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Reducing energy use and greenhouse gas emissions through ınput optimization in Türkiye

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Abstract
The relationship between agricultural production and climate change is bidirectional. As a production activity contingent on climatic conditions, it is the sector most susceptible to fluctuations in climate. However, the sector also contributes to climate change through the generation of energy and the release of carbon emissions associated with production activities. At present, carbon emissions from agricultural production constitute 24% of the total carbon emissions. It is of the utmost importance to reduce the use of fossil fuels and chemicals in agricultural production systems in order to mitigate the effects of global climate change. In order to achieve this, it is essential that agricultural production optimizes inputs without compromising food security. The principal objective of this study is to present an alternative method for reducing energy consumption and carbon emissions by optimizing inputs in sunflower production in Konya province, Turkey. The study analyses the changes in energy use and carbon emissions resulting from optimized input use according to the technical efficiency levels of the enterprises, while maintaining a constant yield. This is achieved by optimizing the inputs used in sunflower production. The results demonstrate 3.16% reduction in energy consumption and approximately 3.68% reduction in carbon emissions in comparison to the current input utilization composition. Upon examination of the technical efficiency levels of the enterprises, it is evident that optimizing the input utilization combinations of those with lower technical efficiency levels results in 7.94% energy savings and a 9.03% reduction in carbon emissions. The results of this study will contribute to the reduction of environmental impacts and the spread of sustainable agricultural practices by optimizing energy consumption and carbon emissions from agricultural production.

Keywords Input optimization · Energy use · Carbon emissions · Sunflower

1 Introduction

The sustainable use of inputs in agricultural production is a crucial component of ensuring food security (Rezaei et al., 2019). The demand for food products has increased due to population growth, a decrease in agricultural land, and an increase in living standards. As

Extended author information available on the last page of the article a result, more inputs are being used in the production of agricultural products, leading to increased energy consumption in this sector (Esengun et al., 2007). In addition to energy consumption, a significant proportion of carbon emissions in agriculture come from the use of inputs (Goglio et al., 2014; Ghosh et al., 2020).

The levels of energy consumption and carbon emissions in agricultural production vary depending on the production pattern. Therefore, it is crucial to have knowledge about energy resources and their optimal consumption to adopt appropriate policies that improve the efficiency of agricultural production systems (Manes and Singh, 2005).

The use of technology in agriculture has led to improvements in agricultural production worldwide. However, this has also resulted in increased use of inputs such as chemical fertilizers and pesticides to ensure food security and increase yields per unit area (Baran et al., 2017). The use of inputs to increase production has had negative impacts on environmental pollution, human health, and resource depletion (Şahin & Külekçi, 2022). While it may not be feasible to eliminate the use of inputs with current technology, optimizing their use can improve resource efficiency and promote environmental sustainability.

The enhancement of energy utilisation efficiency can facilitate the advancement of environmental sustainability in agricultural production. This is achieved by the reduction of energy consumption and carbon emissions, while ensuring the maintenance of food safety and the adherence to sustainable production practices. The enhancement of energy utilisation efficiency can facilitate the sustainability of agricultural production by curbing energy consumption and carbon emissions while upholding food security and the maintenance of sustainable production practices. It is of the utmost importance to exercise caution when considering the input composition, in order to prevent any disruption to the ecological cycle. Input optimisation has the potential to reduce carbon emissions from agricultural production and energy use. Input optimisation can be achieved by employing scarce inputs in an optimal combination while maintaining yield stability. A substantial body of research has been conducted with the objective of determining the optimal input balance between energy use and carbon emissions in agricultural production. Data envelopment analysis is a widely used technique in optimisation studies (Oukil & Zekri, 2021). As a non-parametric approach, DEA is based on linear programming models for the evaluation of homogeneous groups of evaluated units (Oukil & Govindaluri, 2017). A substantial body of research has been conducted on the application of DEA for energy consumption optimisation and environmental impact mitigation in fruit, vegetable and field crops.

Pishgar-Komleh et al. (2020) employed data envelopment analysis for the purpose of optimising energy utilisation in wheat production. In the field of tobacco production, Mushtag et al. (2021) and Zalaghi et al. (2021) have conducted research. Similarly, in apple production, Zalaghi et al. (2021) have also contributed to the existing body of knowledge. Additionally, Nourani and Bencheikh (2020) investigated tomato production, Mardani Najafabadi and Taqi (2020) conducted research on cucumber production, Nabavi-Pelesaraei et al., (2014a, 2014b) on orange production, Lozano et al. (2010) on mussel production, and Vazquez-Rowe et al. (2012) on grape production. Additionally, Bolandnazar et al. (2014) conducted research on cucumber production, while Muhammadi et al. (2013) and Hosseinzadeh-Bandbafha et al. (2018) focused their studies on soya bean production. Furthermore, Elhami et al. (2016) concentrated their efforts on chickpea production. Nabavi-Pelesaraei et al. (2017) employed the DEA method to enhance the efficiency of paddy production while simultaneously reducing its environmental impact. Karadaş and Külekçi (2020) employed a data envelopment analysis (DEA) approach to enhance energy efficiency in sunflower production, resulting in a 4.18% reduction in energy consumption. Mousavi-Avval et al. (2011) demonstrated that a 10% reduction in total energy input is achievable through the application of a DEA methodology to improve energy efficiency in sunflower production, based on a study involving 95 sunflower producers. Nateğ et al. (2020) conducted a comparative analysis of data envelopment analysis (DEA) and multi-objective genetic algorithm (MOGA) methods for the optimisation of energy, economic and environmental indices in sunflower cultivation. Their findings indicated that MOGA demonstrated superior energy saving rates compared to DEA. These studies collectively highlight the necessity of optimisation studies for the advancement of environmental and agricultural sustainability in agricultural production. The DEA is a commonly employed methodology in optimisation studies pertaining to agricultural production. The DEA method is a non-parametric frontier estimation method that is widely used to measure the benchmarking and efficiency of decision-making units (Adler et al., 2002). One of the main benefits of DEA is that it does not require any prior assumptions about the underlying relationships between inputs and outputs (Seiford & Thrall, 1990). The objective of this study is to identify alternative a avenue for reducing energy consumption and carbon emissions by optimising the agricultural inputs employed in sunflower production in Konya province.

Sunflower is a significant agricultural crop with extensive cultivation in Konya province. In 2021, the sunflower cultivation area in Konya (93.373 ha) constituted 10.36% of Turkey's total sunflower cultivation area (901.153 ha). The production of sunflower in the region in question amounts to 348.668 tonnes, which constitutes 14.43% of the total sunflower production in Turkey (2.415.000 tonnes) (TurkStat, 2024).

2 Material and method

This study was conducted in the province of Konya, which is located in the Central Anatolia region of Turkey and has a high agricultural potential. Konya is located between 36°41' and 39°16' north latitude and 31°14' and 34°26' east longitude. The study area is shown in Fig. 1.

To minimize errors and optimize efficiency, a random sampling method was used in this study. The sample size was determined using a proportional sample, which is one of the simple random sampling methods (Newbold et al., 2013).

$$n = \frac{Np(1-p)}{(N-1)\sigma_{px}^2 + p(1-p)} \tag{1}$$

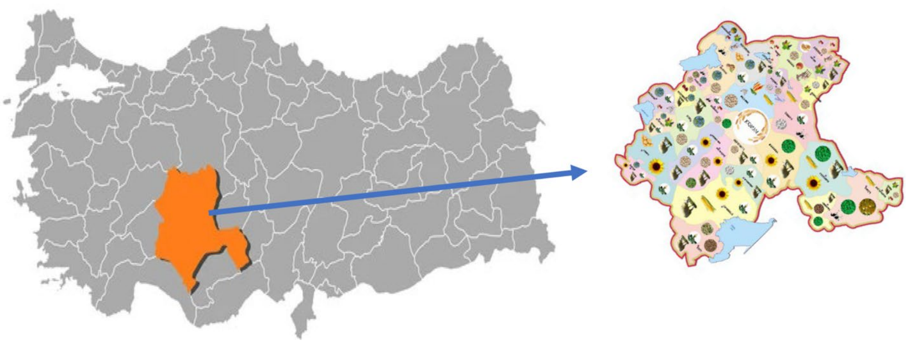

Fig. 1 Location of the studied area in Turkey

or

$$n = \frac{N(pq)}{(N-1)D^2 + (pq)} \tag{2}$$

$$D = d/t$$

where n: Sample size, p: the number of parts in the population with a certain characteristic (as a proportion). If this proportion is unknown, 50% (0.5) should be taken to obtain the maximum sample size. q: 1-p (the proportion of parts that are not p), σ_px^2 = variance of the proportion (margin of error (%)/table value), t: t value corresponding to a certain confidence level, N: sample population, d: acceptable margin of error. As a result, the sample size in this study is 64 and the sample was randomly selected. The sunflower growers surveyed were interviewed and questionnaires were used on the farms to collect data on the content of agricultural inputs used in sunflower production (seeds, fertilizers, chemical pesticides, irrigation water, labor, machine power, etc.).

To analyze the energy consumption and greenhouse gas emissions in sunflower production, the energy and greenhouse gas input–output was calculated in a first step. For this purpose, energy equivalents and GHG emission coefficients are used for all agricultural inputs and outputs (Mousavi-Avval et al., 2011). For each input and output used in sunflower production, the energy and greenhouse gas emission coefficients were multiplied and converted and calculated per hectare. Table 1 shows the values of energy consumption and output as well as the GHG emission coefficients.

The aim of the study was to evaluate the economic efficiency of sunflower production. Data Envelopment Analysis (DEA) was used to determine the extent to which sunflower-producing companies can maximize production with a given input level. DEA is a decision-making tool that managers can use to improve the efficiency of relatively inefficient units. In this study, Farrell's input-orientated efficiency measures were used, as operators need to evaluate the efficiency of inputs rather than outputs. A multi-input

Table 1 Energy equivalents and GHG emission coefficients of inputs and outputs in agricultural production

Inputs/outputs	Unit	Energy equivalents (MJ)	GHG emission coefficients	Sources
Human labor	H	2.3	0.360	Singh et al., 2002; Houshyar et al., 2015
Machinery	H	62.70	0.071	Singh et al., 2002; Khoshnevisan et al., 2013a
Chemical fertilizers				
Nitrogen (N)	Kg	66.14	1.300	Shrestha, 1998; Lal, 2004
Phosphorus (P_2O_5)	Kg	12.44	0.200	Shrestha, 1998; Lal, 2004
Potassium (K_2O)	Kg	11.15	0.200	Shrestha, 1998; Lal, 2004
Chemical pestisits	Kg	199.00	5.100	Ozkan et al., 2004; Lal, 2004
Seed	Kg	1	0.270	Singh, 2002; Houshyar et al., 2015
Diesel fuel	Lt	56.31	2.760	Singh, 2002; Dyer ve Desjardins, 2006
İrrigation water	M^3	0.63	0.170	Yaldız et al., 1993; Houshyar et al., 2015
Electricity	kWh	3.60	0.608	Rezvani et al., 2011; Lal, 2004
Sunflower	Kg	26.3	–	Sabah, 2010

single-output model was created for each group of companies. The linear programming model provided the input-oriented economic efficiency for each company.

$$\lambda xiW_i * X_i *$$

$$-y_i + Y\lambda \geq 0$$

$$X^i * -X\lambda \geq 0 \tag{3}$$

$\lambda \geq$ in formula;

Wi: Vector of input prices for the firm with rank i,

Xi *: Vector of input quantity cost minimization calculated for firm rank i,

yi: production level,

λ: denotes the vector of constants. Of the values obtained, Xi * represents the efficiency value between 0 and 1 for enterprises of rank i. The Xi * value equal to 1 indicates that the enterprises is at the frontier or that the enterprises has technical efficiency as defined by Farrell (1957). For inefficient firms, the Xi * value is less than 1. Solving the problem for each firm in the sample yields N numbers of Xi * (Coelli 1998). The efficiency value of each enterprises varies depending on the other economic and technological units and the socio-economic factors included in the analysis.

In the efficiency analyses, the efficiency measurement estimates were carried out using the DEAP 2.1 programme developed by Coelli (1995). The descriptive statistics of the inputs and outputs used in the analyses are shown in Table 2.

Following the efficiency analysis, enterprise efficiency values of the companies were categorized as fully efficient (TE = 1), efficient (TE = 0.950–0.999), less efficient (TE = 0.900–0.949) and inefficient (TE < 0.899). Table 3 shows the number of enterprises per efficiency category. The results show that 41% of the companies are considered fully efficient, 19% have an efficient performance, 20% are less efficient and 19% remain inefficient. Based on the analysis, the average efficiency score of the enterprises was calculated as 0.953.

Table 2 Descriptive statistics of the data used in the analyses (ha^{-1})

	Unit	Mean	Std. deviation	Min	Max
Human labour	H	53.90	5.50	35.90	70.00
Diesel fuel	L	370.10	46.50	277.90	474.50
Seed	Kg	5.20	0.90	3.00	7.20
Chemical pesticides	L	2.30	0.90	1.00	4.00
Irrigation water	m3	4824.30	138.00	4580.00	5030.00
Nitrogen*	Kg	196.00	48.20	128.00	318.50
Phosphorus*	Kg	123.00	32.30	69.00	211.60
Machinery	Saat	16.20	1.90	10.80	22.00
Electricity	kWh	3015.20	86.20	2862.50	3143.80
Sunflower	Kg	3157.80	233.90	2750.00	3500.00

*Pure nitrogen and pure phosphorus values of the fertilizers used were calculated by the author

Table 3 Number of enterprises according to technical efficiency classifications

	N	Average efficiency score	Std. deviation	Min	Max
Fully Active (TE = 1)	26	1.000	0.000	1.000	1.000
Effective (TE = 0.950–0.999)	12	0.980	0.014	0.954	0.998
Less Active (TE = 0.900–0.949)	13	0.929	0.014	0.904	0.946
Inefficient Enterprises (TE < 0.899)	12	0.850	0.035	0.792	0.892
Total	63	0.953	0.060	0.792	1.000

3 Discussion

The indicator of energy efficiency in agricultural production is the difference between the actual energy used and the optimal amount of energy use. Energy efficiency can be achieved by reducing the amount of energy consumed per unit of product or increasing the amount of product obtained per unit of energy. Increasing energy efficiency can lead to positive outcomes, such as reduced costs in agricultural production, increased incomes, improved competitiveness, resource conservation, and reduced environmental impact. Table 4 displays the energy equivalents of inputs and outputs used in sunflower production by agricultural enterprises.

The study found that each enterprise had an average energy use of 48,165.38 MJ. The largest contributor to energy use was fuel (diesel) at 43.27%, followed by nitrogen at 26.91%, electricity at 22.54%, and other inputs at 7.28%. Similarly, Unakıtan and Aydın (2018) reported that fuel (diesel) constituted the highest energy use factor in sunflower production, accounting for 59.98%. Karadaş and Köksal (2020) determined that fuel (diesel) constituted the second highest energy use factor in sunflower production, accounting for 34.84% of total energy use, after chemical fertiliser. Mousavi-Avval et al. (2011), in their study on sunflower production in Iran, found that fuel (diesel) was the input with the

Table 4 Energy input and output by source in sunflower production

	Unit	Used quantity	Energy equivalents (MJ)	Energy use (MJ)	Ratio (%)
Human labor	H	53.9	2.30	123.97	0.26
Diesel fuel	L	370.1	56.31	20,840.33	43.27
Seed	Kg	5.2	1.00	5.20	0.01
Chemical pesticides	L	2.3	5.10	11.73	0.02
Irrigation water	m3	4824.3	0.17	820.13	1.70
Nitrogen	Kg	196	66.14	12,963.44	26.91
Phosphorus	Kg	123	12.44	1530.12	3.18
Machinery	H	16.2	62.70	1015.74	2.11
Electricity	kWh	3015.2	3.60	10,854.72	22.54
Total energy input	***MJ***			***48,165.38***	***100.00***
Sunflower	Kg	3157.8	26.30	83,050.14	
Total energy output	***MJ***			***83,050.14***	***100.00***

Bold expressions emphasize total energy input and total energy output highest energy use, accounting for 42.30% of total energy use. Machines such as tractors, harvesters, and pumps are widely used in agricultural production processes. They increase efficiency and ease of agricultural activities. However, their energy consumption is high as they run on diesel fuel. Nitrogen and electricity can be considered as the outputs of the most used inputs in production. The use of chemical fertilizers and electricity for irrigation water release nitrogen, which are important production costs in agricultural enterprises. However, they also cause higher energy emissions per unit area. The DEA analysis showed the optimum energy utilization amounts of these inputs (Table 5) and determined differences in utilization rates. Consequently, the overall energy efficiency is enhanced by 3.12%. Nevertheless, this rate fluctuates between 1.04 and 9.52% contingent on the inputs employed. Karadaş and Köksal (2020) ascertained that energy efficiency can be conserved between 1.62% and 8.67% in accordance with optimized inputs in their optimization studies.

Table 6 shows the current and optimal levels of energy utilization for inputs based on the efficiency levels of the enterprises. The DEA results show that maximum energy utilization is achieved in fully efficient enterprises. Efficiency rates in efficient enterprises can be increased by 3.7% with optimal input utilization. While less efficient enterprises increase of 4.58%, the utilization efficiency in inefficient companies can be increased by 7.94% in inefficient enterprises. In terms of inputs, the greatest increase in productivity is achieved using fertilizers, which leads to an increase of between 6.59 and 27.95%, depending on the efficiency level of the enterprises. It should be noted that these results depend on the efficiency level of the enterprises. Of the inputs that contribute most to energy consumption, the use of diesel can increase efficiency by 1.92–7.38%, the use of nitrogen by 7.11–13.79% and the use of electricity by 0.88–2.38%. In their optimisation study, Muosavi-Avval et al. (2011) demonstrated that enterprises with high efficiency levels can achieve savings of 21.2% in phosphate fertiliser energy and 10.8% in labour energy. Karadaş and Köksal (2020) determined that the utilisation of an efficient input composition by sunflower production enterprises would result in a reduction of 8.67% in the energy expenditure associated with irrigation water and a further 2.39% in the energy expenditure associated with chemical inputs.

The efficient and effective selection of energy sources in sunflower production can reduce GHG emissions. As energy consumption is a major contributor to GHG emissions, a standardized calculation method using energy equivalents was used to assess emissions from different energy sources. Emission factors were compiled from the literature to calculate the GHG emissions of the inputs used in sunflower production. The emission coefficient provides information on the greenhouse gas emissions per unit of an energy source. Table 7 shows the GHG emissions based on the inputs used in sunflower production. The calculations result in an average of 3167.75 kg CO_2 emissions per agricultural enterprise. Electricity consumption accounted for 57.87%, fuel (diesel) for 32.24% and total nitrogen for 8.04% of total emissions.

Reducing GHG emissions calculated for the inputs currently used in sunflower production will help Turkey combat climate change and comply with international agreements and commitments. Sunflowers are indeed an important product that is traded both domestically and abroad. However, according to the treaties that Turkey has joined and the European Union, which will introduce a carbon tax at the border from 2026, GHG emissions must be calculated, monitored and reduced. Therefore, the determination of GHG emissions from sunflower production shows the sector's contribution to the fight against climate change. In this context, the current and optimal GHG emissions of the farms are presented according to different inputs (Table 7). While the current GHG emissions of the farms were 3993.91 kg CO_2, the

Table 5 Current amount of energy used in the enterprises and optimum amount of energy use

	Unit	Current input use	Optimum input use	Energy equivalent (MJ)	Current energy use (MJ)	Ratio (%)	Optimum energy use (MJ)	Ratio (%)	Change (%)
Human Labor	H	53.90	52.80	2.30	123.97	0.26	121.44	0.26	−2.08
Fuel (Diesel)	L	370.10	360.70	56.31	20,840.33	43.27	20,311.02	43.50	−2.61
Seed	Kg	5.20	5.10	1.00	5.20	0.01	5.1	0.01	−1.96
Pesticides	L	2.30	2.10	5.10	11.73	0.02	10.71	0.02	−9.52
Irrigation water	M^3	4824.30	4774.80	0.17	820.13	1.70	811.716	1.74	−1.04
Total Nitrogen	Kg	196.00	185.20	66.14	12,963.44	26.91	12,249.13	26.24	−5.83
Total phosphorus	Kg	123.00	116.70	12.44	1530.12	3.18	1451.748	3.11	−5.40
Machinery	H	16.20	15.70	62.70	1015.74	2.11	984.39	2.11	−3.18
Electricity	kWh	3015.20	2984.30	3.60	10,854.72	22.54	10,743.48	23.01	−1.04
Input total					48,165.38	100.00	46,688.73	100.00	−3.16

Table 6 Current amount of energy used and optimum energy utilization levels according to the efficiency level of the enterprises

	Energy use in current input composition				Energy use in optimum input composition				Change ratio (%)		
	Fully efficient (TE = 1)	Efficient (0.95–1)	Less efficient (0.90–0.95)	İnefficient (0.899)	Fully efficient (TE = 1)	Efficient (0.95–1)	Less efficient (0.90–0.95)	İnefficient (0.899)	Efficient (0.95–1)	Less efficient (0.90–0.95)	İnefficient (0.899)
Human Labor	12.36	12.47	12.30	12.48	12.36	12.06	11.93	11.98	− 3.36	− 3.12	− 4.14
Fuel (Diesel)	2074.30	2018.44	2076.47	2178.04	2074.29	1980.37	1992.91	2028.36	− 1.92	− 4.19	− 7.38
Seed	0.50	0.50	0.57	0.52	0.50	0.49	0.54	0.51	− 2.90	− 5.51	− 1.94
Pesticides	41.37	52.48	47.14	48.59	41.48	44.49	44.22	37.98	− 17.96	− 6.59	− 27.95
Irrigation Water	305.11	304.87	299.83	304.87	305.11	302.21	293.73	297.76	− 0.88	− 2.08	− 2.39
Nitrogen	1244.26	1358.16	1286.91	1356.53	1244.27	1240.66	1201.49	1192.17	− 9.47	− 7.11	− 13.79
Phosphorus	150.77	149.26	151.65	162.85	150.77	148.02	135.52	140.54	− 0.84	− 11.90	− 15.87
Machinery	99.24	104.05	101.11	103.52	99.21	100.04	96.37	96.96	− 4.00	− 4.92	− 6.77
Electricity	1089.69	1088.81	1070.83	1088.81	1089.70	1079.33	1049.03	1063.45	− 0.88	− 2.08	− 2.38
Total Energy Use	5017.61	5089.04	5046.80	5256.22	5017.69	4907.68	4825.74	4869.71	− 3.70	− 4.58	− 7.94

Table 7 GHG Emissions by source in sunflower production

	Unit	Used quantity	GHG emission coefficients (kg $CO_{2\text{-eq}}$ unit^{-1})	GHG emission (kg $CO_{2\text{-eq}}$ unit^{-1})	Ratio (%)
Human Labor	H	53.87	0.36	19.39	0.49
Fuel (Diesel)	L	370.07	2.76	1021.39	25.67
Seed	Kg	5.20	0.27	1.40	0.04
Pesticides	L	2.32	5.10	11.83	0.30
Irrigation Water	m^3	4824.29	1.70	820.13	20.40
Total Nitrogen	Kg	195.97	1.30	254.76	6.40
Toplam Phosphorus	Kg	122.96	0.20	24.59	0.62
Machinery	H	16.17	0.071	1.13	0.03
Electricity	kWh	3015.20	0.608	1839.27	46.07
Total Input				3993.91	100.00

optimal GHG emissions were calculated to be 3925.85 kg CO_2. It was found that the GHG emission efficiency will increase by 3.68% compared to the average of the farms with optimal input use. According to the inputs, the highest efficiency increase in the use of pharmaceuticals was found to be 9.95%. Like the results of this study, Bakhtiari et al. (2015), Khoshnevisan et al. (2013b) and Khoshnevisan et al. (2013c) found in their emission measurement studies that the source of emissions is largely from electricity and fossil fuels. Electricity generation processes cause a large amount of N_2O and CO_2 emissions. The use of more efficient electric water pumps and/or the utilization of renewable energy sources (such as solar energy, wind resources) will help to reduce greenhouse gas emissions. In addition, lower energy consumption and/or the use of renewable energy sources in agricultural production will help to create environmentally friendly and sustainable production systems for sunflowers.

Table 8 shows the carbon emissions of the enterprises, broken down according to the degree of technical efficiency, both at the current and the optimized input level. The optimization of input use led to an increase in efficiency of 4.67% for efficient enterprises, 5.13% for less efficient enterprises and 9.13% for inefficient enterprises. Based on the input components, the use of pesticides has increased the most change (6.45–27.75%). With optimization, the use of phosphorus (0.84–15.90%) and nitrogen (7.11–13.79%) is also expected to become more effective (Table 9). In a study conducted by Askhan Nabavi Pelesaraei et al. (2014), it was determined that approximately 28% of CO_2 emissions can be mitigated in orchards by optimising inputs.

Table 8 Current and optimum GHG emissions of enterprises

	Unit	GHG emission coefficients (kg CO_2-eq unit^{-1})	Current input use	Current GHG emission (kg CO_2- eq unit^{-1})	Ratio (%)	Optimum input use	Optimum GHG emission (kg CO_2- eq unit^{-1})	Change (%)
Human Labor	H	0.36	53.87	19.39	0.49	52,79	19,00	−2,05
Fuel (Diesel)	L	2.76	370.07	1021.39	25.57	360,66	995,42	−2,61
Seed	Kg	0.27	5.2	1.40	0.04	5,09	1,37	−2,16
Pesticides	Kg	5.1	2.32	11.83	0.30	2,11	10,76	−9,95
Irrigation Water	M^3	0.17	4824.29	820.13	20.53	4774,78	811,71	−1,04
Total Nitrogen	Kg	1.3	195.97	254.76	6.38	185,19	240,75	−5,82
Total phosphorus	Kg	0.2	122.96	24.59	0.62	116,68	23,34	−5,38
Machinery	H	0.07	16.17	1.13	0.03	15,69	1,10	−3,06
Electricity	kWh	0.61	3015.2	1839.27	46.05	2984,26	1820,40	−1,04
Total emission				3993.91	100		3923.85	−3.68

Table 9 Carbon emission at current and optimum input level according to the efficiency level of the enterprises

	GHG emission in current input composition				GHG emission at optimum input composition				Change ratio (%)		
	Fully efficient (TE=1)	Efficient (0,95-1)	Less efficient (0,90-0,95)	Inefficient (0,899)	Fully efficient (TE=1)	Efficient (0,95-1)	Less efficient (0,90-0,95)	Inefficient (0,899)	Efficient (0,95-1)	Less efficient (0,90-0,95)	Inefficient (0,899)
Human labor	19.33	19.52	19.26	19.54	19.33	18.87	18.67	18.75	−3.335	−3.06	−4.04
Fuel (Diesel)	1016.70	989.33	1017.78	1067.54	1016.70	970.67	976.80	994.18	−1.89	−4.03	−6.87
Seed	1.35	1.37	1.53	1.43	1.35	1.33	1.47	1.39	−2.92	−3.92	−2.80
Pesticides	10.61	13.43	12.07	12.47	10.63	11.41	11.34	9.76	−15.04	−6.05	−21.73
Irrigation water	823.32	822.66	809.07	822.66	823.32	815.49	792.60	803.49	−0.87	−2.04	−2.33
Total nitrogen	244.57	266.97	252.95	266.64	244.57	243.86	236.15	234.33	−8.66	−6.64	−12.12
Total phosphorus	24.25	24.00	24.39	26.18	24.25	23.80	21.79	22.59	−0.83	−10.66	−13.71
Machinery	1.12	1.18	1.15	1.17	1.12	1.14	1.09	1.12	−3.39	−5.22	−4.27
Electricity	1840.37	1838.88	1808.51	1838.88	1840.37	1822.85	1771.71	1796.03	−0.87	−2.03	−2.33
Total emission	3981.62	3977.33	3946.71	4056.52	3981.64	3909.41	3831.62	3881.63	−1.71	−2.92	−4.31

4 Conclusion

The study aims to minimize energy consumption and greenhouse gas emissions by optimizing farming inputs when producing sunflowers. The application of DEA analysis is in line with this goal. The data was gathered from 63 surveys conducted in Konya province, a region of great agricultural potential in Turkey. Total input and output energies for sunflower production stand at 48,165.36 MJ and 83,050.14 MJ, respectively. Furthermore, the overall greenhouse gas emissions emanating from sunflower production were determined to be 3993.91 kg CO_2-equivalent per unit. Additionally, by optimizing input usage through DEA, a reduction of 3.16% in energy consumption (46,688.73 MJ) and 3.68% in GHG emissions (3923.85 kg CO_2-equivalent per unit) were attained, while maintaining constant efficiency levels. Moreover, optimization outcomes were evaluated based on the technical efficiency levels of the businesses. Efficient, less efficient and inefficient enterprises achieved savings of 3.70%, 4.58% and 7.94% in energy use, respectively. Additionally, greenhouse gas emissions were reduced by 4.67%, 5.13% and 9.03% for efficient, less efficient, and inefficient enterprises, respectively.

By ensuring enterprises produce in the optimum input composition, it is possible to achieve an energy saving of 3.12% and a reduction in GHG emissions of 3.68%. Optimization models are implemented to easily identify the highly consumed inputs and to optimally adjust their quantities. These outcomes enable reduction of negative impacts on the environment and ecological balance caused by agriculture through input optimization, without compromising food security. Additionally, optimizing inputs will result in a reduction in sunflower production expenses, leading to greater profits for producers, economic stability, and sustainable development.

Future investigations in this domain may expand upon the findings of the current study by examining the optimization of agricultural inputs across diverse regions and varying production conditions. Such research would facilitate an evaluation of how regional disparities influence energy consumption and greenhouse gas emissions. Additionally, given the growing incorporation of technology within agricultural practices, it is imperative to assess the contributions of precision agriculture and artificial intelligence-based analytics to these optimization efforts. Furthermore, the social and economic aspects, including producers' adaptation to these methodologies and the economic advantages associated with such optimizations, warrant consideration. Ultimately, the outcomes of these inquiries could inform the formulation of agricultural policies and the execution of strategies aimed at promoting sustainable agriculture on a global scale through international comparisons.

Author contributions SC designed this study, KA performed data analyses, and drafted and edited the manuscript. ZB and HGD perform statistical analyses and edited this manuscript.

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Data availability The data supporting this study's findings are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

Ethics approval The study was approved by the Republic of Turkey Malatya Turgut Özal Unıversity Social Sciences and Humanities Research Ethics Committee on 27.12.2023 with the decision of the ethics committee board numbered 20/4.

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