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# Investigation of Input and Output Energy for Wheat Production: A Comprehensive Study for Tehsil Mailsi (Pakistan)

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**Abstract:** The global increasing food demand can be met by efficient energy utilization in mechanized agricultural productions. In this study, input–output energy flow along with CO<sub>2</sub> emissions for different wheat production cases (C-I to C-V) were investigated to identify the one that is most energy-efficient and environment-friendly case. Data and information about input and output sources were collected from farmers through questionnaires and face-to-face interviews. Input and output sources were converted into energy units by energy equivalents while CO<sub>2</sub> emissions were calculated by emission equivalents. Data envelopment analysis (DEA) was conducted to compare technical efficiencies of the developed cases for optimization of inputs in inefficient cases. Results revealed that case C-V (higher inputs, larger fields, the tendency of higher fertilizer application and tillage operations) has the highest energy inputs and outputs than the rest of the cases. Moreover, it possesses the lowest energy use efficiency and energy productivity. The highest CO<sub>2</sub> emissions (1548 kg-CO<sub>2</sub>/ha) referred to C-V while lowest emissions per ton of grain yield were determined in C-IV (higher electricity water pumping, moderate energy input). The grain yield increases directly with input energy in most of the cases, but it does not guarantee the highest values for energy indices. C-III (moderate irrigations, educated farmers, various fertilizer applications) was found as an optimum case because of higher energy indices like energy use efficiency of 4.4 and energy productivity of 153.94 kg/GJ. Optimum input and better management practices may enhance energy proficiency and limit the traditionally uncontrolled CO<sub>2</sub> emissions from wheat production. Therefore, the agricultural practices performed in C-III are recommended for efficient cultivation of wheat in the studied area.

**Keywords:** input–output energy; wheat production; CO<sub>2</sub> emissions; Pakistan

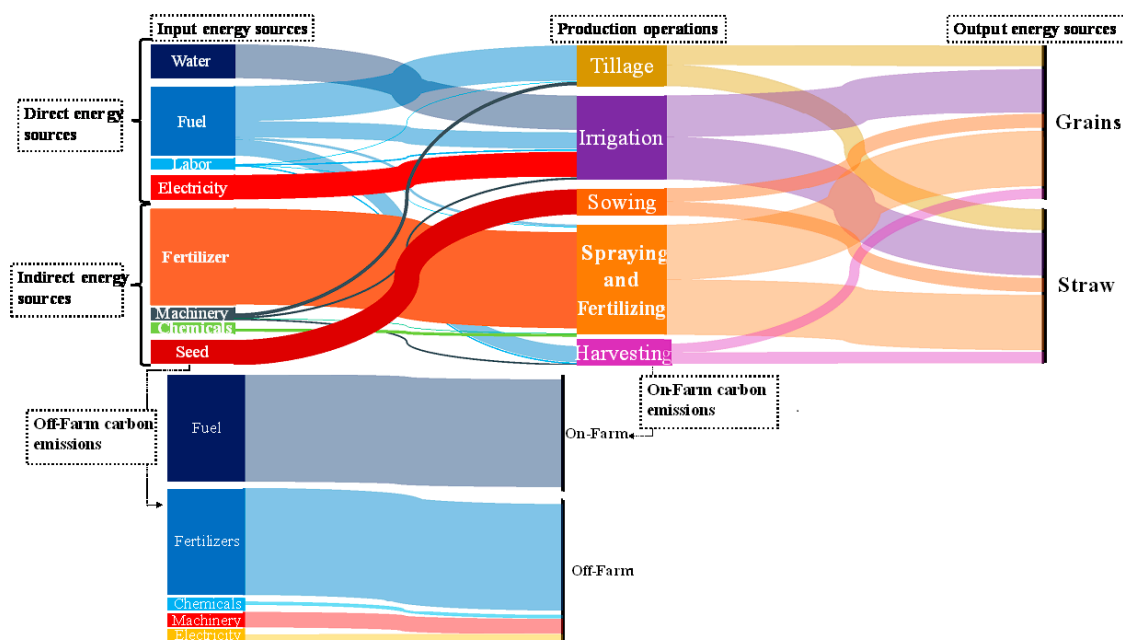
## 1. Introduction

Wheat (*Triticum aestivum*) is a main cereal crop which provides staple food to 35% of the world and 60% of Pakistan's population [1,2]. It covers about 25% of world cultivable area devoted to cereal crops to produce 771.7 million tons per annum [3,4]. The rise in global wheat demand is forecasted to be about 60% by 2050 [5]. Thus, annual wheat production must increase by 1.6% [5]. Pakistan has a share of 3.5% in global wheat production [6]. Agriculture is the largest economic sector of the country contributing 24% to GDP [7]. There will be demand of 31 million tons of wheat until 2025 [8] against current production of 24.3 million tons [6]. This necessitates a crucial increase in annual wheat production. On the other hand, lack of storage facilities further aggravates the risk of food shortage [9–14]. However, intensive energy input is required to increase wheat production which highlights the importance of efficient energy use in agricultural production.

Energy plays a pivotal role in wheat cultivation. Wheat production mainly depends upon the input energy. Input energy is the energy provided in the form of different sources (i.e., fertilizer, water, machinery, labor, electricity, fuel, seed and pesticides) during various operations in wheat cultivation. It is categorized as direct and indirect input energies. Direct energy is the energy used directly on farm in the form of labor, electricity, water and fuel. Indirect energy is the off-farm energy used in manufacturing processes, in the form of seed, fertilizer, pesticides and machinery [15]. Furthermore, input energy can also be classified as renewable and non-renewable energies. Renewable energy comprises of energy input from human labor and machine operations while non-renewable energy covers fertilizers, irrigation water, pesticides and fuel. Input energy in agriculture depends on arable land, population engaged in agriculture, farmers' education, irrigation systems, tillage practices, local weather climate, crop and soil types [16–18]. It is evident that there is a need to increase the energy efficiency in agriculture to stabilize the relationship between energy input and crop production. Agronomic modifications and conservative agriculture systems can play an important role to enhance energy use efficiency in agriculture [19]. Agricultural productivity, energy use and Greenhouse Gas (GHG) emissions have a strong interrelationship. Fertilizers, machinery, electricity and fossil fuels are the primary energy sources for agricultural productions [20]. The production processes of these industrial sources indirectly contribute to GHG emissions. GHG emissions have increased exponentially in recent decades to 36.81 Gt. CO<sub>2</sub> eq. in 2019 [21]. Agriculture, forestry and other land uses constitute 24% of global GHG emissions [22]. This increasing trend of GHG emissions leads to global warming [23]. United Nations Framework Convention on Climate Change proposed a target of limiting global warming to two degrees Celsius in this century. Current decarbonization rates of 1.6% per year needs to be increase up to 6.4% per year to achieve this target. Otherwise, the present trajectory will lead to four degrees Celsius increment in global temperature in the current century [24]. Increasing energy use efficiency is a key factor to reduce global environmental risks [25]. Pakistan is one of the minor contributor to the global GHG emissions with only a share of 0.72% [26]. The energy and agriculture sectors of the country are the major constituents of total GHG emissions comprising 46% and 41%, respectively [26]. These emissions have increased from 178 Mt. CO<sub>2</sub> eq. to 367 Mt. CO<sub>2</sub> eq. from 1994 to 2012 with an average increment of 4.1% per year [27]. Furthermore, Pakistan is ranked among the top ten countries affected by climate change over the past two decades [28], though per capita emissions are among the lowest in the world.

Many studies have quantified the energy use and GHG emissions in agriculture and specifically, in wheat production, e.g., energy use and efficiency evaluation in wheat production in China [20], energy auditing in different cropping systems in India [3,15,29–36], energy analyses and GHG emissions from different crops in Iran [37–53], assessment of on-farm energy use and GHG emissions from wheat in New Zealand [1,18,54,55], analyses of agricultural energy in Bangladesh [56], energy input–output analysis in Turkey for production of cotton, vegetables, grapes, sugar beet and dry apricot [17,57–63], effect of fertilizer management on GHG emissions in agriculture [64], energy and economic analyses for different vegetables in Indonesia [65] and estimation of energy use and CO<sub>2</sub> emissions in Thailand [66]. To the best of authors' knowledge, no study of such type was found for Pakistan in the literature.

The aim of this study was to compare energy inflow and outflow among different wheat production cases to indicate the best practices for future energy efficient cultivation in the study area. The input and output energy flow for wheat cultivation was ascertained in Tehsil Mailsi (Pakistan). The data were collected using questionnaires and face-to-face interviews. The system boundaries for energy evaluation of wheat production in the present study are defined in Figure 1. The energy indices like energy use efficiency, energy productivity and net energy were calculated for different production cases. The grain yield was predicted by multiple regression technique and further compared with actual values. Moreover, CO<sub>2</sub> emissions for all the production cases were also estimated. Finally, the optimum production case was identified for wheat cultivation.

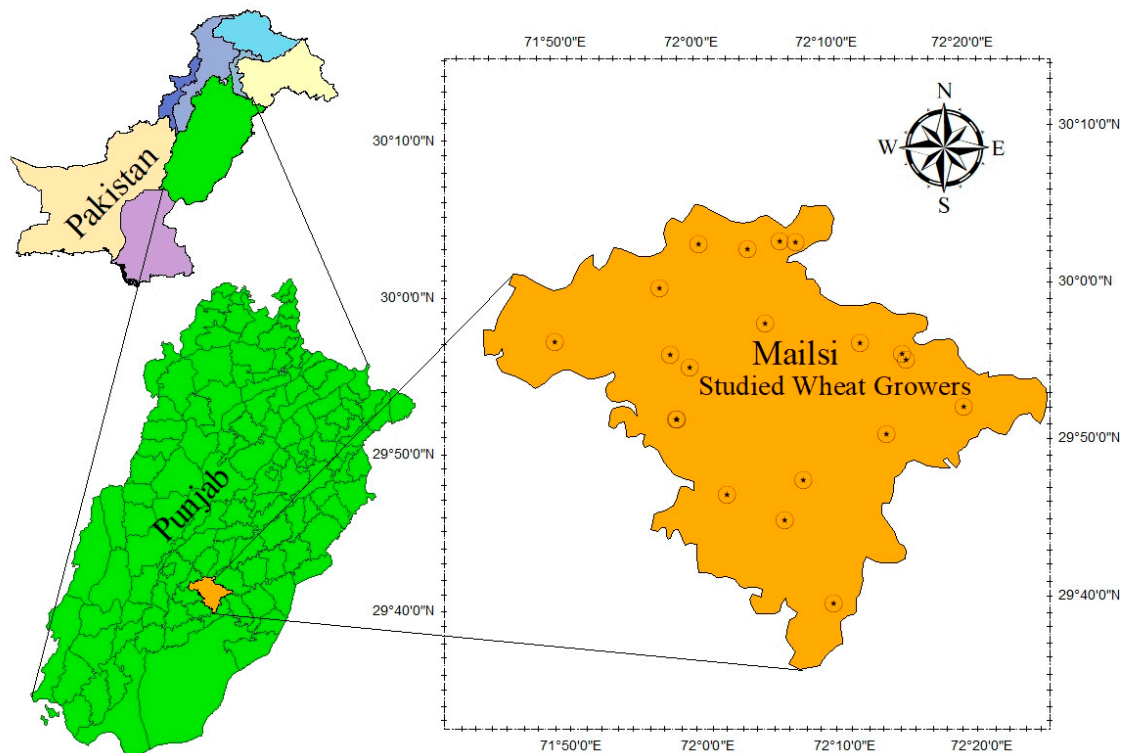


**Figure 1.** Defining the system boundaries for investigation of input and output energy flow for wheat cultivation in the present study.

## 2. Research Methodology

### 2.1. Input–Output Energy Analysis

The study was conducted in Tehsil Mailsi of District Vehari (30°2' N, 72°21' E), Pakistan. Annual maximum and minimum mean temperatures of the study area are 33.35 °C and 18.77 °C, respectively. The study area is comprised of loamy and clayey soil with an average annual rainfall of 246.7 mm. Wheat is grown as a cash crop in the study area covering most of the arable land. Moreover, it lies among the top ten wheat producing districts of the country covering 4% of the total wheat cultivable area in Punjab [67]. The sample size was calculated by Cochran formula [50]. After preliminary evaluation from wheat growers/farmers of the area, twenty fields were selected, and the data were collected using face-to-face questionnaires in the 2019 work season as shown in Figure 2. The data on inputs for wheat production included the utilization of water, fuel, labor, electricity, fertilizer, machinery, chemicals and seeds while output data derives from production of wheat grain and straw.



**Figure 2.** Map of studied wheat growers of the tehsil Mailsi, Punjab.

The data collection process revealed that variations existed in socioeconomic characteristics of the studied farms. These discrepancies in collected data were sorted out by developing five cases (C-I to C-V) in consultation with farmers and local agricultural experts. The details of each case are presented as follows:

- C-I (Case 1) Lower energy input, smaller fields, poor management practices;
- C-II (Case 2) Conventional management practices, which represent 60–70% of farmers in the study area;
- C-III (Case 3) Moderate irrigation, educated farmer, variable fertilizer applications;
- C-IV (Case 4) Higher electric water pumping, moderate energy inputs;
- C-V (Case 5) Higher energy input, tendency of higher fertilizer applications & tillage operations.

The developed five cases (C-I to C-V) were organized in ascending order of their energy use, i.e., lower to higher energy inputs. Furthermore, farm management practices of the studied farms also differentiate the developed cases. The variations in inputs among all the production cases is mainly due to socio-economic characteristics such as farmer's education and age, farm size, cultivated wheat area and farm labor (etc.) as shown in Table 1. The highest and lowest farmer's education was fourteen (C-III) and five (C-I) years of schooling, respectively. It reflects the higher technical knowledge of the farmers in C-III. Maximum farm size was 141.7 hectares (C-III) with 85% cultivated wheat area, while minimum farm size was 3.64 hectares (C-I) with 3.24 hectares under wheat cultivation. However, the maximum number of farmers (60–70%) and hence, wheat cultivated area belong to C-II with conventional management practices. The greater planting area makes C-II more important for potential improvements in inputs and management operations. These farms have lesser economic resources and machinery availability. The number of farm tractors and laborers also varied correspondingly with farm size. Thus, the largest farm size (C-III) holds four (04) farm tractors and thirty (30) laborers. Irrigation source (canal/tube well) is one of the main energy consumers in agricultural production. Water pumping by electric motors/diesel engines (tube well) is higher energy consuming operation than canal irrigation. The primary source of irrigation was canal water in all the cases except in C-IV,

where the electric tube well was solely used for irrigation. The use of tube well irrigation in C-IV was primarily due the geographic location of these farms which do not have access to canal water supply. Tube well was also used as a secondary/supplementary irrigation source in C-I, C-II and C-V.

**Table 1.** Socioeconomic characteristics of studied farms and farmers.

Property	Wheat Production Cases				
	C-I	C-II	C-III	C-IV	C-V
Farmer education (yrs.)	5	8	14	12	8
Farmer age (yrs.)	35	47	45	42	50
Farm size (ha)	3.64	7.29	141.7	60.73	70.85
Wheat cultivated area (ha)	3.24	6.07	121.46	20.25	68.83
Farm labor (No.)	1	2	30	8	10
Number of tractors	0	0	4	2	2
Source of Irrigation	C+T	C+T	C	T <sub>e</sub>	C+T
Canal-to-tube-well ratio	(2:1)	(2:2)	(4:0)	(0:3)	(2:3)

C, T and T<sub>e</sub> stands for Canal, Tube well and Electrical pumping, respectively.

The data about input and output sources obtained from the farmers were converted into energy units using appropriate equivalents. These equivalents were taken from literature and presented in Table 2 [20,34,48,57,68,69]. The variations in equivalents for input and output energy sources (Table 2) is due to climatic, environmental and socioeconomic factors of the studied areas. Most of the equivalents used in this study were selected from the literature [20,34,57,69] based on approximately similar input conditions as presented in bold in Table 2. However, the energy equivalent ( $E_e$ ) for tractor and farm implements in MJ/h is determined using Equation (1) [69] given below:

$$E_e = \frac{C W}{L} \quad (1)$$

$$\eta_e = \frac{E_o}{E_i} \quad (2)$$

$$\eta_p = \frac{G_a}{E_i} \quad (3)$$

$$\omega = E_o - E_i \quad (4)$$

where,  $C$  is the constant (MJ/Kg),  $W$  is the implement or tractor weight (kg), and  $L$  is the economic life (h) of implements or tractor. The values of  $C$  for tractor and farm implements were taken from [69]. The corresponding values of  $W$  and  $L$  are given in literature [70,71]. There were no significant differences in the type of farm implement or tractor in all the cases. Whereas  $\eta_e$  is energy use efficiency,  $\eta_p$  is energy productivity (kg/GJ),  $\omega$  is net energy (GJ/ha).  $E_i$  and  $E_o$  represent total input and output energy in (GJ/ha), respectively.  $G_a$  is actual grain yield (kg/ha). Energy efficiency or proficiency is the term used in this study to denote the measure of energy indices (i.e.,  $\eta_e$ ,  $\eta_p$  and  $\omega$ ). It reflects the total performance of a specific case. The grain yield as a function of input energy is also predicted by multiple regression technique (Equation (5)). This equation is developed using yield as response, whereas machinery, water and fertilizer energies as continuous predictors. These energy input sources were chosen because of strong correlation between said response and predictors.

$$G_p = 1060.025(W) + 148.589(F) - 1295.87(M) - 518.282 \quad (5)$$

where,  $G_p$  represents predicted grain yield (kg/ha).  $W$ ,  $F$  and  $M$  represent water, fertilizer and, machine energy (GJ/ha), respectively.

**Table 2.** Details of the equivalents used for input–output energy analyses.

Inputs	Equivalent (MJ/Unit)					
	A. A. Saad (2016) India [34]	Yousefi M. (2014) Iran [48]	Yuan S. (2018) China [20]	Esengun K. (2007) Turkey [57]	Saunders C. (2007) NZ [68]	Kitani O. (1999) USA [69]
Seed (kg)	–	–	<b>20.1</b>	–	–	13
Diesel (L)	<b>56.31</b>	51.33	56.31	56.31	43.6	47.8
Labor (hr.)	<b>1.96</b>	1.96	1.96	1.96	–	–
Fertilizer (kg)						
N	<b>60.6</b>	66.14	66.14	66.14	65	78.1
P <sub>2</sub> O <sub>5</sub>	<b>11.1</b>	12.44	12.44	12.44	15	17.4
K <sub>2</sub> O	<b>6.7</b>	–	11.15	11.15	10	13.7
Water (m <sup>3</sup> )	<b>1.02</b>	0.63	1.02	0.63	–	–
Machinery (kg)						
Tractor	64.8	–	–	–	–	<b>138</b>
Farm implements	62.7	–	–	–	–	–
Plough	–	–	–	–	–	<b>180</b>
Disc harrow	–	–	–	–	–	<b>149</b>
Rotavator	–	–	–	–	–	<b>148</b>
Combine harvester	83.5	–	–	–	–	<b>116</b>
Chemicals (mL)	<b>0.102</b>	–	–	–	–	–
Insecticides (kg)	–	–	101.2	<b>101.2</b>	315	–
Fungicides (kg)	–	–	216	<b>216</b>	210	–
Herbicides (kg)	–	–	238	<b>238</b>	310	–
Electricity (kWh)	–	3.6	<b>11.93</b>	11.96	8.14	–
Outputs						
Grain (kg)	<b>15.7</b>	–	14.48	–	–	13
Straw (kg)	<b>12.5</b>	–	9.25	–	–	–

Note: The bold values represent the equivalents used in this study for input–output energy analyses.

Data envelopment analysis (DEA) based CCR (Charnes–Cooper–Rhodes) model [72] was used to calculate technical efficiencies (TE) of different cases. DEA is a benchmarking technique used to rank decision making units (DMUs) based on their comparative performance [73]. DMUs are the distinct units that must be compared while five different cases (C-I to C-V) were considered as DMUs in the present study. Technical efficiency (TE) is the ratio from weighted output to weighted inputs of a specific DMU. It depends on the ability of a distinct DMU to convert inputs into outputs. Three major inputs, i.e., fertilizer, water and fuel were considered as controlled inputs while yield as an output in the CCR model. Moreover, technically efficient and inefficient cases were distinguished from each other to analyze the potential improvements in inefficient cases. In this regard, an input oriented CCR model was used to optimize inputs level in inefficient DMUs while efficient DMUs were considered as the best possible production cases in the study area. The input oriented CCR model is a model in which inputs are minimized to obtain the same level of outputs. The Frontier Analyst 4 software was used to perform data envelopment analysis. However, TE can be written mathematically as follows [74]:

$$TE_j = \frac{\sum_{r=1}^n u_r y_{rj}}{\sum_{s=1}^m v_s x_{sj}} \quad (6)$$

Equation (6) can be solved by linear programming as follows [73]

$$\begin{aligned} \text{Maximize } TE &= \sum_{r=1}^n u_r y_{rj} \\ \text{Subject to } &\sum_{r=1}^n u_r y_{rj} - \sum_{s=1}^m v_s x_{sj} \leq 0 \\ \text{Df } &\sum_{s=1}^m v_s x_{sj} = 1, u_r \geq 0, v_s \geq 0, j = 1, 2, 3, \dots, k \end{aligned}$$

where,  $TE_j$  refers to technical efficiency of  $j^{\text{th}}$  DMU,  $u_r$  is the weight assigned to output  $n$ ,  $y_r$  is the quantity of output  $n$ ,  $r$  is the number of outputs ( $r = 1, 2, 3, \dots, n$ ),  $v_s$  refers to weight assigned to input  $m$ ,  $x_s$  is the quantity of input  $m$ ,  $s$  is the number of inputs ( $s = 1, 2, 3, \dots, m$ ) and  $j$  refers to  $j^{\text{th}}$  of DMUs ( $j = 1, 2, 3, \dots, k$ ).

## 2.2. CO<sub>2</sub> Emissions and Carbon Footprint

In this study, CO<sub>2</sub> emissions from production sources were also calculated using emission equivalents. The effects of N<sub>2</sub>O and CH<sub>4</sub> were not considered because of lesser contribution (kilograms per hectare) towards GHG emissions as compared to CO<sub>2</sub>. In this regard, CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub> emissions are reported as 2668.35, 22.92 and 3.49 kg/ha, respectively [48]. The CO<sub>2</sub> emissions (kg-CO<sub>2</sub>/ha) from production sources like fertilizers, pesticides, electricity, fuel and machinery were determined using CO<sub>2</sub> equivalents. These equivalents (kg CO<sub>2</sub>/MJ) are given Table 3 [68,75]. Moreover, kg-CO<sub>2</sub> emissions per ton of grain yield were also calculated to compare yield response with respect to emissions. Total electricity generation in Pakistan comprises of 64% from thermal power plants and 36% from hydro power plants [76]. Therefore, only 64% of total input electricity energy in wheat production was converted into GHG equivalents.

**Table 3.** CO<sub>2</sub> equivalents used for the estimation of CO<sub>2</sub> emissions [68].

Input Energy (MJ)	Equivalent (kg CO <sub>2</sub> /MJ)
Fertilizers	
N	0.05
P <sub>2</sub> O <sub>5</sub>	0.06
K <sub>2</sub> O	0.06
Herbicides	0.06
Machinery	0.1
Diesel	0.0687
Electricity	0.0192

### 3. Results and Discussion

#### 3.1. Input–Output Energy Consumption

Input energy is analyzed and discussed separately based on various energy sources (Table 4) and production operations (Table 5). The direct and indirect input energies consumed by all the sources in each predefined case (C-I to C-V) are shown in Figure 3. It is evident from the figure that indirect energy remains dominated in all cases except for C-IV. Fertilizer remained the top input energy source among all other sources and in all the cases. In this regard, it is ascertained that fertilizer constitutes about 31%, 40% and 39% of total input energy in C-III, C-IV and C-V, respectively which are higher energy consuming cases. The highest fertilizer energy input belongs to C-V which is almost twice the fertilizer energy consumed in C-I (the lowest energy consuming case). Therefore, fertilizer represented the highest energy input with mean value of 9.94 GJ/ha in all wheat production cases (Figure 3), in accordance with the literature [3,20,35,45,54,55,77]. Singh et al. [3] investigated energy use pattern for wheat cultivation in India and found a similar trend in fertilizer energy use in Punjab province. The present study was also conducted in Punjab occupied by Pakistan. Therefore, there are no significant differences in the farm characteristics of these two studies. Moreover, Mani et al. [35] studied energy consumption in wheat and maize production and found similar trends for wheat cultivations. Soltani et al. [45], Yuan et al. [20] and Safa et al. [55] also found similar energy use pattern in their studies. However, Erdemir and Zeki [58] conducted a study on organic farming and reported fuel as the highest energy input source. The contradiction in the results of present study to their study was due to difference in management practices by the farmers. Thus, input energy can be optimized by prudent fertilizer application, e.g., use of potassium fertilizer along with urea and diammonium phosphate (DAP) makes C-III unique from others. This combination of fertilizers enhanced the energy efficiency of this case. Furthermore, the total indirect energy can be minimized by controlling single source applications (i.e., fertilizer).

**Table 4.** Description of the input and output energy sources used for the wheat cultivation.

Inputs	Units	Wheat Production Cases				
		C-I	C-II	C-III	C-IV	C-V
Direct						
Labor	h	135.85	107.445	77.1875	106.21	77.5827
Electricity	kWh	154.375	154.375	0	617.5	154.375
Water	m <sup>3</sup>	2540.65	3302.846	4065.041	3302.846	4065.031
Fuel	L	91.39	111.15	158.08	98.8	190.19
Indirect						
Chemicals in kg	mL	1235	2470	2470	2470	0
Chemicals in mL	kg	0	0	0.741	0	0.247
Machinery						
Tractor	–	7.41	14.2025	21.6125	9.2625	23.2427
Plough	–	1.235	1.235	1.8525	1.8525	2.47
Disc harrow	–	0	0	0	0	1.6302
Rotary hoe	–	1.235	1.235	1.235	1.235	1.235
Combine harvester	–	0	0	0.6175	0	0.6175
Stationary thresher	–	4.94	4.94	0	4.94	0
Seed	kg	123.5	123.5	123.5	123.5	148.2
Fertilizer						
N	–	101.27	135.85	158.08	135.85	203.775
P <sub>2</sub> O <sub>5</sub>	–	113.62	56.81	113.62	56.81	87.685
K <sub>2</sub> O	–	0	0	61.75	0	0
Outputs						
Grain	kg	2964	3655.6	4149.6	3952	4446
Straw	kg	2964	3655.6	4149.6	3952	4446



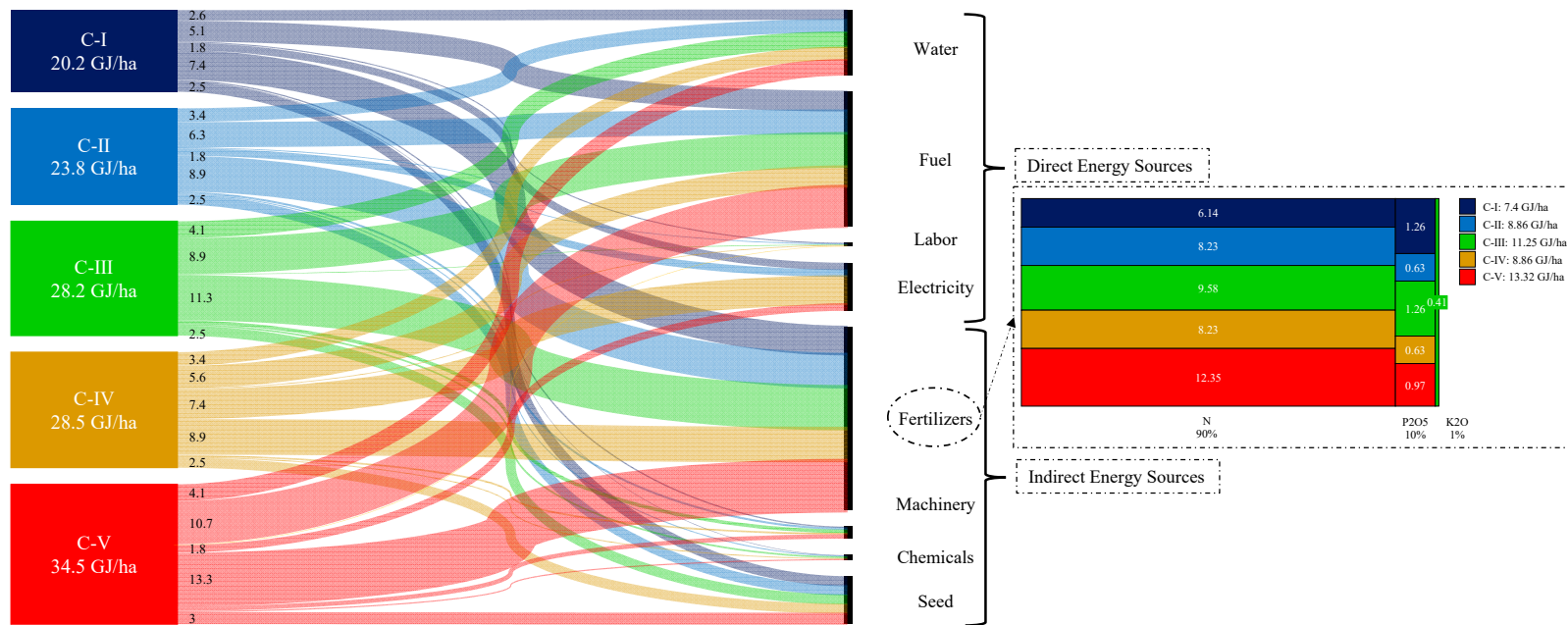
**Table 5.** Operational energy consumption (GJ/ha) resulting from different field operations, divided into sources and shown by each case.

Operation	Source	Wheat Production Cases				
		C-I	C-II	C-III	C-IV	C-V
Tillage	Labor	0.005	0.005	0.016	0.006	0.020
	Machinery	0.181	0.181	0.387	0.245	0.619
	Fuel	2.364	2.364	4.033	3.060	6.120
	Total	2.551	2.551	4.436	3.311	6.759
Irrigation	Labor	0.073	0.097	0.121	0.073	0.121
	Machinery	0.001	0.178	0.355	0.001	0.355
	Fuel	0.001	1.669	3.338	0.001	3.338
	Electricity	1.840	1.840	0.000	7.370	1.840
Total	1.915	3.783	3.814	7.445	5.654	
Sowing *		0.001	0.001	0.001	0.001	0.001
Spraying and fertilizing	Labor	0.008	0.008	0.011	0.006	0.007
	Machinery	0.001	0.001	0.071	0.018	0.018
	Fuel	0.001	0.001	0.556	0.278	0.278
	Total	0.010	0.010	0.638	0.302	0.303
Harvesting and fhreshing	Labor	0.213	0.098	0.002	0.098	0.002
	Machinery	0.142	0.160	0.107	0.160	0.107
	Fuel	1.808	2.225	0.974	2.225	0.974
	Total	2.163	2.483	1.083	2.483	1.083
Grand Total		6.640 <sup>a</sup>	8.829 <sup>ac</sup>	9.973 <sup>bc</sup>	13.542 <sup>b</sup>	13.801 <sup>b</sup>

\* Manual seed broadcasting sowing in all cases. <sup>a, b, ac, bc</sup> Letters indicate the significant differences by ANOVA test.

Fuel is the second highest energy input source after fertilizer in all the cases except C-IV where electricity was the second highest energy input source. The higher electricity consumption in C-IV was due to higher electrical water pumping for irrigation. The highest fuel consumption belongs to C-V comprising 31% of total input energy while the lowest corresponds to C-I. Fuel consumption is the measure of machining practices in different production operations. Furthermore, higher fuel consumption results from extensive tillage practices and vice versa. Therefore, judicious fuel energy use is important to optimize direct energy usage in wheat production.

Water was the third highest energy input source in all the cases except C-IV. Highest water consumption was observed in C-III and C-V accounting for 14.7% and 12%, respectively of total input energies in these cases. On the other hand, the lowest water energy input was noted in C-I due to lesser availability of costly tractor operated tube well for economically poor farmers in this class. Therefore, socioeconomic status of farmers also effects the farming practices for wheat cultivation. Electricity is also a major energy input for some cases like C-IV, but not very important for other cases. The reason for this difference is the use of alternatives, e.g., use of diesel engines/tractors instead of electric powered motors for water pumping. There are no significant differences among other input sources (labor, seed, herbicides and machinery) in all the cases. These sources are considered as minor energy input sources for wheat cultivation due to their lesser input values as depicted in Figure 3. Finally, C-V utilized the highest energy inputs in the form of fertilizers, fuel and machinery among all the cases (Table 4) due to extensive tillage and fertilization. However, the lowest amount of energy in fuel, machinery and fertilizer sources highlights the lesser machine operations due to poor economic status of farmers in C-I. Thus, socioeconomic characteristics of farms and farmers play an important role in energy use and energy proficiency. It is difficult for economically poor farmers (C-I) to improve management practices for energy efficient wheat cultivation. However, another low input case C-II has potential to improve its inputs and hence, energy efficiency by increasing energy inputs up to optimum level.



**Figure 3.** Distribution of the energy input (GJ/ha) from different sources for wheat production for the production cases of C-I to C-V. Fertilizer energy input is further classified based on type, i.e., N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O.

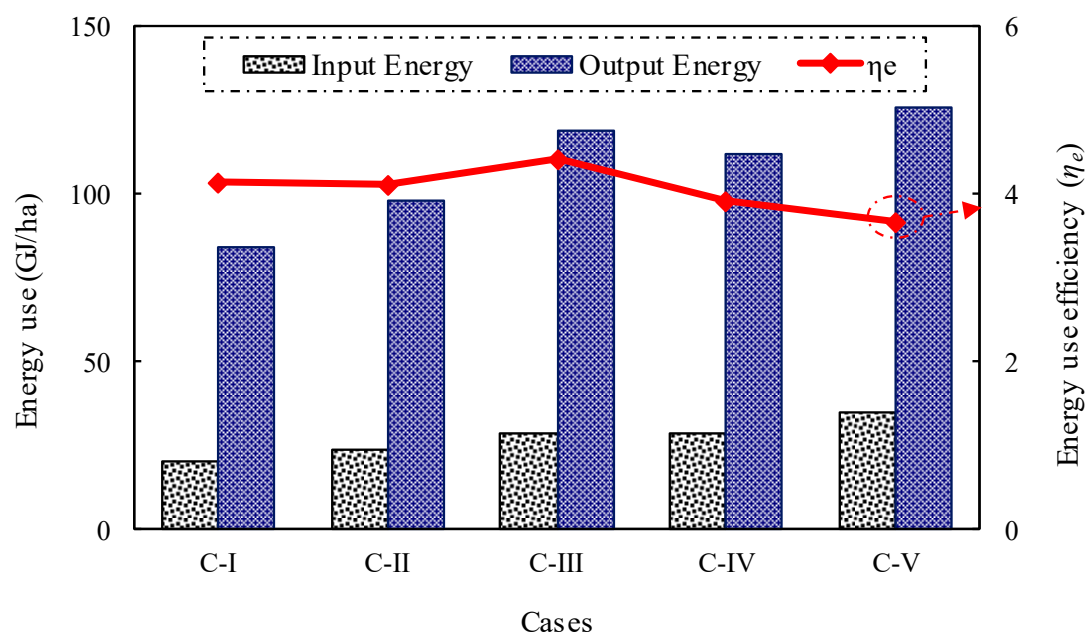
Energy from pre-described input sources is utilized in different production operations i.e., irrigation, tillage, sowing, spraying & fertilizing and harvesting & threshing. Labor, fuel and machinery are main energy sources employed in every operation. The operational energy with respect to these sources was calculated and presented in Table 5. Irrigation is the energy consuming operation in which water is pumped and delivered to the field through a watercourse. The energy consumed in this operation is known as irrigation energy. On an average of all the cases, it was the highest energy consuming operation comprising 42.8% of average total operational energy, which is in accordance with previous literature Safa et al. [55]. However, irrigation energy was ranked second after tillage energy in some cases i.e., C-III and C-V, where low energy irrigation water was available. Safa et al. [55] investigated input and output energy flow for dry and irrigated lands. Results of the present study match with their results for irrigated lands which have similar farm properties to studied farms in the present study area. However, their results for dry lands differ due to lesser availability of irrigation water and complete dependence on rainfall in the studied area. The maximum (7.44 GJ/ha) and minimum (1.92 GJ/ha) irrigation energies were calculated in C-IV and C-I, respectively. Irrigation was performed by different sources (i.e., canal, electric/diesel tube well) in the studied area. In this regard, the source of irrigation is a key driver to control input energy. Canal water and diesel engine operated tube wells water pumping consume less energy than electrical motors driven pumps. It is due to higher electrical energy (kWh) expenditure than diesel (liter) expenditure for pumping equal amounts of water as exhibited in Table 4. Therefore, electricity consumption is an important energy input source in irrigation constituting 57% of average total irrigation energy among all the cases. However, fuel is more important in some cases like C-III and C-V, where fuel driven engines/tractors were used for water pumping. Moreover, low irrigation-energy usage (C-I) reflects the poor economic status of farmers leading to a fewer number of irrigations.

Tillage energy is the energy consumed in soil pulverization and land preparation for wheat sowing. It was the second highest energy consuming operation when considering average of all the cases. However, tillage is the top energy consuming operation in much of the cases as described earlier. It constitutes an average of 37% of mean total operational energy in all the cases. The maximum and minimum tillage energy consumption were 6.76 GJ/ha and 2.55 GJ/ha in C-V and C-I/C-II, respectively. Higher tillage energy consumption represented the higher availability of farm implements in C-V. Fuel energy is crucial in tillage operation comprising an average of 91.5% of mean total energy consumed in this operation.

Harvesting and threshing is carried out by combine harvester in C-III and C-V. A tractor mounted/operated reaper and thresher is used by C-IV and C-II. However, harvesting is done by hand-held sickle in C-I, while threshing was conducted with same machinery as of C-IV and C-II. The maximum harvesting and threshing energy was 2.48 GJ/ha in C-IV and C-II, while the minimum was 1.08 GJ/ha in C-III and C-V. The average harvesting and threshing energy expenditure represent 18.42% (1.86 GJ/ha) of the total operational energy. Fertilizing and spraying of the crop were performed by broadcasting (manual) and sprayer, respectively. Pesticides are sprayed by boom and knapsack sprayers in C-III, C-IV, C-V and C-I, C-II, respectively. The higher pesticides application in C-II results in consumption of 6.4% (0.64 GJ/ha) of total operational energy. The average fertilizing and spraying energy were about 0.25 GJ/ha (i.e., 2.5% of total energy consumption). On the other hand, broadcasting was used for sowing in all cases. Thus, lowest labor energy (Table 5) is used in sowing among all the operations and cases (C-I to CV)—amounting to 0.012% of the total energy consumption. Finally, the total average operational energy is determined as 10.19 GJ/ha in consistence with results of [55]. Overall, ANOVA test in the last row of Table 5, shows that operational energy in C-I and C-II was the lowest among all cases. Furthermore, the highest operational energy is observed for C-IV and C-V.

The total energy use by input and output sources is illustrated in Figure 4. The input energy use in C-I, C-II, C-III, C-IV and C-V was 20.18 GJ/ha, 23.8 GJ/ha, 28.25 GJ/ha, 28.53 GJ/ha and 34.54 GJ/ha, respectively. The corresponding output energy use in all cases was 83.58 GJ/ha, 97.52 GJ/ha, 117.02 GJ/ha, 111.45 GJ/ha and 125.38 GJ/ha, respectively. The highest input energy is consumed in C-V which leads

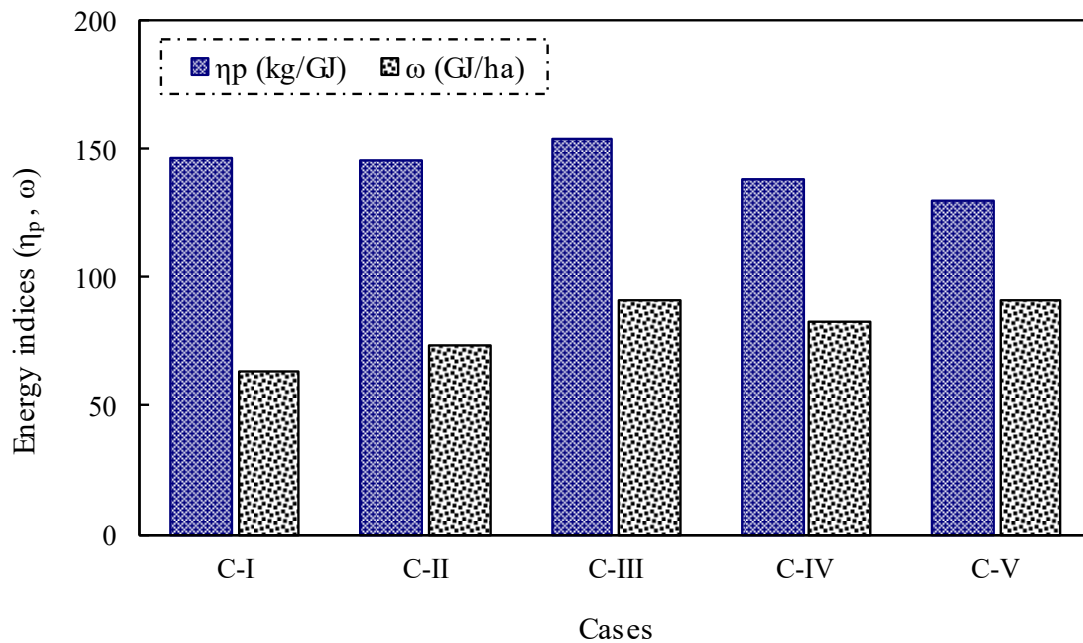
to highest output energy as shown in Figure 4. However, lowest input and output energy is found in C-I due to poor management practices. Thus, average input and output energy consumed in wheat production is determined as 27.06 GJ/ha and 108.1 GJ/ha, respectively. These energy consumptions are found in agreement with results from references [45,55]. Soltani et al. [45] conducted their study in a similar way by developing six different classes of farms on the basis of energy use pattern and found similar results.



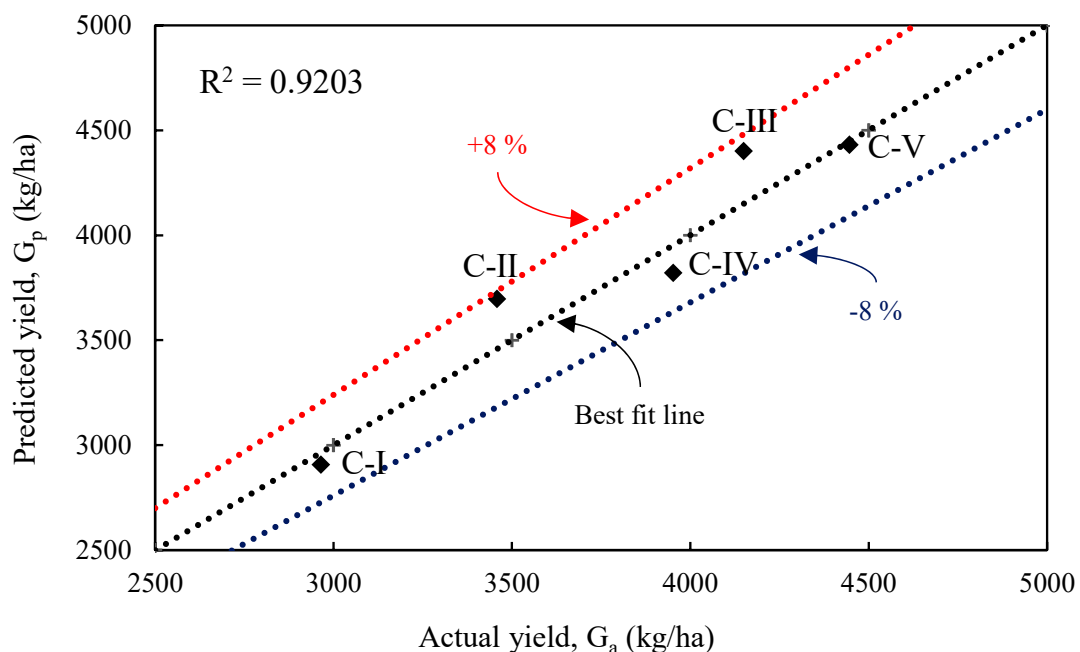
**Figure 4.** Observed energy inputs and outputs for wheat production in Mailsi (Pakistan) for five studied cases. Red diamond line indicates energy use efficiency referring to the secondary vertical axis.

The  $\eta_e$  is considered one of best indicators for efficient energy usage [20]. The highest energy use efficiency was found in C-III while the lowest corresponds to C-V as shown in Figure 4. The figure shows a trend in energy use efficiency with respect to energy inputs. Energy use efficiency increases with the increase in input energy up to a moderate energy input (C-III) and then decreases with further increases in energy input (C-IV & C-V). It necessitates the use of optimum energy input to ensure highest energy use efficiency. Energy productivity and net energy ( $\omega$ ) for each case are shown in Figure 5. The figure shows the highest energy productivity and net energy in C-III while the lowest energy productivity in C-V and net energy in C-I. The lower energy input cases (C-I and C-II) have comparatively good energy proficiency as compared to higher energy input cases (C-IV and C-V). Thus, C-III is an optimum case because of higher energy indices such as  $\eta_e = 4.4$ ,  $\eta_p = 153.94$  kg/GJ and  $\omega = 91.13$  GJ/ha when compared to the other cases (Figures 4 and 5). Therefore, the agricultural practices performed in C-III are recommended for efficient cultivation of wheat in the studied area. An equation (Equation (5)) was developed, based on all cases (C-I to C-V), using multiple regression to predict grain yield. Now, only the data of three input sources (i.e., machinery, water and fertilizers) was used to predict yield rather than all other inputs as presented in Tables 4 and 5. The negative sign with machinery (Equation (5)) shows a decrease in yield with increase in machine operations. The reason behind such inverse relationship may be the effect of tillage on water retention capacity in the root zone. Higher tillage practices (which reflects higher machining operations) decrease the water retention time in the root zone and hence, there will be lesser water availability for the crop. This water shortage in the root zone leads to decreased crop yield. Thus, higher machine operations have adverse effects on grain yield as depicted in Equation (5). The actual and predicted grains yield is compared as shown in Figure 6. The yield was predicted well in C-I, C-IV and C-V but is overestimated in C-II and C-III. The reason behind such over estimation (C-II & C-III) may be the higher difference

between water and machinery energy inputs than in the other cases. The coefficient of determination between actual and predicted yields was acceptable, i.e., 0.92 (Figure 6). Therefore, grain yield in the study area can be predicted (Equation (5)) before cultivation by assuming three input sources (water, fertilizer, machinery). This equation may be helpful for farmers to optimize inputs for energy efficient cultivation of wheat in the study area.



**Figure 5.** Comparison of energy indices (i.e., energy productivity and net energy gain) for the studied five cases.



**Figure 6.** Graphic representation of the actual and estimated grain yields ( $\pm 8\%$  error bars). The best fit line depicts ideal behavior of predicted and actual values.

Data envelopment analysis (DEA) was also conducted in this study and the results revealed that moderate energy input and slightly higher input cases i.e., C-III and C-IV were technically efficient

while low and high energy input cases i.e., C-I, C-II and C-III were technically inefficient as shown in Figure 7. The 100% technical efficiency of C-IV and C-V shows that these cases lie on the frontier line and are the best production cases in converting their input sources (i.e., fertilizer, water and fuel) into output sources (i.e., yield). On the other hand, technically inefficient cases (i.e., C-I, C-II and C-V) lie in the envelopment region developed by the frontier line and their inputs can be optimized to get the same level of outputs. The optimization of energy input sources in these cases is shown in Figure 7. The figure shows highest improvement potential in the high energy input case i.e., C-V with 25.2%, 41.6% and 8.6% reduction in fertilizer, fuel and water, respectively. There is also considerable amount of reduction potential in the two other inefficient cases to achieve the same level of output. Thus, such improvements in inputs can make these cases more efficient and should be adopted by the farmers in the study area. Furthermore, actual energy inputs and output (i.e., yield) for all the five cases was also compared by DEA and exhibited in Figure 8. Figure shows comparative energy use behavior of each farm class. Higher values of inputs and outputs tend to move the curve towards the origin while lower values away from the origin. The high energy inputs and output case, i.e., C-V lies exactly in origin while other cases show the comparative behavior of energy use with respect to this case. In this figure, an important point to note is the energy use and output producing behavior on C-II and IV. Both cases consumed the same amount of water and fertilizer energies while C-IV produced higher yield than C-II. The reason behind this is the higher electrical energy input in C-IV that increased the total input energy and hence, enhanced outputs. Moreover, other reason may be the higher available nutrient contents in the soils of C-IV than C-II before application of fertilizers. Thus, it is important to measure the available soil NPK before fertilizing the field in wheat cultivation. This highlights the potential value of precision agriculture for efficient cultivation of wheat crop in the study area.

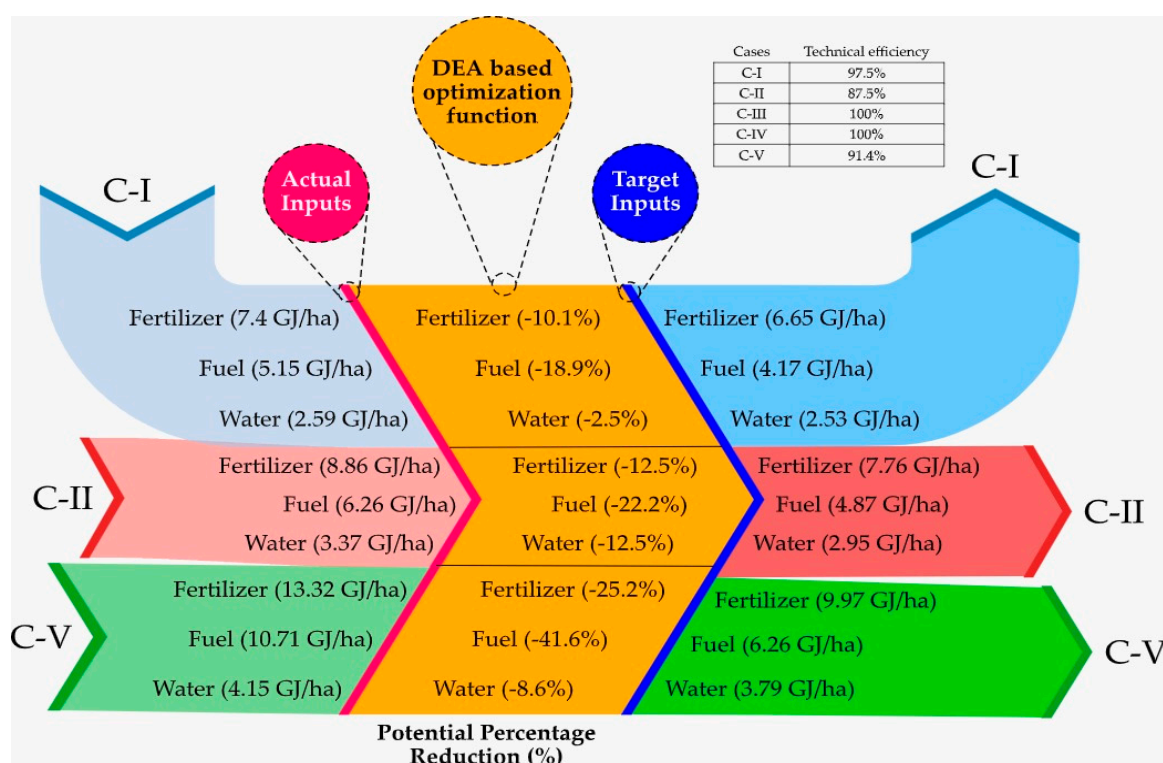
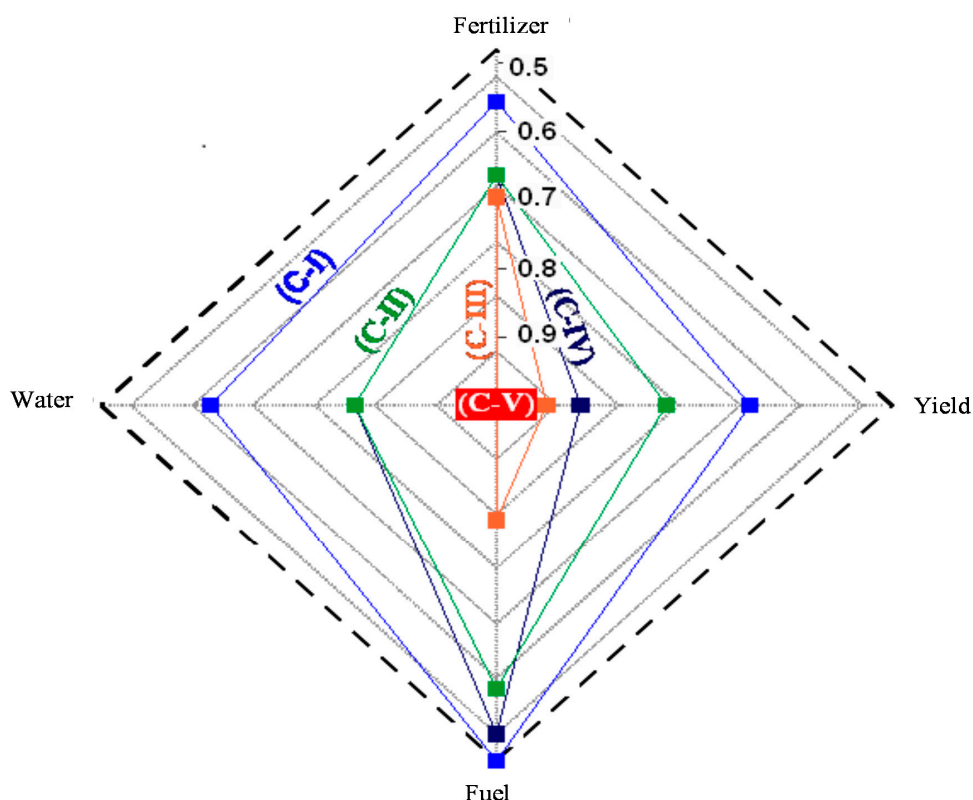


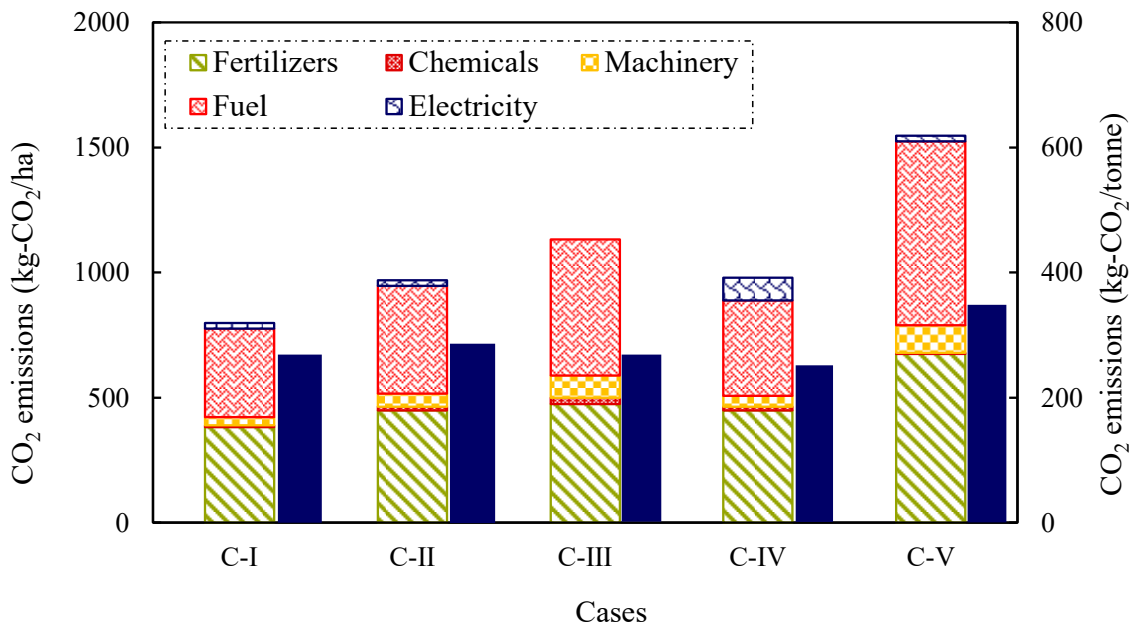
Figure 7. Data envelopment analysis (DEA)-based comparison of technical efficiencies among five studied cases and potential improvement pattern in energy inputs of inefficient cases.



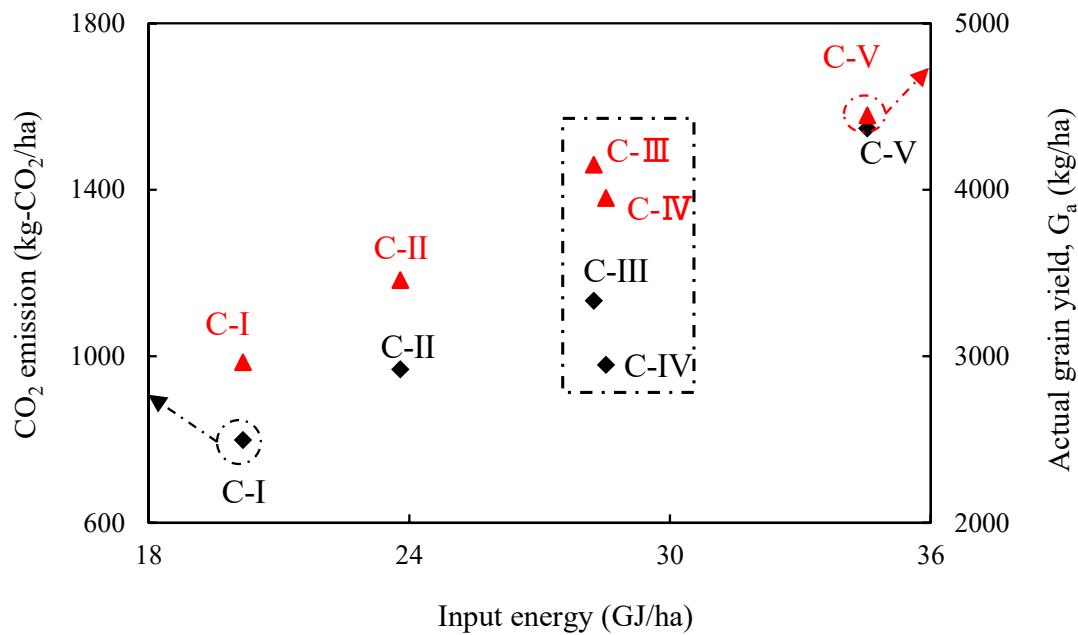
**Figure 8.** DEA-based comparison of major energy inputs and yield among five studied cases with higher inputs the data point tends to move towards the origin while with lower values tend to move away from the origin. Input scale marked from 0.5 to 1 shows the comparative behavior of energy use.

### 3.2. CO<sub>2</sub> Emissions

In this study, CO<sub>2</sub> emissions (kg-CO<sub>2</sub>/ha) from the production sources including fertilizers, pesticides, electricity, fuel, and machinery was calculated using CO<sub>2</sub> equivalents (Table 3). The total average CO<sub>2</sub> emissions from the studied production sources was determined as 1120 kg-CO<sub>2</sub>/ha and 283.7 kg-CO<sub>2</sub>/ton, which was consistent with the results of Safa et al. [1]. The highest share of CO<sub>2</sub> emissions comes from fertilizer and fuel energy in all cases as shown in Figure 9. On an average of all the cases, fertilizer and fuel comprises 44.7% and 45% of total CO<sub>2</sub> emissions, respectively. Safa et al. [1] in a study with irrigated and rainfed wheat found fertilizer and fuel as the top contributor to carbon emissions. However, their study revealed fuel as the second highest contributor after fertilizer while fuel was the highest contributor in the present study, though the difference among both studies is not significant. Moreover, Soltani et al. [45] and Moghimi et al. [41] found a similar pattern for carbon emissions in wheat production. It necessitates the judicious use of these sources to minimize the CO<sub>2</sub> emissions. Other energy input sources (i.e., machinery, chemicals and electricity) are minor contributors to carbon emissions. The highest CO<sub>2</sub> emissions were found in the higher energy input case, i.e., C-V as 1548 kg-CO<sub>2</sub>/ha while lowest emissions were calculated as 798.6 kg-CO<sub>2</sub>/ha in the low energy input case, i.e., C-I. The data thus shows a relationship between energy use and CO<sub>2</sub> emissions. Both CO<sub>2</sub> emissions and grain yield increased by increasing the input energy as evident from Figure 10 for C-I, C-II and C-V. In contrast, C-IV consumed higher input energy than C-III but produced lower grain yield and CO<sub>2</sub> emissions. The greater energy input in relation to yield observed in C-IV occurred because electric water pumps in C-IV consume higher input energy, but emit less CO<sub>2</sub> than the gasoline operated pumps and/or canal used water in C-III. It is important to mention that higher grain yield does not guarantee a higher energy use efficiency due to corresponding input energy (Figure 4). However, it may result in greater emissions of greenhouse gases particularly CO<sub>2</sub> as depicted in C-V.



**Figure 9.** Comparison of CO<sub>2</sub> emissions from various sources for wheat production in Mailsi (Pakistan) for five studied cases. Blue columns refer to the secondary vertical axis depicting emissions per ton of grain yield.



**Figure 10.** Defining the relationship between CO<sub>2</sub> emissions in kg-CO<sub>2</sub> per hectare and actual grain yield in kg per hectare against the input energy employed for studied five cases of wheat production in Mailsi (Pakistan). Black diamonds refer to primary vertical axis while red triangles refer to the secondary vertical axis.

**4. Conclusions**

This study projected input–output energy analyses and estimations of CO<sub>2</sub> emissions for wheat production in five different cases (C-I to C-V) in Pakistan. The study analyzed one high energy input case (C-V), two low energy input cases (C-I and C-II) and two moderate energy input cases, i.e., C-III, C-IV. However, C-IV was found to be the highest energy consumer in terms of operational energy due



higher electrical water pumping for irrigation. It was concluded that high energy input tends to result in higher energy output and grain yield, but it did not confirm higher energy proficiency. In this regard, highest values of energy indices belonged to the moderate energy input case, i.e., C-III. Moreover, the low energy input cases (C-I and C-II) were better in energy efficiency than high energy input cases, i.e., C-V. Primary factors found by the study to affect energy efficiency include fertilizers type and combination, source of irrigation, farmer's education and proper management practices. Therefore, it is important to use proper fertilizer combinations, educating farmers and use of high efficiency irrigation systems to achieve higher energy efficiencies. Most farmers follow the conventional management system; therefore, it is crucial to raise awareness about the latest techniques to increase energy use efficiency. In this regard, local government may play a role by conducting seminars and providing guidance for farmers.

This study found that the moderate energy input case (C-III) showed the best production scenario in terms of energy efficiencies and CO<sub>2</sub> emissions per ton of grain yield. The management practices in this case were found to be best in converting input sources into output energy and are recommended for future energy efficient and environment friendly wheat cultivation in the study area.

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## Nomenclature

GHG	greenhouse gas
CO <sub>2</sub>	carbon dioxide
$E_e$	energy equivalent for machinery (MJ/h)
$C$	energy constant for machinery (MJ/kg)
$W$	weight of machinery (kg)
$L$	economic life of machinery (h)
$\eta_e$	energy use efficiency
$E_o$	output energy (GJ/ha)
$E_i$	input energy (GJ/ha)
$\eta_p$	energy productivity (kg/GJ)
$\omega$	net energy gain (GJ/ha)
$G_a$	actual grain yield (kg/ha)
$G_p$	predicted grain yield (kg/ha)
$W$	water energy input (GJ/ha)
$F$	fertilizer energy input (GJ/ha)
$M$	machinery energy input (GJ/ha)
DEA	data envelopment analysis
TE	technical efficiency
DMU	decision-making unit

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