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# Energy budgeting and carbon footprint of pearl millet – mustard cropping system under conventional and conservation agriculture in rainfed semi-arid agro-ecosystem

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A B S T R A C T

Modern agricultural systems are energy and carbon intensive. Reducing the carbon footprint and increasing energy use efficiency are two important sustainability issues of the modern agriculture. Realizing the implications of energy and carbon use, the present study was conducted to compare pearl millet–mustard production system in conventional and conservation agriculture practices. The results showed that zero tillage with 4 t ha$^{-1}$ crop residue increased grain yield of pearl millet and mustard by 22.3 and 24.5% respectively in comparison to conventional tillage without residue which ultimately helped to maintain higher net returns (1270 US$ ha$^{-1}$). Mulching of crop residue consumed considerable energy and carbon. It comprised 72.3–87.1% of the total energy consumption. Thick residue cover (4 t ha$^{-1}$) noticed significantly higher energy output and energy intensiveness in both conventional and zero tillage whereas energy-use efficiency (11.5), net energy return (201,977 MJ ha$^{-1}$) and energy productivity (0.32 kg MJ$^{-1}$) was highest under no-residue cover. Carbon foot print value was increased with intensity of residue cover and found least under no-residue treatment. Therefore, crop residue should be judiciously used in arid and semi-arid region where livestock mainly depends on it for their fodder requirement.

## 1. Introduction

Energy, economics, and the environment are mutually dependent [1]. There is a close relationship between agriculture and energy. While agriculture uses energy, it also supplies it in the form of bio-energy [2]. At the present time, the productivity and profitability of crop production depend upon energy consumption. The amount of energy used depends on the mechanization level, quantity of active agricultural work and cultivable land [2,3]. In all production systems, increasing the productivity ratio is a main concern. Energy input–output relationships in cropping systems vary with the crops grown in a sequence, type of soils, type of tillage operations, nature and amount of organic manure and chemical fertilizers, plant protection measures, harvesting and threshing operations, yield levels, and biomass production [4,5]. Modernization is, in general, tied with increasing inputs of energy and carbon in crop production. The energy and carbon use efficiencies are declining [6]. As energy and carbon inputs in agriculture rapidly increased and accrued several benefits to farmers, at the same time, these also adversely influence the environment [7] by deteriorating water and land resources, contributing to global warming through increased GHGs emissions [8]. Increasing GHGs concentration is causing weather fluctuations which ultimately reducing agricultural productivity [9].

Conventional agriculture has largely been characterized by tillage which leaves soil vulnerable to erosion [10]. The objectives of tillage include, soil loosening and levelling for seed bed preparation, mixing fertilizer into soil, weed control, and crop residue management [11]. Tillage helps to modify soil physical, chemical and biological properties [12–14], which improves conditions for crop growth by enhancing the availability of nutrients [15], resulting in higher crop yields [16]. Zero tillage (ZT) is the major component of conservation agriculture (CA), requires less fuel resulting in lower CO$_2$ emissions, one of the gas responsible for

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global warming [17]. Crop yield potential with CA in rainfed systems is often greater than with conventional tillage (CT) systems, particularly where sub-optimal rainfall limits crop yields [18]. Use of crop residue as mulch is a viable approach to retain soil moisture and nutrients under such situations because mulch is considered as poor conductor of heat that effectively moderates soil temperature, maintains soil profile moisture and increases soil fertility [13,19]. In spite of these advantages, crop residue as mulch is not being used by farmers as it has competing uses like fodder in rainfed areas because of dominance of livestock [20]. Further, costs are also involved in their application. Therefore, it is necessary that suitable amount should be applied to enhance crop productivity in a cost-effective manner.

Pearl millet–mustard has been most important cropping system of arid and semi-arid regions of Indian sub-continent and Africa. Pearl millet (*Pennisetum glaucum* L.) is a staple diet for the vast majority of poor farmers and also forms an important fodder crop for livestock population in arid and semi-arid regions of the globe [21]. From quality point of view, it is nutritionally better than many cereals, as it is a good source of iron, protein and fat [22]. This crop is mostly confined to low fertile water deficit soils. Because of its remarkable ability to withstand and grow in harsh environment, reasonable and nearly assured harvests are obtained. Therefore, it is getting more attention due to increasing evidence of erratic seasonal rainfall, terminal heat, and frequent occurrence of extreme weather events coupled with scanty water resources [23]. Mustard [*Brassica juncea* (L.) Czern and Coss.] is an important oilseed crop, cultivated for edible oil but used as condiments, spices, leafy vegetable and as fodder for livestock. Generally mustard cultivation is dependent on the residual soil moisture from previous monsoon season. Such residual moisture quickly dries up with mustard growth that caused limitation of soil moisture during reproductive stage which is one of the major causes for the poor yield of mustard [24].

The enhanced energy and carbon use efficiencies in crops and cropping systems have definite role in overall environmental sustainability in terms of lowering carbon foot print values. However, the information on the energy and carbon budgeting of pearl millet–mustard cropping system under conservation agriculture practices is very limited in India as well as in other semi-arid tropics of Asia and Africa. Therefore, the present experiment was planned to study energy and carbon use in pearl millet–mustard cropping system under conventional and conservation agriculture practices. This paper identifies key farm operations, budgets farm resources used in pearl millet—mustard cropping system and compares energy and carbon efficiencies through energy and carbon indicators.

## 2. Materials and methods

### 2.1. Study site and climate

A field experiment was conducted during 2013–2015 at the Indian Agricultural Research Institute, New Delhi, situated at 28°38′N latitude and 77°09′ E longitude at an altitude of about 228.6 m above mean sea level (Arabian Sea). The region has a semi-arid climate with hot dry summers and severe cold winters. It received an average (mean of last 30 years) annual rainfall of 652 mm (70–80% of which received during July–September) with the mean annual evaporation of 850 mm. Rainfall received during the experimental period is depicted in Fig. 1. The soil (Typic Haplustept, Inceptisol) was sandy loam (65.3% sand, 15.0% silt and 19.7% clay) in texture having pH 7.8, EC 0.31 dS $m^{-1}$, 4.5 g organic carbon $kg^{-1}$ soil, 62.3 mg $KMnO_4$ oxidizable N $kg^{-1}$ soil, 6.8 mg 0.5 N $NaHCO_3$ extractable P $kg^{-1}$ soil and 79.8 mg 1.0 N $NH_4OAc$ exchangeable K $kg^{-1}$ soil in the top 15 cm soil.

### 2.2. Experimental details

The experiment was laid out in randomized complete block design with three replications. The treatment consisted of five tillage and crop residue management practices *viz.* conventional tillage without crop residue (CT-CR0), CT with 2 and 4 t $ha^{-1}$ residue (CT-CR2 and CT-CR4), zero tillage with 2 and 4 t $ha^{-1}$ residue (ZT-CR2 and ZT-CR4). The plot size was 20.0 m × 3.6 m and was fixed throughout the experimentation. The CT involved one ploughing with disc plough followed by two pass of disc harrow and planking in the last to have a uniform seed bed of fine tilth. In ZT, crops seeds were direct drilled using ZT planter. The technical properties of tillage implements is provided in Supplementary Table 1. Residues of previous season crop (mustard and pearl millet) were applied in succeeding crop by spreading the material uniformly on the field just after sowing as mulch to reduce evaporation of moisture from soil surface.

### 2.3. Crop establishment and management

Pearl millet composite variety ‘Pusa-443’ was sown with seed rate of 5 kg $ha^{-1}$ during first fortnight of July. The pearl millet crop was harvested in the first fortnight of October in both the years. The mustard (‘Pusa Mustard-28’) was sown with a seed rate of 5 kg $ha^{-1}$ in the second fortnight of October at a row spacing of 0.45 m in the same field. Pearl millet received a common fertilizer dose of 60 kg N + 60 kg $P_2O_5$ + 30 kg $K_2O$ per hectare and mustard was fertilized with 80 kg N + 40 kg $P_2O_5$ + 30 kg $K_2O$ per hectare. In both the seasons, 2/3rd N and whole phosphorus and potassium were applied as basal at sowing, while remaining 1/3rd N was top dressed by broadcasting urea at 25–40 days after sowing depending on soil moisture. For managing weeds, Glyphosate 41 SL was sprayed @ 2.0 L $ha^{-1}$ in the ZT plots about 7–10 days before sowing of each crop. However, Atrazine 50 WP @ 1.0 kg $ha^{-1}$ as pre-emergence (PE) in pearl millet and Pendimethalin 30 EC @ 2.5 kg $ha^{-1}$ as PE in mustard were also applied uniformly. In addition to chemical weed management, one hand weeding was also done in all the conventional tilled plots at 25–35 days after sowing. Pearl millet crop was raised as rainfed and subsequent mustard crop on conserved soil moisture. Pearl millet and mustard were harvested manually in first fortnight of October and March, respectively in both the years. The cultural practices adopted is given in Supplementary Table 2.

### 2.4. Energy input-output relationship

The energy inputs include both operational (direct) and non-operational (indirect) energy. Operational energy comprised manual work, fuel, machinery, etc., whereas non-operational energy consisted of seed, manure, and chemical fertilizers and pesticides. The primary data on various inputs and management practices were used for computation of energy consumption on the basis of energy. Energy output from the product (grain and stover) was calculated by multiplying the amount of production and its corresponding energy equivalent as given in Table 1. The energy use indices were calculated as per the procedure given by Devasenapathy et al. [25] and Mittal and Dhawan [26].

$$\begin{aligned}\text{Net Energy} &= \text{Energy output}\left(\text{MJ ha}^{-1}\right)\\ &\quad - \text{Energy input}\left(\text{MJ ha}^{-1}\right)\end{aligned}$$

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

$$\text{Energy productivity} = \text{Economic yield}\left(\text{t ha}^{-1}\right)/\text{Energy input}\left(\text{MJ ha}^{-1}\right)$$

$$\text{Energy intensiveness} = \text{Energy input}\left(\text{MJ ha}^{-1}\right)/\text{Total cost}\left(\text{US\$ ha}^{-1}\right)$$

### 2.5. *Carbon budgeting*

Carbon equivalent (CE) was estimated by multiplying the input (diesel, chemical fertilizer and pesticides) with its corresponding emission coefficient as given by Lal [8] and West and Marland [29]. However the emission coefficient for each individual pesticide and herbicide are unavailable, so it was assumed that the emission during the processes of production, transportation, storage, and field application are same for the pesticides within a class [8]. Total carbon input and output were calculated as the sum of the carbon equivalent of all inputs and outputs of crop production.

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

*Plant biomass contains on an average 44% carbon content as given by Lal [8].

$$\text{Carbon efficiency} = \text{Carbon output/carbon input}$$

The carbon footprint of crop production was calculated as per the methodologies given by Ma et al. [30].

Carbon footprint (kg CE $\text{kg}^{-1}$ grain) = Total carbon emission or input (kg CE $\text{ha}^{-1}$)/pearl millet equivalent yield (kg $\text{ha}^{-1}$)

### 2.6. *Economic analysis*

The economic analysis was done by considering the variable production costs only. The variable costs included human labour, use of machinery (tractor, plough, planter etc.), the input cost (seed, fertilizer and pesticide), harvesting and threshing. The production cost however did not include the value of the land. Net returns (NR) were calculated by deducting the total cost (TC) from gross returns (GR) (NR = GR−TC). Benefit to cost (B:C) ratio was calculated by dividing net returns by total cost (B:C= NR/TC).

### 2.7. *Statistical analysis*

All the data were subjected to analysis of variance (ANOVA) using the general linear model procedures of the Statistical Analysis System (SAS Institute, Cary, NC). The F-test was used to determine significant effects of the tillage systems and least significant difference (LSD) was used to compare means.

**Table 1**
Energy equivalent of inputs and outputs in agricultural operations used in the study.

| S. No. | Particulars | Units | Equivalent Energy (MJ) | Reference |
|---|---|---|---|---|
| *A.* | *Input* | | | |
| 1. | Machinery | | | |
| | a) Electric motor | kg | 64.8 | [25] |
| | b) Farm machinery excluding self-propelled machines | kg | 62.7 | [25,27] |
| 2. | Diesel | litre | 56.31 | [25,27] |
| 3. | Irrigation water | $m^3$ | 1.02 | [25] |
| 4. | Electricity | KWh | 11.93 | [25] |
| 5. | Human power | man-hour | 1.96 | [25] |
| 6. | Fertilizer | | | |
| | a) Nitrogen (N) | kg | 60.60 | [25] |
| | b) Phosphate ($P_2O_5$) | kg | 11.10 | [25] |
| | c) Potash ($K_2O$) | kg | 6.70 | [25] |
| | d) Gypsum | kg | 10.0 | [25] |
| 7. | Superior chemical | kg | 120 | [25] |
| *B.* | *Output* | | | |
| 1. | Seed/grain | | | |
| | a) Pearl millet | kg | 14.7 | [25,28] |
| | b) Mustard | kg | 25.0 | [25,28] |
| 2. | Stover/stalk | kg | 12.5 | [25] |

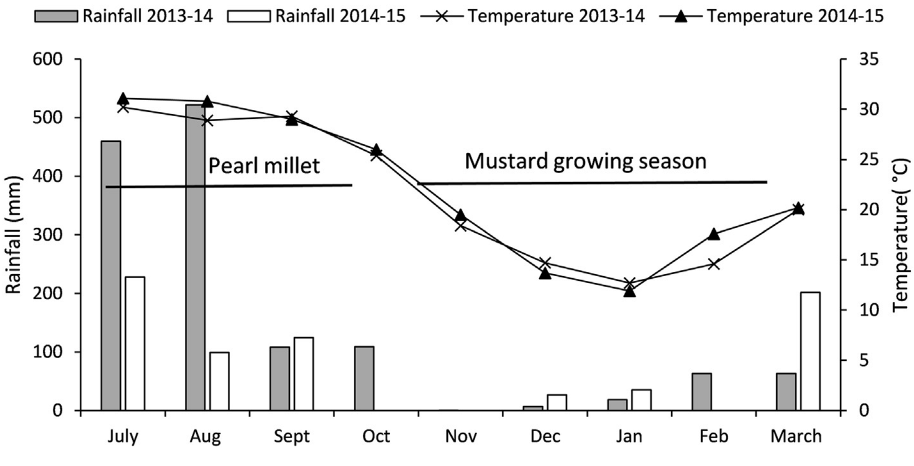

**Fig. 1.** Monthly rainfall and mean temperature during crop growing season.
Source: Agromet Observatory, Division of Agricultural Physics, IARI, New Delhi.

## 3. Results

### 3.1. Crop productivity

The different tillage practices had significant ($P < 0.05$) effect on mean pearl millet grain, stover and biomass yields (Table 2) and was recorded highest in CT-CR4 (2302, 7589 and 9891 kg $ha^{-1}$, respectively). The grain, stover and biomass yield with CT-CR4 were increased significantly by 24.6, 16.5 and 18.3% compared to CT-CR0, respectively. Application of higher level of residue (4 t $ha^{-1}$) had significant ($P < 0.05$) effect on grain yield under both the tillage system. However, at same residue level, CT yielded at par with ZT.

Based on the analysis of variance, mustard yield values were found to be different in different tillage systems at the 5% level of significance (Table 2). ZT-CR4 had the highest yields, with a mean seed yield of 2184 kg $ha^{-1}$, by-product mean of 6900 kg $ha^{-1}$ and mean biomass yield of 9084 kg $ha^{-1}$. The lowest yield (1754 kg seed yield, 5504 kg by-product yield and 7258 kg biomass yield $ha^{-1}$) was observed in CT-CR0. Furthermore, seed yield of mustard was significantly ($P < 0.05$) higher by 9.1% in ZT and 10.1% in CT planting with thick residue cover (4 t $ha^{-1}$) compared to low residue (2 t $ha^{-1}$). However, irrespective of mulching intensity conventional tilled plots yielded at par with ZT.

### 3.2. Energy use pattern

The source and operation-wise energy use pattern were computed for pearl millet–mustard cropping system (Figs. 2 and 3). The mean total energy of 77,613 MJ $ha^{-1}$ was consumed in the cropping system. Overall, renewable energy through crop residues contributed highest input energy followed by non-renewable resources viz. diesel, fertilizers, chemicals and machineries. Contributions of renewable and non-renewable energy sources in the system were about 79% and 21%, respectively. Diesel and electricity are direct non-renewable energy sources, contributed about 6.0%. Of the inputs for the different operations, mulching of crop residue consumed the bulk of the energy in all tillage practices in pearl millet-mustard cropping system (Table 3). It comprised 72.3–87.1% of the total energy consumption. Furthermore, fertilizer application was the second major input that accounted for around 52.6% of total energy in no residue plots to 8.5% in CT-CR4. Field preparation also consumed a considerable amount of energy. The energy consumed for field preparation in conventional tilled plots were 4662 MJ $ha^{-1}$, however no-energy consumed in ZT plots for this operation. Among various tillage practices total energy requirement was the highest for CT-CR4 (119,413 MJ $ha^{-1}$), followed by ZT-CR4 (115,074 MJ $ha^{-1}$) > CT-CR2 (69,349 MJ $ha^{-1}$) > ZT-CR2 (65,010 MJ $ha^{-1}$) > CT-CR0 (19,225 MJ $ha^{-1}$) tillage practices.

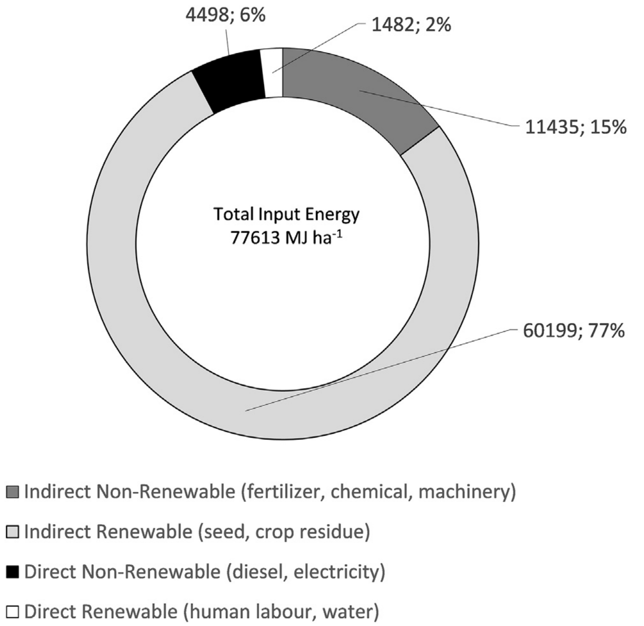

**Fig. 2.** Renewable and non-renewable input energy (MJ $ha^{-1}$) in pearl millet – mustard cropping system irrespective of different treatments.

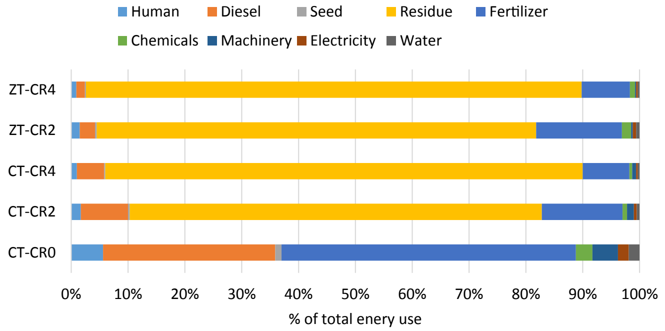

**Fig. 3.** Source-wise energy use pattern in pearl millet – mustard cropping system under different tillage and crop residue management practices (average of two years).

### 3.3. Energy input-output relationship

On an average, the highest amount of energy was accumulated in the biomass of mustard (126.6 GJ $ha^{-1}$), where 39% of the energy is accumulated in seeds and 61% in straw (Fig. 4). However the energy accumulated in seeds of pearl millet was 25.7% and rest in straw. The total cropping system output bio-energy produced by pearl millet – mustard rotation ranged from 221,200 MJ $ha^{-1}$ (CT-CR0) to as high as 268,817 MJ $ha^{-1}$ (ZT-CR4) (Table 4). Conventional tillage without residue produced significantly least energy output (221,200 MJ $ha^{-1}$) and energy intensiveness (31 MJ US$^{-1}$) however energy-use efficiency (11.5), net energy return (201,977 MJ $ha^{-1}$)

**Table 2**
Yield of pearl millet and mustard crop under different tillage and residue management practices (average of two years).

| Treatment[a] | Grain yield (kg $ha^{-1}$) | | By-product yield (kg $ha^{-1}$) | | Biomass yield (kg $ha^{-1}$) | |
|---|---|---|---|---|---|---|
| | Pearl millet | Mustard | Pearl millet | Mustard | Pearl millet | Mustard |
| CT–CR0 | $1848^{d}$ | $1754^{d}$ | $6511^{b}$ | $5504^{c}$ | $8359^{b}$ | $7258^{c}$ |
| CT–CR2 | $2110^{bc}$ | $1890^{d}$ | $7196^{a}$ | $5918^{bc}$ | $9306^{a}$ | $7808^{bc}$ |
| CT–CR4 | $2302^{a}$ | $2062^{b}$ | $7589^{a}$ | $6362^{ab}$ | $9891^{a}$ | $8424^{ab}$ |
| ZT–CR2 | $2079^{c}$ | $1984^{bc}$ | $7082^{ab}$ | $6222^{b}$ | $9161^{a}$ | $8206^{b}$ |
| ZT–CR4 | $2261^{ab}$ | $2184^{a}$ | $7578^{a}$ | $6900^{a}$ | $9839^{a}$ | $9084^{a}$ |

Means followed by a superscripted similar lowercase letter within a column are not significantly different (at $P < 0.05$) according to LSD test.
[a] CT– conventional tillage; ZT– zero tillage; CR0– no crop residue; CR2– crop residue at 2 t $ha^{-1}$; CR4– crop residue at 4 t $ha^{-1}$

**Table 3**
Energy consumption (MJ ha$^{-1}$) in different agronomic practices for pearl millet-mustard cropping system under different tillage practices (average of two years)[a].

| Agronomic practices | CT–CR0[b] | CT–CR2 | CT–CR4 | ZT–CR2 | ZT–CR4 |
|---|---|---|---|---|---|
| Field preparation | 4662 (24.2) | 4662 (6.7) | 4662 (3.9) | 0 (0.0) | 0 (0.0) |
| Fertilizer application | 10,174 (52.9) | 10,174 (14.7) | 10,174 (8.5) | 10,174 (15.6) | 10,174 (8.8) |
| Seed and Sowing | 1524 (7.9) | 1524 (2.2) | 1524 (1.3) | 1524 (2.3) | 1524 (1.3) |
| Weeding and thinning | 802 (4.2) | 802 (1.2) | 802 (0.7) | 1125 (1.7) | 1125 (1.0) |
| Mulching | 0 (0.0) | 50,124 (72.3) | 100,188 (83.9) | 50,124 (77.1) | 100,188 (87.1) |
| Irrigation | 739 (3.8) | 739 (1.1) | 739 (0.6) | 739 (1.1) | 739 (0.6) |
| Plant protection | 154 (0.8) | 154 (0.2) | 154 (0.1) | 154 (0.2) | 154 (0.1) |
| Harvesting and threshing | 1170 (6.1) | 1170 (1.7) | 1170 (1.8) | 1170 (1.8) | 1170 (1.0) |
| Total | 19,225 (100) | 69,349 (100) | 119,413 (100) | 65,010 (100) | 115,074 (100) |

[a] Figures in the parentheses are the percentage contribution of input energy for each agronomic practice.
[b] CT– conventional tillage; ZT– zero tillage; CR0– no crop residue; CR2– crop residue at 2 t ha$^{-1}$; CR4– crop residue at 4 t ha$^{-1}$

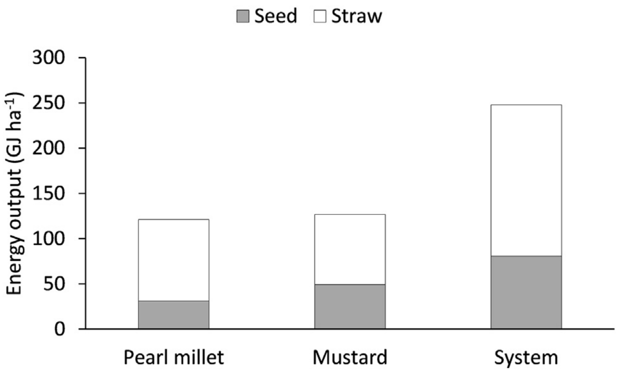

**Fig. 4.** Energy output value (GJ ha$^{-1}$) of the biomass yield of pearl millet and mustard cropping system (average of two years).

and energy productivity (0.32 kg MJ$^{-1}$) was highest in this treatment. Thick residue cover (4 t ha$^{-1}$) noticed significantly higher energy output and energy intensiveness in both the tillage systems.

### 3.4. *Carbon budgeting*

Among the various conservation agriculture practices, fertilizers consumed 61.4% of the total carbon input in no-residue conventionally tilled plots (Table 5). Whereas, its contribution in residue applied plots ranged from 5.4 to 10.1%. The residue used as mulch consumed bulk of carbon (83.9–92.5% of total carbon input) in different tillage practices. Diesel used in field preparation, sowing and threshing activities also consumed the considerable amount of the total carbon input (95.4 kg CE in CT plots and 29.6 kg CE ha$^{-1}$ in ZT plots). The highest carbon consumption was recorded in CT-CR4 (3857 kg CE ha$^{-1}$) followed by ZT-CR4 (3806 kg CE ha$^{-1}$). Least amount of carbon (337 kg CE ha$^{-1}$) was consumed in CT-CR0 than that of consumed by other tillage practices. Surprisingly, 6–12 times increase in the carbon consumption was observed in residue applied plots. Among all the tillage practices, ZT-CR4 maintained significantly the highest carbon outputs (8326 kg CE ha$^{-1}$) followed by CT-CR4 > ZT-CR2 > CT-CR2 > CT-CR0. Unlike, CT-CR0 maintained significantly the highest carbon efficiency (20.4) and the least carbon footprint (0.05 kg CE kg$^{-1}$ grain of pearl millet). CT-CR4 maintained the least carbon efficiency (2.1) and highest carbon footprint values (0.52 kg CE kg$^{-1}$ grain of pearl millet) than other tillage practices.

### 3.5. *Economic analysis*

The production cost and economic returns of different tillage

**Table 4**
Energy input-output relationship of different tillage practices in pearl millet—mustard rotation (average of two years)[a].

| Tillage | Residue (t ha$^{-1}$) | Energy output (MJ ha$^{-1}$) | Energy use efficiency | Net energy (MJ ha$^{-1}$) | Energy productivity (kg ha$^{-1}$) | Energy intensiveness (MJ US\$$^{-1}$) |
|---|---|---|---|---|---|---|
| CT | 0 | 221,200$^{d}$ | 11.5$^{a}$ | 201,977$^{a}$ | 0.32$^{a}$ | 31$^{e}$ |
| | 2 | 242,198$^{c}$ | 3.5$^{b}$ | 172,849$^{b}$ | 0.10$^{b}$ | 88$^{d}$ |
| | 4 | 259,785$^{ab}$ | 2.2$^{c}$ | 140,374$^{c}$ | 0.06$^{c}$ | 127$^{b}$ |
| ZT | 2 | 246,473$^{bc}$ | 3.8$^{b}$ | 181,463$^{b}$ | 0.11$^{b}$ | 96$^{c}$ |
| | 4 | 268,817$^{a}$ | 2.3$^{c}$ | 153,745$^{c}$ | 0.07$^{c}$ | 139$^{a}$ |

[a] Means followed by superscripted a similar lowercase letter within a column are not significantly different (at $P < 0.05$) according to LSD test.

**Table 5**
Carbon consumption or equivalent carbon emission and carbon output (kg CE ha$^{-1}$); and carbon footprint (kg CE kg$^{-1}$ grain of pearl millet) of different tillage practices in pearl millet—mustard rotation.

| Inputs | CT–CR0[a] | CT–CR2 | CT–CR4 | ZT–CR2 | ZT–CR4 |
|---|---|---|---|---|---|
| Fertilizers | 207.0 | 207.0 | 207.0 | 207.0 | 207.0 |
| Herbicide | 4.2 | 4.2 | 4.2 | 19.1 | 19.1 |
| Insecticide | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 |
| Electricity | 25.5 | 25.5 | 25.5 | 25.5 | 25.5 |
| Diesel | 95.4 | 95.4 | 95.4 | 29.6 | 29.6 |
| Crop residue | 0 | 880.0 | 1760.0 | 880.0 | 1760.0 |
| Total carbon input (kg CE ha$^{-1}$)[b] | 337 | 2097 | 3857 | 2046 | 3806 |
| Total carbon output (kg CE ha$^{-1}$) | 6871$^{d}$ | 7530$^{c}$ | 8059$^{ab}$ | 7642$^{bc}$ | 8326$^{a}$ |
| Carbon efficiency | 20.4$^{a}$ | 3.6$^{b}$ | 2.1$^{c}$ | 3.7$^{b}$ | 2.2$^{c}$ |
| Carbon foot print (kg CE kg$^{-1}$ pearl millet equivalent yield) | 0.05$^{d}$ | 0.31$^{c}$ | 0.52$^{a}$ | 0.29$^{c}$ | 0.50$^{b}$ |

Means followed by a superscripted similar lowercase letter within a row are not significantly different (at $P < 0.05$) according to LSD test.
[a] CT– conventional tillage; ZT– zero tillage; CR0– no crop residue; CR2– crop residue at 2 t ha$^{-1}$; CR4– crop residue at 4 t ha$^{-1}$; CE–carbon equivalent.

**Table 6**
Economic efficiency of different tillage practices in pearl millet—mustard rotation (average of two years).

| Treatment[a] | Cost of cultivation (US$ $ha^{-1}$) | | | Gross returns (US$ $ha^{-1}$) | | | Net returns (US$ $ha^{-1}$) | | | Benefit:Cost ratio | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pearl millet | Mustard | Total | Pearl millet | Mustard | Total | Pearl millet | Mustard | Total | Pearl millet | Mustard | System |
| CT–CR0 | 309 | 316 | 625 | 721 | 991 | 1712 | 412 | 675 | 1087 | 1.33 | 2.14 | 1.74 |
| CT–CR2 | 356 | 433 | 789 | 811 | 1068 | 1878 | 454 | 635 | 1089 | 1.27 | 1.47 | 1.38 |
| CT–CR4 | 397 | 543 | 940 | 871 | 1163 | 2034 | 474 | 620 | 1094 | 1.20 | 1.14 | 1.16 |
| ZT–CR2 | 297 | 380 | 677 | 798 | 1121 | 1919 | 502 | 741 | 1242 | 1.69 | 1.95 | 1.84 |
| ZT–CR4 | 337 | 490 | 827 | 862 | 1235 | 2097 | 525 | 744 | 1270 | 1.56 | 1.52 | 1.53 |

[a] CT– conventional tillage; ZT– zero tillage; CR0– no crop residue; CR2– crop residue at 2 t $ha^{-1}$; CR4– crop residue at 4 t $ha^{-1}$.

practices are shown in Table 6. In general, the production cost of mustard crop was higher than pearl millet however in no residue treatment production cost is almost similar in both crops. The production cost of pearl millet –mustard cropping sequence varied from minimum with CT-CR0 (625 US$ $ha^{-1}$) to maximum under CT-CR4 (940 US$ $ha^{-1}$). The maximum net returns were calculated in ZT–CR4 (1270 US$ $ha^{-1}$) and minimum in CT-CR0 (1087 US$ $ha^{-1}$). Benefit to cost ratio was calculated by dividing the net returns value to the production cost in order to determine the economic efficiency. Unlike returns, highest benefit to cost ratio was calculated in ZT-CR2 (1.84) followed by CT-CR0 (1.74) and lowest in CT-CR4 (1.16).

## 4. Discussion

### 4.1. *Crop productivity and profitability*

Results from the study revealed that peal millet and mustard grain yields were higher to the tune of about 17–24% in residue (4 t $ha^{-1}$) applied plots than that of yield obtained under no-residue plot (CT-CR0) (Table 2) chiefly because of favourable effect of crop residue on soil moisture and nutrient availability [31–33]. As the experiment was carried out under rainfed situation of semi-arid tropics and moisture is the major limiting factor of yield in these areas [34]. In pearl millet, CT recorded slightly higher grain yield than ZT (but not statistically significant) while vice-versa in mustard. This might be due to more weed infestation in *kharif* (rainy) season under ZT which caused reduction in yield [35]. The effectiveness of thick residue (4 t $ha^{-1}$) was noticed in both the tillage system. This could be attributed to residue effect on soil surface characteristics. It is likely that applying the same amount of residue in both tillage regimes (4 t $ha^{-1}$ in ZT and CT) have assisted the soil with the same benefits in terms of developing favourable soil surface [36].

The higher cost of cultivation of pearl millet–mustard cropping system for CT-CR4 can be attributed to cost involved in thick residue cover (8 t $ha^{-1}$ $year^{-1}$), field preparation and labour required for manual weeding. CT-CR4 maintained lower benefit to cost ratio (1.16) due to the higher cost of cultivation. Ozpinar and Ozpinar [37] reported high production cost with conventional tillage using plough compared with shallow tillage unburied crop residues under semi-arid conditions, in a wheat-vetch/maize rotation. In pearl millet and mustard the total cost of conventional tilled plots was around 10–14% higher than the zero tillage treatments at corresponding residue level. In mustard, cost of cultivation of residue applied plots was much higher than no-residue plots due to higher cost of pearl millet residue (50–53 US$ $t^{-1}$ residue). Lower benefit to cost ratio under ZT with 4 t $ha^{-1}$ crop residue in comparison to 2 t $ha^{-1}$ crop residue mainly because of proportionate returns from residue was less in comparison to cost involved.

### 4.2. *Energy requirements and input–output relationship*

Total energy input used in CT-CR4 was 119,413 MJ $ha^{-1}$, which is about six times more than that of CT-CR0 (19,225 MJ $ha^{-1}$). The main factor resulting in excessive energy use in CT-CR4 was thick residue cover. Also the amount of energy used in different agronomic practices and inputs such as machinery, diesel and weeding in CT-CR4. However the ratio of energy use of total energy for diesel, seed, machinery and labour were higher in CT-CR0. Conventional tillage practices were regarded to be energy-intensive [37] and poor in resource utilization [38]. About 25–30% of energy was required to field preparation and crop establishment [39]. Zero tillage practices reduced the energy requirement due to saving of energy in land preparation and weeding operations [40]. However, ZT and CT practices with residue increased the input energy requirement. The effect of energy saving by zero tillage was nullified by heavy energetic crop residues. This is in conformity with the findings of Chaudhary et al. [41]. In a study conducted at Indo-Gangetic Plain Zone, Parihar et al. [38] observed that crop residue consumes the bulk of input energy (71–89%) in maize based cropping system. ZT-CR4 recorded higher productivity which ultimately helped to maintain higher energy output and energy intensiveness. Energy-use efficiency, net energy return and energy productivity was higher in CT-CR0 because of lowest energy input as there was no application of crop residues as mulch.

### 4.3. *Carbon sustainability*

Among tillage practices highest share of C input was from crop residue followed by fertilizers and fossil fuel (Diesel). In no-residue applied plots, fertilizer was major consumer of carbon. The higher carbon input in residues applied plots, mainly due to application of crop residue contains 44% carbon. Gan et al. [42] and Goglio et al. [43] observed similar increase in C input with increase in quantity of residues. In CT and ZT carbon emitted through fossil fuel was 95.4 and 29.6 CE $ha^{-1}$, respectively. This difference in fossil fuel in different tillage treatment was due to savings in fossil fuel from reduced number of passes and also emissions associated with energy consumed in manufacture, transport, repair and use of machines [37,44]. Carbon output was higher in ZT-CR4 followed by CT-CR4 and least in CT-CR0 (Table 5). This increase in C output is due to higher biomass yields of pearl millet and mustard. The higher carbon efficiency in CT-CR0 (20.4) can be explained by the lower C input in this treatment mainly due to absence of residue. Significantly, the highest carbon footprint value was observed in CT-CR4 (0.52 kg CE $kg^{-1}$ pearl millet grain equivalent yield) and least in CT-CR0 (0.05 kg CE $kg^{-1}$ pearl millet grain equivalent yield). At the same residue, lower carbon footprint value was calculated in zero tilled plots than conventional tilled. This is because of lower C emission in the form of fossil fuel in ZT.

## 5. Conclusions

The study evaluated economics, energy, and environmental performance of different tillage and residue management practices in pearl millet-mustard crop sequence. It was observed that ZT with crop residue at 4 t $ha^{-1}$ maintained higher productivity and profitability in pearl millet-mustard cropping system. However, high energy and carbon input were noticed in thick residue applied plots in both tillage practices which reduced the energy and carbon efficiency in comparison to no-residue applied plot. Therefore, farmers have to strike a balance among the amount of crop residue used as mulch, fodder for livestock and other industrial uses.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.energy.2017.09.136.

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