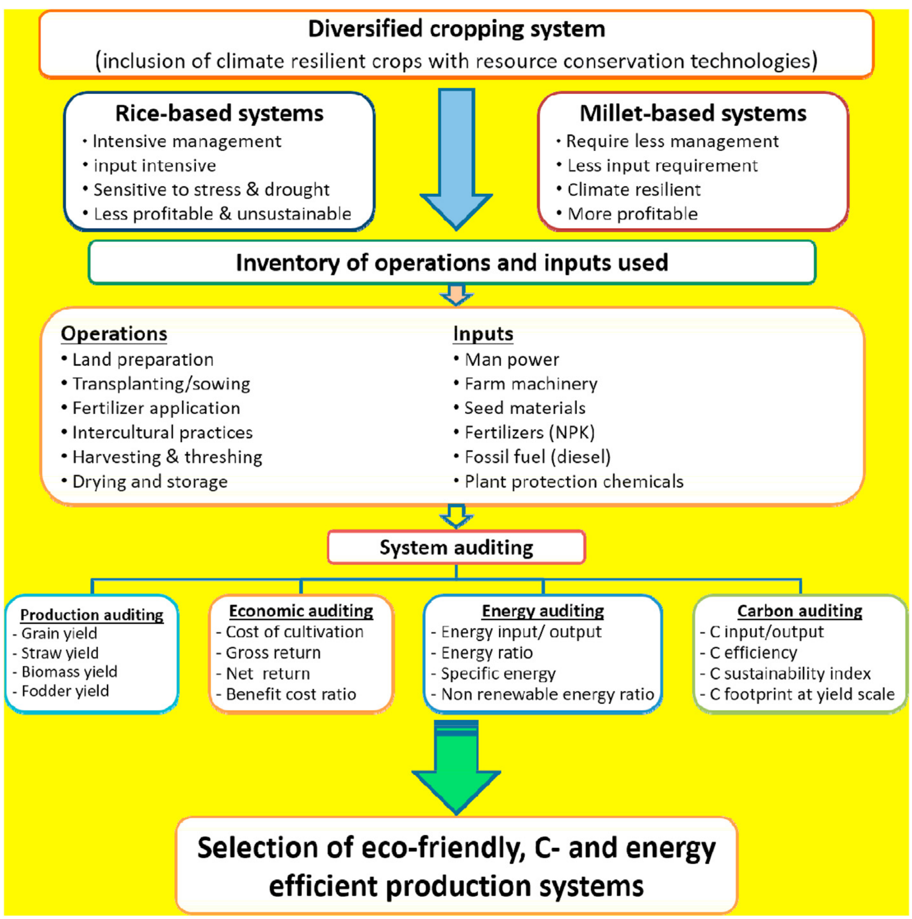

Fig. 3. Methodology used in the experiment.

$$\text{Energy output efficiency}\left(\text{MJ d}^{-1}\right) = \frac{\text{Gross energy output}}{\text{Duration of the cropping period}} \tag{7}$$

$$\text{Nutrient energy use efficiency} = \frac{\text{Total energy output}}{\text{Nutrient energy input}} \tag{8}$$

$$\text{Non}-\text{renewable energy use efficiency} = \frac{\text{Total energy output}}{\text{Non}-\text{renewable energy input}} \tag{9}$$

$$\text{Energy intensity in physical term}\left(\text{MJ kg}^{-1}\right) = \frac{\text{Energy input}}{\text{System rice equivalent yield}} \tag{10}$$

$$\text{REY}\left(\text{t ha}^{-1}\right) = \frac{\text{Grain yield of the winter/summer crop} \times \text{MSP of winter/summer crops)}}{\text{Price of rice}} \tag{15}$$

$$\text{Energy intensity in economic term}\left(\text{MJ US\$}^{-1}\right) = \frac{\text{Gross energy output}}{\text{Cost of cultivation}} \tag{11}$$

2.5. Carbon auditing

Cumulative photosynthates of crops, representing total C-output, was computed by multiplying respective crop yields with an average C- content of biomass (~44% on a dry weight basis) [25]. The C-equivalent (CE) was computed by multiplying the respective inputs (diesel, fertilizer, pesticide) with related emission-coefficients (Table 3) as reported by Lal [25]. Computed CE was used in assessing C-emission based on production, transportation, storage, and farm operations. The sum of C-input and output were computed by summing up CE of all the inputs and outputs, respectively [13]. The C-budgeting of diverse cropping production systems was computed by using the following equations [28]:

Table 3
Emission factors of agriculture inputs used in estimation in the study.

Particulars	Unit	kg CO_2e unit^{-1}	References
Electricity	kWh	0.075	[25]
Human labour	man-day	0.86	[26]
Diesel	litre	3.32	[26]
Diesel farm machinery	hour	3.32	[26]
Seeds	kg	1.22	[27]
Chemical fertilizers			
N	kg	4.96	[25]
P_2O_5	kg	1.35	[25]
K_2O	kg	0.58	[25]
Plant protection chemicals			
Fungicides	litre	3.90	[25]
Herbicides	litre	6.30	[25]
Insecticides	litre	5.10	[25]

$$\text{Carbon output}\left(\text{kg CE ha}^{-1}\right) = \text{Total biomass (economic yields + by-product of yields)} \times 0.44 \tag{12}$$

$$\text{Carbon footprint (CFy) (kg CE kg} - 1\ \text{SREY)} = \frac{\text{Total carbon emission of inputs}}{\text{System rice equivalent yield}} \tag{13}$$

$$\textit{Carbon efficiency}(CE) = \frac{\textit{Carbon output}}{\textit{Carbon input}} \tag{14}$$

$$\text{Carbon sustainability index(CSI)} = \frac{\text{Carbon output} - \text{Carbon input}}{\text{Carbon input}} \tag{15}$$

$$\text{Carbon efficiency ratio(CER)} = \frac{\text{Grain yield in terms of carbon}}{\text{Carbon input}} \tag{16}$$

2.6. System equivalent yield measurements

System productivity of the different cropping sequences was converted into the rice equivalent yield (REY) by the following formula [18].
where, MSP is the minimum support price as fixed by the Government of India (GOI).

System rice equivalent yield (SREY) or system productivity and system production efficiency (SPE) was computed as per the following equations [18]:

$$\text{SREY}\left(\text{t ha}^{-1}\right) = \text{Grain yield of rice} + \text{REY of winter crops} + \text{REY of summer crops} \tag{16}$$

$$\text{System production efficiency (SPE)}\left(\text{kg d}^{-1}\right) = \frac{\text{SREY}}{\text{Total duration of the cropping period}} \tag{17}$$

2.7. Economic analysis

Economics was worked out by considering all the incurred variable costs for a diverse cropping system. Major variable costs include uses of energy (human/machinery) for land preparations, fertilizer, insecticide, irrigation, harvesting and thrashing. The labour cost was computed by multiplying the wage rate of GOI with man-day ha^{-1}. All the input cost was totalled to get the total variable cost (TVC). The gross returns (GR) were computed by multiplying the marketable outputs (grains/cob/fodder and straw/stover yield of individual crops) with their market price. Net returns (NR) were computed by taking the difference between gross returns (GR) and TVC (NR = GR-TVC).

2.8. Statistical analysis

The collected data were subjected to analysis of variance (ANOVA) with a general linear model [29]. The F−test was done to determine the significant effect of treatment [30].

3. Results

3.1. Biomass productivity

The total annual biomass production differed among the cropping systems (Table 4). Intensive cropping systems [three crops year^{-1}, T1 (farmers' practice), T2, T4, and T10] produced higher total biomass (27.6–32.1 Mg ha-yr^{-1}) on annual crop rotations. However, the maximum biomass production was registered in treatment T9 (40.2 Mg ha-yr^{-1}), which was higher by 46, 30, 41, 55, 247, 36, 232, 27, and 25% over T1, T2, T3, T4, T5, T6, T7, T8, and T10, respectively. Irrespective of the cropping system, treatment T9, and T10 had higher root biomass (5.4–5.7 Mg ha-yr^{-1}) than other treatments. Among the rainy season crops, sorghum, dual-purpose maize, and pearl millet were the most productive followed by wheat and rice. Among the pulses, pigeonpea produced the highest stover biomass during the winter cropping.

3.2. Energy use and input-output relationships

The energy requirement for crop production is directly related to the management techniques followed and inputs used. Energy analysis is an important tool for judging the system production efficiency of the diverse production system and achieving the Sustainable Development Goals (SDGs). A production system is considered efficient when it produces higher energy output and consumes comparatively lesser energy. The data on energy use patterns revealed that rice-based cropping system [T1 (farmers' practice), T2 and T4] were the most energy-intensive with an energy input of 36872–53511 MJ ha^{-1} followed by T3 (30596 MJ ha^{-1}). Whereas, the energy requirement of the millet-based production system was lower and varied between 16353 (T5) and 20405 MJ ha^{-1} (T8). Among the intensive cropping systems (T1, T2, T4, T3 and T10], the lowest energy requirement was registered for T10 treatment (Table 5). Total energy input used followed the trends of T1 (53511)> T2 (47403)> T4 (36872)> T3 (30596)> T10 (29293)> T9 (22667)> T8 (20405)> T6 (19808)> T7 (17999)> T5 (16353) MJ ha^{-1}.

The operation-wise energy use data showed that nutrient and water management consumed major shares of the total energy inputs (51–71%). The energy input used for irrigation in rice-based cropping systems [T1, T2, and T4] was 8356–13370 MJ ha^{-1} as compared to 1672 MJ ha^{-1} in the millet-based production systems (T5, T6, T7, T8) (Fig. 4). The energy inflow through crop nutrition ranged between 43 and 49% being higher in T1, T2, T3, T4, and T10 (Fig. 5). Among the different millet-based cropping system, the maximum energy input was consumed through inputs of nutrients (Table 5).

Among the various inputs, diesel was the most energy-intensive. The maximum consumption of diesel was noted in T1 treatment (Fig. 5). Diesel and electricity (direct non-renewable energy) accounted for 11.9–20.9 and 4.0–12.3% of energy inputs, respectively (Fig. 4). Overall, these items contributed to the maximum energy inputs, followed by direct-renewable energy (labours and water). The energy used for land preparation was higher in cereal-based production systems and varied from 3324 MJ ha^{-1} (T10) to 6728 MJ ha^{-1} (T1) compared to millet-based cropping (2630 MJ ha^{-1}) (Table 5).

Among the various sources of energy inputs for different operations, fertilizers contributed a major share of total energy inputs under cereal and millet-based production systems. The total energy input (indirect non−renewable energy) by fertilizer for T1 to T10 treatments were 23285, 22649, 13210, 16686, 7400, 8732, 9922, 8732, 11059, and 13753 MJ ha^{-1}, respectively (Table 5). The share of energy used for fertilizer was the highest followed by irrigation, land preparations, harvesting, and threshing in the cereal-based cropping systems. A similar trend was also noted in millet-based production system (Fig. 6).

The gross energy output of cropping production systems ranged from T5 (153699 MJ ha^{-1})-T9 (512589 MJ ha^{-1}) (Table 6 and Fig. 7). Irrespective of the cropping system, the maximum energy output was recorded in T9 (512589 MJ ha^{-1}), of which 14, 72.1, and 13.9% of the energy output were credited by green cob, fodder, and root biomass, respectively. The energy ratio and energy profitability were also higher with T9 (22.6 and 21.6) followed by T8 (20.2 and 19.2). The highest and the lowest energy intensiveness was recorded for T1 (0.36 MJ US\$$^{-1}$) and T9 (0.24 MJ US\$$^{-1}$), respectively (Table 6). It was evident from the data that the nutrient energy use and non-renewable energy use efficiency were significantly higher under the millet-based production systems compared to cereal-

Table 4
Yields of rainy, winter and summer crops of diverse cropping system under the agro-ecosystem of eastern India (average of four years).

Cropping system	Rainy crops (Mg ha^{-1})			Winter crops (Mg ha^{-1})			Summer crops (Mg ha^{-1})			Biomass (Mg ha^{-1})			Total biomass (Mg ha^{-1})
	Grain/green cob yield	Straw yield	Root yield	Grain yield	Straw yield	Root yield	Grain yield	Straw yield	Root yield	Rainy crop	Winter crop	Summer crop	
T1:Transplanted rice–wheat–mungbean (CT)	4.59	5.31	1.85	5.05	6.32	2.11	1.05	0.67	0.63	11.75	13.48	2.35	27.60^{DE}
T2:CTDSR–wheat (ZT)–mungbean (ZT)	5.15	6.55	2.08	5.31	7.03	2.11	1.21	0.76	0.71	13.78	14.45	2.68	30.90^{BC}
T3:Soybean–maize (ZT)	1.92	3.70	0.84	11.00	7.36	3.73	–	–	–	6.46	22.09	–	28.60^{D}
T4:CTDSR–mustard–urdbean (ZT)	5.01	6.43	1.95	2.78	5.23	1.69	1.12	1.11	0.68	13.39	9.70	2.91	26.00^{E}
T5:Foxtail millet-lentil–fallow	1.61	3.55	1.22	2.06	2.57	0.64	–	–	–	6.38	5.27	–	11.60^{F}
T6:Pearl millet–chickpea–fallow	3.79	11.60	3.35	2.39	4.11	0.71	–	–	–	18.74	7.21	–	29.60^{CD}
T7:Finger millet–*toria*–fallow	1.59	4.71	1.15	1.48	2.40	0.79	–	–	–	7.45	4.67	–	12.10^{F}
T8:Sorghum (Grain)–chickpea (ZT)–Fallow	4.21	15.75	4.14	2.43	4.49	0.72	–	–	–	24.1	7.64	–	31.70^{BC}
T9:Maize cob–pigeon pea (ZT)	2.12*	15.45#	3.54	2.75	14.10	2.19	–	–	–	21.11	19.04	–	40.20^{A}
T10:Sorghum (F)–mustard–urdbean (ZT)	–	18.11**	3.11	2.42	4.62	1.66	0.91	0.65	0.63	21.22	8.70	2.19	32.10^{B}

*Dry cob yield, # Dry maize fodder yield, **Dry sorghum fodder yield, ZT: Zero tillage, CTDSR: Conventional-tilled direct seeded rice.

Table 5
Energy consumption (MJ ha^{-1}) in different agronomic management practices under diverse cropping system (average of four years).

Agronomic practices	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Field preparation	6728	3324	2630	3324	2630	2630	2630	2630	2630	3324
Fertilizer application	23285	22649	13210	16686	7400	8732	9922	8732	11059	13753
Seed and sowing/planting	3232	2813	2300	1016	695	1385	250	1605	1332	1111
Weeding/thinning/earthing up	1068	1811	1775	2001	1033	1365	969	1444	1542	1132
Irrigation	13370	10863	5850	8356	1672	1672	1672	1672	2508	5850
Plant protection	855	970	672	1305	843	873	602	1093	957	1234
Harvesting and threshing	4973	4973	4159	4184	2080	3151	1954	3229	2639	2889
Total	53511	47403	30596	36872	16353	19808	17999	20405	22667	29293

T1:Transplanted rice–wheat–mungbean (CT) (FP), T2: CTDSR–wheat–mungbean (ZT), T3: Soybean–maize (ZT), T4:CTDSR–mustard–urdbean (ZT), T5:Foxtail millet–lentil (ZT)–fallow,T6: Pearl millet–chickpea (ZT)–fallow, T7: Finger millet–*toria* (ZT)–fallow, T8: Sorghum (Grain)–chickpea (ZT)–fallow, T9: Maize cob–pigeonpea (ZT), T10:Sorghum (F)–mustard–urdbean (ZT),ZT: Zero tollage, CTDSR: Conventional-tilled direct seeded rice, F: Fodder, FP: Farmers practices.

based cropping systems. Nutrient and non-renewable energy use efficiencies were 55.8 and 58.3% higher, respectively, in the millet-based than cereal-based cropping systems (Table 6).

3.3. Carbon budgeting

3.3.1. Carbon emission

Energetics and C-footprints have close nexus to the modern agricultural production systems. Irrespective of the cropping systems, retention of crop residues consumed ~28.6 (T10) to 58.5% (T2) of total C-input in residues recycled plots. Residues retained or incorporated as a source of C- consumed ~29–59% of the total C-inputs in the cereal-based production system. Next to crop residues, fertilizers consumed ~27.3 (T2) to 69.8% (T7) of total C-inputs (Fig. 8). Diesel used for land preparation, planting, threshing operations consumed 205.9–421.2 kg CE ha^{-1} C-input in cereal-based cropping and 159.1–196.6 kg CE ha^{-1} C-input in the millet-based production system (Table 7). The maximum and minimum C-inputs were used in T2 (6271 kg CE ha^{-1}) and T5 (914 kg CE ha^{-1}). The trend followed for C-input was T2> T1> T4> T10> T9> T3> T8> T6> T7> T5. The treatment T9 had the highest C-output (17200 kg CE ha^{-1}) and the lowest was with T5 (5126 kg CE ha^{-1}).

3.3.2. Carbon sustainability index

The sustainability of agricultural production systems mainly depends on their C-footprints. The C-footprints of diverse cropping production systems are highly dependent on the ability of crops to convert the absorbed nutrients into grains. Irrespective of the cropping systems, treatment T8 had the highest C-efficiency and CSI (11.3 and 10.3) and T2 (2.2 and 1.2) the lowest (Table 7). The maximum C-footprint was recorded for T2 (0.40 kg $CEkg^{-1}$ SREY), the maximum CER was for T10 (8.9), and the minimum for the T2 treatment (1.9).

3.4. Economics

The cost of cultivation and economic returns obtained from the diverse cropping systems of the present study are given in Table 8. The mean cost of cultivation of all the intensified cropping systems (triple) was significantly higher than that for the double cropping system. The cost of cultivation was higher in cereal-based cropping systems and varied from US$ 1400 ha^{-1} (T3) to US$ 2080 ha^{-1} (T1). The maximum net returns and benefit: cost ratio (BCR) was noted for T9 (US$ 3665 ha^{-1} and 3.75), while the lowest with T7 (US$ 500 ha^{-1} and 1.61).

3.5. Principal components analysis

Results of the PCA bi-plot revealed that the first two principal components (PC1 and PC2) were T6 and T8 treatments, which were also positively correlated with C-auditing (CE, CSI, C-footprints) and energy budgeting variables (energy ratio, energy profitability, energy productivity) (Fig. 9).

4. Discussion

4.1. Biomass productivity

Rotation of crop/cultivar and cropping systems, a widely adopted management practice in the entire globe, is widely practiced to resolve the issues of the adverse effect of climatic changes in the intensive production system to achieve the environmental sustainability [21]. Crop diversification through climate-resilient cropping system is one of the main approaches for improving the productivity of the agro-ecosystem and resolving the issues of ecological sustainability [22]. It also helps in a reduction of C-footprint and energy use [31]. Thus, designing a resilient crop production system must be aimed at optimizing the energy input and C-footprints (CFs) of the entire production system. The emission of GHG and CFs of the individual crop must be assessed thoroughly. While designing an efficient cropping system, it is necessary to choose the crops/cultivars that require low input and have lower C-footprints [32]. Irrespective of the cropping systems, the maximum biomass production was noted for the T9 treatment. The variation in biomass production was attributed to differences in the genetic potential of individual crops [21]. Higher total biomass production in maize/sorghum/pearl millet-based cropping system was due to more production potential of C4-plants. The dual-purpose maize/millets (sorghum/pearl millet) and pigeonpea utilize the solar energy efficiently, and thus, had higher total biomass production [23]. The present investigation was also validated for upland rainfed conditions, where the soil moisture is the primary constraint to achieving high crop yields [13]. Further, better crop management practices (residual fertility/moistures) are also equally responsible for higher yield benefits [33].

4.2. Energy uses and input-output relationship

Energy-based system productivity, energy output, net energy returns, and energy ratio are some of the pertinent indicators for efficient appraisal of energy utilization in modern crop production. These indicators are helpful in assessing the enterprises, their composition, adoption to the specific management practices, and appraising the feasibility of energy requirement [11]. The necessity of energy, and its production potential mostly depend on inputs used, crops/cultivars, types of cropping system and crop establishment practices also [12]. The total energy input requirement was the highest in the cereal-based production system for T1 (farmers practice) (53511 MJ ha^{-1}), which was ~2.6 higher than that of the millet-based production system (Table 6). The key factor

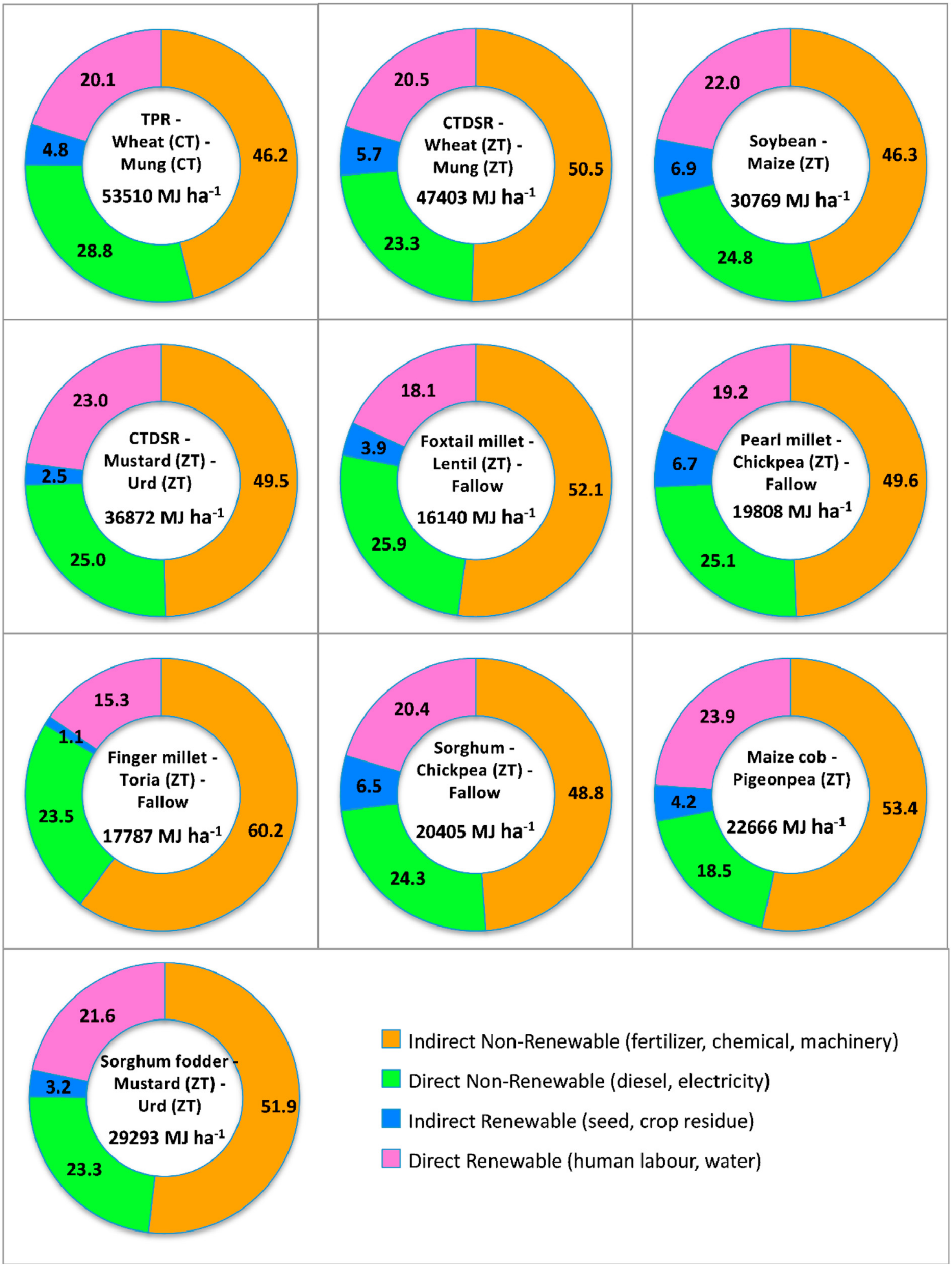

Fig. 4. Renewable and non-renewable input energy (%) under diverse cropping system (average of four years). T1:Transplanted rice–wheat–mungbean (CT) (FP), T2: CTDSR–wheat–mungbean (ZT), T3:Soybean–maize (ZT), T4:CTDSR–mustard–urdbean (ZT), T5:Foxtailmillet–lentil (ZT)–fallow,T6: Pearl millet–chickpea (ZT)–fallow, T7: Finger millet–*toria* (ZT)–fallow, T8: Sorghum (Grain)–chickpea (ZT)–fallow, T9: Maize cob–pigeonpea (ZT), T10: Sorghum (F)–mustard–urdbean (ZT); ZT: Zero tollage, CTDSR: Conventional-tilled direct seeded rice, F: Fodder, Fp: Farmers practices.

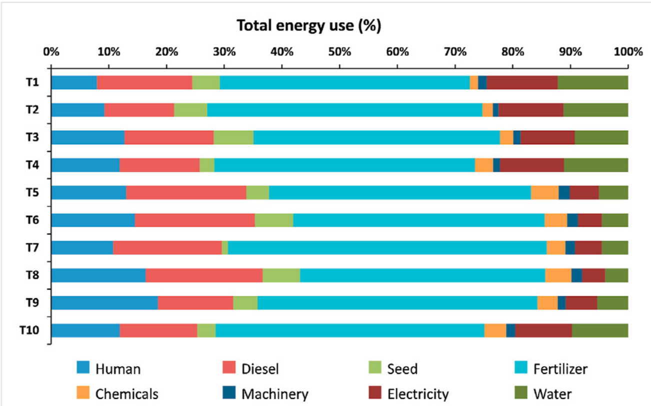

Fig. 5. Source-wise energy use pattern under diverse cropping system (average of four years).

responsible for the use of more input energy was intensive crop management practices for better crop productivity in cereal-based cropping system [18]. Crop production based on the CT was energy-input intensive and have lower resources use efficiency [5]. About 30–35% of energy input was used for land preparations and crop establishment as also reported by various researchers [32]. Of the total inputs for diverse farm operations, fertilizers contributed the maximum share of energy input (42.8–55.1%) (Fig. 5). Tuti et al. [23] also reported that fertilizer and seeds were the prime contributors to energy use (~83%). Next to the fertilizers, diesel used for crop production was the most energy-intensive item (Table 6). Diesel used was the highest in cereal-based production systems (~11.9–20.9%) and the lowest in millet-based cropping (~4.04–12.3%) (Fig. 5). It also differs due to the adoption of high yielding crop/cultivars and different farm operations (ploughing, irrigation, machinery) under the diverse production system [24]. However, ZT production systems had a lower energy requirement owing to the omission of tillage and minimum intercultural operations [34].

The energy output of diverse production systems is governed by total biomass production including the main product and by-products [12]. Multiple cropping systems produced a higher energy output by yielding the more grain/seeds/fodder/cob and total biomass production except for T6 and T8 (Table 5). Irrespective of cropping systems, energy input contribution was the maximum for fertilizers (42.8–55.1%) due to higher levels of nitrogen fertilization in the rice, wheat, maize and mustard. In terms of energy productivity, dual-purpose maize, pigeonpea and sorghum grain/fodder were the most productive compared to rice/wheat. In general, the cereal-based cropping sequence had higher energy outputs than non-cereal systems. System-based energy ratio ranged from 6.8 to 22.6 and it depended on the total biomass production and energy input used. The energy ratio of the millet-based production system was higher due to the production of more biomass with minimum energy input [13]. The treatment of T9 was identified as the most energy-efficient. The farmers' practices (T1) was the least energy-efficient due to the use of more energy input in the form of fertilizer and human labours [18]. The treatment T1, involving a third crop in rotation had more energy input and relatively lower energy output resulting in a lower energy ratio. The higher energy ratio and productivity were noted with higher economic yields [23]. The farmers' practices (T1) and T2 treatment had minimum energy productivity. The effectiveness of energy use was better in maize cob/fodder, sorghum, pigeonpea as indicated by better energy ratio. The most energy-intensive cropping system was T1 due to the use of more energy inputs for the production of comparable energy outputs [16].

Thus, the optimal selection of crop/cultivars is necessary for designing the resource, energy, and C-efficient production systems [35]. The cropping systems involving maize/sorghum/pearl millet had the highest energy outputs with the use of lower energy input. Higher energy productivity of the millet-based production system was due to higher yields of pearl millet/sorghum/maize/sorghum fodder in terms of rice equivalent yield. The key factors responsible for higher energy inputs in the cereal-based production system was due to more energy input in the form of fertilizers, machinery, diesel and weeding [24]. Thus, there is a need to minimize these components in crop management to increase the EUE. In the present investigation, millet-based cropping sequences had lower energy requirement (16353–20405 MJ ha^{-1}) compared to cereal-based cropping systems (30596–53511 MJ ha^{-1}). The diminution in energy input in millet-based cropping system was mostly due to lower fertilizer use and intercultural operations, while intensive tillage in cereal-based cropping increased energy use [36]. The adoption of ZT production system reduced the energy use to some extent, while the use of pesticides augmented the same than that of CT [13]. Thus, the higher biomass of millet-based cropping sequences resulted in higher energy outputs under poor resource availability [37].

4.3. *Carbon budgeting*

4.3.1. *Carbon emission*

The cereal-based cropping system had the highest C-inputs. This might be due to residues added and more fertilizers used [T1 (farmers practice), T2, T4, T10]. Higher C-inputs in ZT production system were due to applied residues (contaiñ44% C-content on a dry weight basis) [25]. Goglio et al. [38] also noted an increased C-input due to retention of crop residues. In cereal-based production systems, fertilization alone contributes ~27.3 [T2] to 51.6% [T3] of C-input, whereas it ranged from 51.8 [T8)] to 69.8% [T7] in millet-based systems (Fig. 8). These differences in C-inputs were due to alteration in existing cropping systems [16]. Generally, fertilizer was the major consumer of C-inputs in cereals as well as in millet-based cropping systems. Among the agronomic management, the maximum shares of C-inputs were noted from residues followed by that from fertilizer and fossil fuel (diesel) [28]. The maximum C-outputs were recorded in T9 due to production of more biomass [12].

Substitution of rice-based cropping system by a millet-based production system significantly reduced carbon input and carbon footprint (CF). Such a trend suggested that CF of crop production largely depended on the ability of crop/cultivars to convert the mineral nutrition into total biomass [16]. These results are in agreement with the view of others who stated that CF of the cereal-based production system can be reduced markedly by the better agronomic management practices and sustainable cropping intensification through the adoption of climate-resilient production systems [14]. In the present study, regardless of crops and cropping systems, fertilizers contributed to the maximum GHG emissions followed by the use of diesel and machinery. Hence, emphasis should be focused on selecting those crop/cultivars for intensification of the existing rice-wheat system, which requires less tillage and fertilizers and has a higher conversion efficiency.

4.3.2. *Carbon use efficiency*

Improvement in EUE and CUE of all crops in diverse production systems have a specific role in environmental sustainability by lowering the C-emission. Higher CE/CSI/CER in millet-based

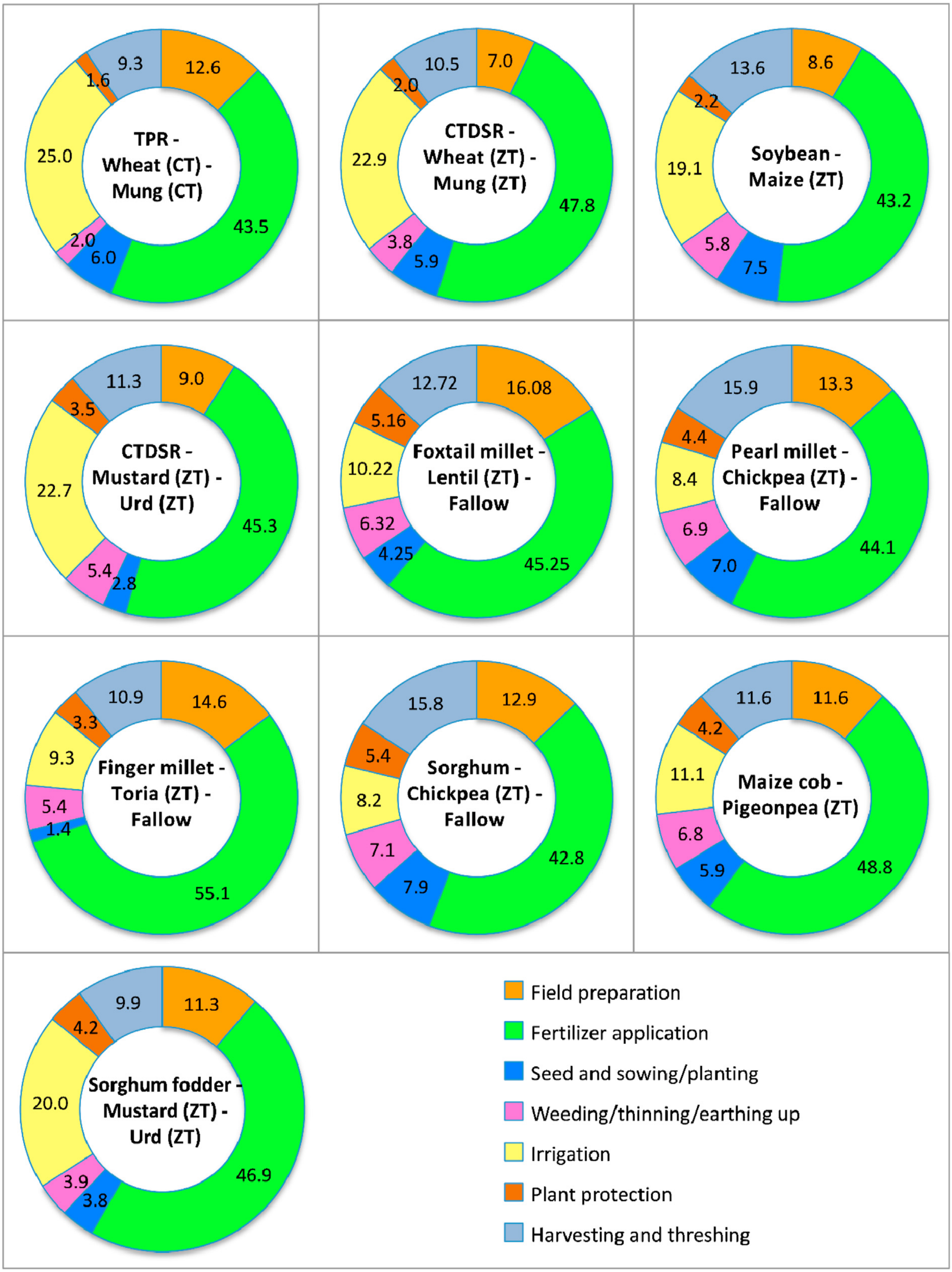

Fig. 6. Share of energy consumption (%) in different agronomic practices of diverse cropping system (average of four years). T1:Transplanted rice–wheat–mungbean (CT) (FP), T2: CTDSR–wheat–mungbean (ZT) T3:Soybean–maize (ZT),T4:CTDSR–mustard–urdbean (ZT), T5:Foxtail millet–lentil (ZT)–fallow,T6: Pearl millet–chickpea (ZT)–fallow, T7: Finger millet–*toria* (ZT)–fallow, T8:Sorghum (Grain)–chickpea (ZT)–fallow, T9:Maize cob–pigeon pea (ZT), T10: Sorghum(F)–mustard–urdbean (ZT); ZT: Zero tollage, CTDSR: Conventional-tilled direct seeded rice, F: Fodder, FP: Farmers practices.

Table 6
Energy input-output relationship of diverse cropping system under the agro-ecosystem of eastern India (average of four years).

Cropping system	System gross energy output (MJ ha^{-1})	System net energy returns (MJ ha^{-1})	System energy ratio	System energy profitability	System energy productivity (kg MJ^{-1} ha^{-1})	System energy intensiveness (MJ US^{-1})	System human energy profitability	System specific energy (MJ kg^{-1})	Nutrient energy use efficiency	Non−renewable energy use efficiency	System energy output efficiency (MJ ha^{-1}days^{-1})
T1:Transplanted rice−wheat −mungbean (CT)	365958^{CD}	312447^{E}	6.84^{H}	5.84^{H}	0.26^{G}	0.36^{A}	83.7^{F}	25.9^{C}	15.8^{E}	9.11^{G}	1099^{E}
T2:CTDSR −wheat (ZT) −mungbean (ZT)	409387^{B}	361984^{D}	8.64^{G}	7.64^{G}	0.33^{F}	0.35^{A}	104.7^{D}	26.3^{BC}	18.1^{E}	11.70^{F}	1233^{D}
T3:Soybean −maize (ZT)	405075^{B}	374479^{CD}	13.24^{E}	12.24^{E}	0.47^{D}	0.30^{BC}	92.7^{EF}	28.1^{B}	30.8^{C}	18.50^{D}	1337^{C}
T4:CTDSR −mustard −urdbean (ZT)	370772^{C}	333900^{E}	10.06^{F}	9.06^{F}	0.41^{E}	0.28^{CD}	176.6^{A}	24.3^{CD}	22.3^{D}	13.49^{E}	1204^{D}
T5:Foxtail millet-lentil −fallow	153699^{E}	137346^{F}	9.40^{FG}	8.40^{FG}	0.43^{DE}	0.27^{D}	53.3^{G}	21.6^{E}	20.9^{D}	12.21^{EF}	596^{G}
T6:Pearl millet −chickpea −fallow	337971^{D}	318163^{E}	17.06^{C}	16.06^{C}	0.53^{C}	0.27^{D}	176.9^{A}	32.1^{A}	39.0^{B}	22.86^{C}	1271^{CD}
T7:Finger millet −*toria*−fallow	173498^{E}	155499^{F}	9.64^{FG}	8.64^{FG}	0.34^{F}	0.31^{B}	51.9^{G}	28.1^{B}	17.7^{E}	11.67^{F}	818^{F}
T8:Sorghum (Grain) −chickpea (ZT)−fallow	411358^{B}	390953^{BC}	20.16^{B}	19.16^{B}	0.60^{B}	0.26^{DE}	98.1^{DE}	33.5^{A}	47.5^{A}	27.56^{B}	1541^{B}
T9:Maize cob −pigeon pea (ZT)	512589^{A}	489922^{A}	22.61^{A}	21.61^{A}	0.92^{A}	0.24^{E}	147.1^{B}	24.5^{CD}	46.6^{A}	31.46^{A}	1786^{A}
T10:Sorghum (F) −mustard −urdbean (ZT)	431625^{B}	402332^{B}	14.73^{D}	13.73^{D}	0.62^{B}	0.27^{D}	123.9^{C}	23.7^{DE}	31.6^{C}	19.59^{D}	1357^{C}

Different letters in continuous column are significantly different at $p < 0.05$ according to Duncan's multiple range test (DMRT, ZT: Zero tollage, CTDSR: Conventional tilled direct seeded rice, F: Fodder.

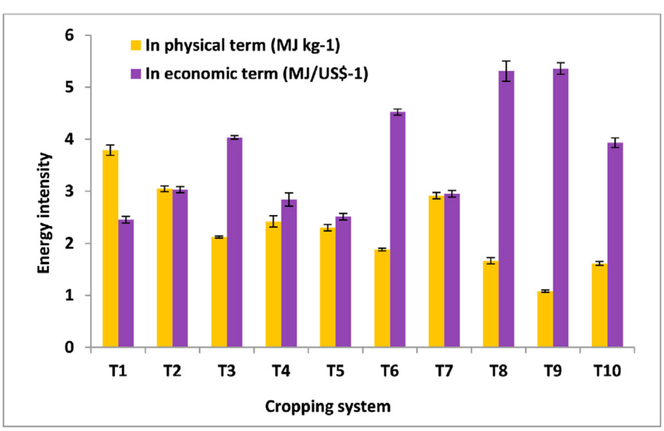

Fig. 7. Energy output intensity in physical and economic terms as influenced by the diverse cropping system (average of four years).

production system [T6 and T8)] is explicated by lower C-input due to lack of residues and the minimal use of inputs (fertilizers/insecticides/pesticides/irrigation). The highest C-footprint noted for treatment T2 (0.40 kg CE kg^{-1} SREY) might be due to the minimum emission of C from fossil fuels [13]. Higher C-input has recorded in residue added plots in ZT compared to that for the control plots. These data are in close agreement with those of Jat et al. [28]. Higher C-input used in the -based production system was due to more application of inorganic fertilizers. Higher values of CE/CSI/CER in millet-based production system were due to lower C-input through crop residues, fertilizer use and fossil fuel (diesel) and production of more C-outputs [16].

Diesel use was the 3rd most significant contributor towards C-emission in the cereal-based production system, but these values ranked 2nd with the adoption of a millet-based cropping system (Table 7 and Fig. 5). The total CE emission was higher in the cereal-based cropping system (262.1–421.2 kg CE ha^{-1}) than that of millet-based production system (159.1–196.6 kg CE ha^{-1}). This gap of GWP among these cropping systems might be due to differences in the amount of diesel used [39]. The minimum tillage has lower GHG emissions than that of conventional production systems [11]. Residues retention increased the C-emission compared to non-residues added plots. This increase in GWP was due to added N-rich crop residues [38]. The cereal-based cropping system had higher CFs (0.32–0.40 CE kg Mg^{-1} SREY) than that to the millet-based production system. Millet-based cropping system required lower C-input (913.7–1236.7 kg CE ha^{-1}) and had C-output at par (13935 kg CE ha^{-1}) to those of the cereal-based cropping systems. These results from the present experimentation are in close agreement to those reported by Choudhary et al. [13]. The marked effects of crop establishment and tillage practices on CE/CSI were reported by other researchers [40]. Crop residue retention/mulching on soil enhanced C-output and CE/CSI [39]. In the perspective of the climatic change scenario and human-induced emission, the viability of the diverse cropping system is based on C-efficiency [25]. Thus, conversion from the rice-based production system to

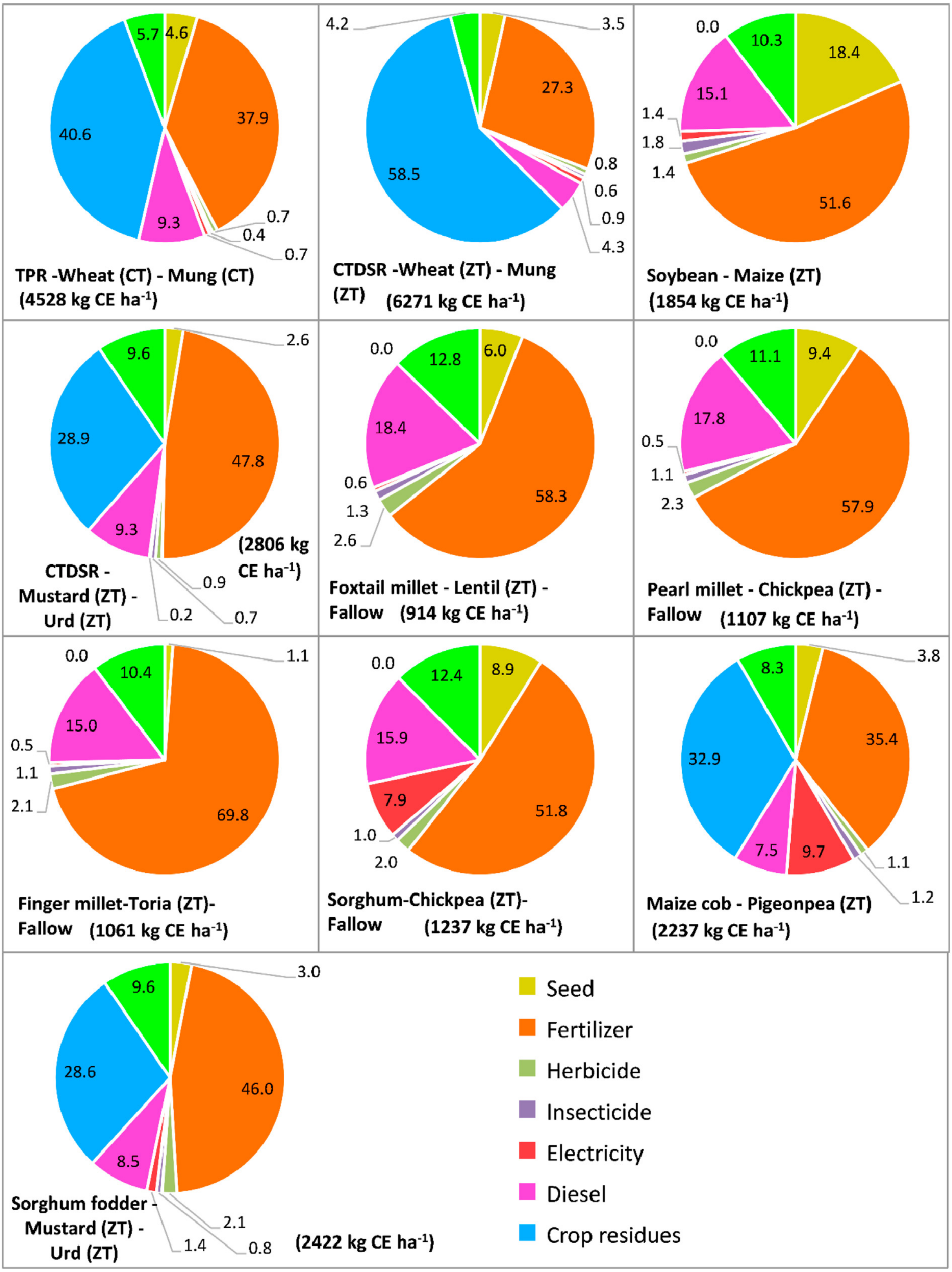

Fig. 8. Share of the various inputs towards carbon footprints of different cropping system (average of four years). CE1: total carbon input; CE2: total C-outputs; CE3: C-efficiency; CE4: CSI; CE5: C-foot print; CE6: CER; SGEO: system gross energy output, SNER: system net energy returns, SER: system energy ratio, SEPF: system energy profitability, SEPD: system energy productivity, SEI: system energy intensiveness, SHEP: system human energy profitability, SSE: system specific energy, SEOE: system energy output efficiency.

Table 7
Carbon consumption or equivalent carbon emission and carbon output (kg CE ha^{-1}), carbon efficiency and carbon footprint (kg CE kg^{-1} SREY) as influenced by different cropping system (average of four years).

Inputs	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Seeds	207.4	219.6	341.6	73.2	54.9	103.7	12.2	109.8	85.4	73.2
Fertilizers	1714.3	1714.3	955.9	1340.1	532.8	640.7	740.9	640.7	791.7	1114.7
Herbicides	32.8	47.6	25.2	25.2	23.6	25.2	22.1	25.2	25.2	50.4
Insecticides	20.25	35.20	32.60	20.19	12.08	12.61	11.90	12.61	27.37	18.35
Electricity	33.67	54.40	25.90	5.18	5.18	5.18	5.18	97.89	216.3	33.67
Diesel	421.2	271.4	280.8	262.1	168.5	196.6	159.1	196.6	168.5	205.9
Crop residues	1840	3668	–	811	–	–	–	–	736	694
Human labour	258.0	260.5	191.8	269.2	116.6	123	110.1	153.9	186.6	232.2
Parameters										
Total carbon input	4528	6271	1854	2806	914	1107	1062	1237	2237	2422
Total carbon output	12060	13856	12386	11691	5126	11422	5315	13935	17200	14608
Carbon efficiency	2.66	2.21	6.68	4.17	5.61	10.32	5.01	11.27	7.69	6.03
Carbon sustainability index	1.66	1.21	5.68	3.17	4.61	9.32	4.01	10.27	6.69	5.03
Carbon foot print	0.32	0.40	0.13	0.18	0.13	0.11	0.17	0.10	0.11	0.13
Carbon efficiency ratio	2.36	1.86	6.97	3.17	4.02	5.58	2.89	5.37	4.65	8.85

T1: Transplanted rice–wheat–mungbean (CT) (FP), T2: CTDSR–wheat–mungbean (ZT), T3: Soybean–maize (ZT), T4:CTDSR–mustard–urdbean (ZT), T5:Foxtail millet–lentil (ZT)–fallow,T6: Pearl millet–chickpea (ZT)–fallow, T7: Finger millet–*toria* (ZT)–fallow, T8: Sorghum (Grain)–chickpea (ZT)–fallow, T9: Maize cob–pigeon pea (ZT), T10:Sorghum (F)–mustard–urdbean (ZT), ZT: Zero tollage, CTDSR: Conventional-tilled direct seeded rice, F: Fodder, FP: Farmers practice.

Table 8
Economics as influenced by of diverse cropping system under the agro-ecosystem of eastern India (average of four years).

Cropping system	COC (US$ ha^{-1})			SCOC (US$ ha^{-1})	Gross returns (US$ ha^{-1})			SGR (US$ ha^{-1})	Net returns (US$ ha^{-1})			SNR (US$ ha^{-1})	SBCR
	Rainy	Winter	Summer		Rainy	Winter	Summer		Rainy	Winter	Summer		
T1:Transplanted rice–wheat–mungbean (CT)	842	668	570	2080	1148^{D}	1425^{E}	970^{A}	3542^{C}	305^{F}	757^{G}	400^{A}	1463^{E}	1.70^{F}
T2:CTDSR–wheat (ZT)–mungbean (ZT)	797	565	520	1882	1260^{C}	1520DE	817^{C}	3597^{C}	463DE	955^{E}	296^{C}	1715^{D}	1.91^{E}
T3:Soybean–maize (ZT)	448	952	–	1400	930^{E}	2278^{A}	–	3208^{D}	482DE	1326^{B}	–	1808^{CD}	2.29^{C}
T4:CTDSR–mustard–urdbean (ZT)	797	535	488	1820	1239^{CD}	1618^{CD}	858^{B}	3715^{C}	441^{E}	1083^{E}	370^{B}	1894^{C}	2.04^{DE}
T5:Foxtail millet-lentil–fallow	420	434	–	854	485^{F}	1394^{E}	–	1879^{F}	65^{G}	960^{E}	–	1025^{F}	2.20^{CD}
T6:Pearl millet–chickpea–fallow	505	536	–	1041	1032^{E}	1702^{BC}	–	2734^{E}	526^{D}	1166^{CD}	–	1692^{D}	2.62^{B}
T7:Finger millet–*toria*–fallow	431	389	–	820	481^{F}	839^{F}	–	1320^{G}	50^{G}	450^{H}	–	500^{G}	1.61^{F}
T8:Sorghum (Grain)–chickpea (ZT) –Fallow	544	536	–	1080	1200^{CD}	1783^{B}	–	2983DE	656^{C}	1247^{BC}	–	1903^{C}	2.76^{B}
T9:Maize cob–pigeon pea (ZT)	721	612	–	1334	2708^{A}	2290^{A}	–	4998^{A}	1987^{A}	1677^{A}	–	3665^{A}	3.75^{A}
T10:Sorghum (F)–mustard –urdbean (ZT)	506	535	488	1529	2100^{E}	1391^{E}	575^{D}	4066^{B}	1594^{B}	856^{F}	87^{D}	2537^{B}	2.66^{B}

Different letters in continuous column are significantly different at $p < 0.05$ according to Duncan's multiple range test (DMRT), COC: Cost of cultivation, SCOC: System cost of cultivation, SGR: system gross returns, SNR: system net returns, SBCR: system benefit: cost ratio, ZT: Zero tillage, CT DSR: Conventional-tilled direct seeded rice; F: Fodder.

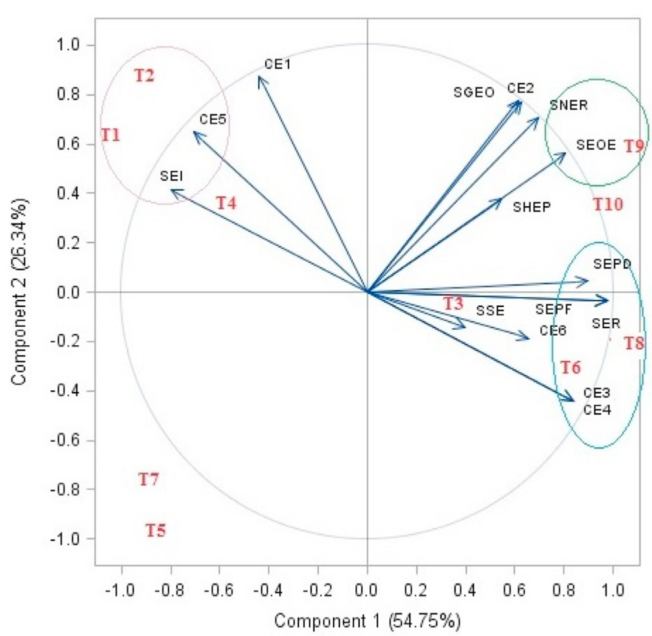

Fig. 9. Bi-plot relationship of C-auditing and energetic budgeting variables of diverse cropping system (average of four years).

millet-based cropping diminishes the fossil fuel use and improves environmental sustainability. Hence, the adoption and promotion of a millet-based production system saves the energy, improves the EUE, reduces the C-footprints, and maintains the equilibrium of food, nutritional security, and environmental sustainability issues in the IGP of South Asia. The Bi-plot PCA analysis also confirmed that a millet-based production system (T6 and T7) is highly correlated with C-auditing attributes (CE, CSI, C-footprints) and energetic variables (energy ratio, energy profitability, energy productivity) (Fig. 9). Similar results were also reported by Kumar et al. [41].

4.4. Economics

Net returns are the main evaluation tool to assess the effectiveness of enterprises, management options, and production economics [32]. The 4-year mean expenditure incurred on the cereal-based production sequences was higher and could be attributed to excessive tillage operation, and high use of fertilizers, irrigation, and human labours (Table 8). Comparatively lower B: C ratio in the cereal-based production system was due to lower returns and higher expenditure involved per unit production [41]. Thus, higher net returns in millet-based cropping system in the present investigation suggest that these alternative production systems are highly remunerative due to lower investment and at par economic yields in terms of rice equivalent yield to the cereal-based production system. Therefore, the efficient use of the natural resources (energy, water, labour) with the adoption of the millet-based production system in the diverse agro-ecosystem are feasible and viable options for improving the productivity, profitability and provides a cleaner/safer environment to the resource-poor farmers of the region [21].

Although the millet-based production systems have been proved to be highly efficient in terms of system productivity, profitability, energy ratio, reducing C-footprints and GHG emission; their adoption and substitution for rice-wheat cropping system with millets is a difficult task in eastern IGP due to the fact that rice and wheat have become a major food staple. However, with the increase in temperature and rainfall variability, there is a need to identify and target the areas suitable for the millet-based production systems. Being rich in nutrients and dietary fibres, millets needs to be promoted as nutri-cereals in the diets of rural poor. The Government policies should be changed in favour of millet-based production systems for wider adoption.

5. Conclusion

The dominant rice-wheat cropping system is intensively cultivating in the Indo-Gangetic Plains zone of South Asia, it is an energy and C-intensive zone for rice-based cropping systems, there is an urgent need to deigns more efficient production systems, which are more productive, climate-resilient, C-and energy-efficient, and environmentally sustainable. This study has designed as a more productive, energy-cum-C-efficient production system that promote the profitability and environmentally safer production system for upland rainfed as well as irrigated ecosystems of India and South Asia.

The major findings of the study are summarized as follows:

1. The adoption of a millet-based production system reduced energy consumption, C-input, C-footprint, and enhance the energy use efficiency by 84, 172, 58, and 61%, respectively, in comparison to cereal-based cropping systems.
2. The inclusion of millets in the existing system also improved the energy productivity, system productivity, and economic efficiency under the diverse agro-ecological zone of eastern India.
3. The fertilizer, a non-renewable energy input, was responsible for the major share of the total energy input (42−55%) followed by diesel used for machinery during agricultural operations (12−21%) for all the diverse cropping systems.
4. The nutrient and non-renewable energy use efficiencies were 55.8 and 58.3% higher, respectively, in the millet-based produce than those for the cereal-based cropping systems.

Hence, the existing rice-wheat cropping system may be diversified with the substitution of climate-resilient millet-based production systems, which are more productive, resource use-efficient, energy-cum-carbon-efficient, and low emitter of GHGs. The information generated from this study would enhance the knowledge and strengthen the database of policymakers and researchers for promoting safer, cleaner, sustainable as well as productive climate-resilient cropping systems in the Indo-Gangetic Plains of South Asia to achieve the 'Sustainable Development Goals'.

Authorship contribution statement

Rakesh Kumar: Conceptualization, Methodology. J.S. Mishra: Conceptualization, Methodology. Surajit Mondal: Conceptualization, Methodology. Ram Swaroop Meena: Formal analysis, Writing. P. K. Sundaram: Writing - original draft. B. P. Bhatt: Writing - review & editing. R. S. Pan: Writing - original draft. Rattan Lal: Review and editing. Kirti Saurabh: Writing - original draft. Naresh Chandra: Formal analysis, Writing. S. K. Samal: Formal analysis, Writing. Hansraj Hans: Review and editing. R. K. Raman: Writing - review & editing.

Declaration of competing interest

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

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Abbreviations

ANOVA	Analysis of variance
BCR	Benefit cost ratio
BHU	Banaras Hindu University
C	Carbon
CE	Carbon efficiency
CE	Carbon equivalent
CER	Carbon efficiency ratio
CF	Carbon footprint
CFy	Yield scaled carbon footprint
CH_4	Methane
CO	Carbon mono-oxide
CO_2	Carbon di-oxide
CO_2-e	Carbon dioxide equivalent
CRBD	Completely randomized block design
CSI	Carbon sustainability index
CT	Conventional tillage
CTDSR	Conventional till-direct seeded rice
DAS	Days after sowing
DAT	Days after transplanting
EI	Energy input
EOP	Energy output
EP	Energy productivity
EUE	Energy use efficiency
FAO	Food and Agriculture Organization
GHG	Greenhouse gases
GOI	Government of India
GR	Gross returns
GWP	Global warming potential
IGP	Indo-Gangetic Plain
MSL	Mean sea level
MSP	Minimum support prices
N_2O	Nitrous oxide
NE	Net energy
NR	Net returns
NT	No-tillage
PE	Pre-emergence
POE	Post-emergence
QPM	Quality protein maize

RCER	Research Complex for Eastern Region
REY	Rice equivalent yield
RT	Reduced tillage
RWCS	Rice—wheat cropping system
SAS	SDGs Statistical Analysis System Sustainable development goals
SE	Specific energy
SO_2	Sulphur dioxide
SOC	Soil organic carbon
SOM	Soil organic matter
SP	System productivity
SPE	System production efficiency
SREY	System rice equivalent yield
TVC	Total variable cost
ZT	Zero tillage

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