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Energy Balance and Greenhouse Gas (GHG) Emissions of Sesame (*Sesamum indicum* L.) Production in Türkiye

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ABSTRACT

The objective of this study was to determine the energy use and greenhouse gas emissions associated with sesame production. Energy use efficiency indicators and greenhouse gas emission rates were calculated for the 2022-2023 production season. The energy input and output for sesame production were found to be 12079.15 MJ ha^{-1} and 30052.44 MJ ha^{-1}, respectively. The study found an energy use efficiency of 2.49, with a specific energy of 12.20 MJ kg^{-1}, an energy productivity of 0.08 kg MJ^{-1}, and a net energy value of 17973.29 MJ ha^{-1}. The direct and indirect energy inputs were calculated to be 4584.41 MJ ha^{-1} (37.95%) and 7494.74 MJ ha^{-1} (62.05%), while the renewable and non-renewable energy inputs were calculated to be 469.12 MJ ha^{-1} (3.88%) and 11610.03 MJ ha^{-1} (98.65%), respectively. The calculation shows that the total greenhouse gas emissions are 380.52 $kgCO_{2-eq}$ ha^{-1} and the greenhouse gas emission rate is 0.38 $kgCO_{2-eq}$ ha^{-1}. Sesame production is highly profitable for the 2022-2023 production season in terms of energy use efficiency.

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Introduction

Sesame is one of the oldest oil crops cultivated by humans and archaeological records show that sesame was cultivated in India about 5000 thousand years ago (Baydar and Erbaş, 2014). Sesame belongs to the genus Sesamum of the family Pedaliaceae, and only the species Sesamum inducum L. (2n=26) is cultivated (Kobayashi 1981). Although it is known that the genetic centre of sesame is Africa (Arıoğlu, 2014), the second genetic centre is Türkiye (Yılmaz et al. 2005).

Sesame (*Sesamum inducum* L.) is an annual herbaceous plant that grows to a height of 80-180 cm. Its seeds are used in various foods, including tahini, bagels, cakes, and cosmetics. Sesame is also an important oilseed (İlisulu, 1973), with its seeds containing approximately 50-60% oil (Yermanos et al., 1972) and 25% protein (Tan, 2012), as well as 20-25% carbohydrates and about 5% mineral matter. Sesame oil is a valuable vegetable oil due to its high content of important unsaturated fatty acids (oleic and linoleic) (Liu et al., 1992). Additionally, the chemical composition of sesame oil contains sesamin, sesamolin, and tocopherols, which exhibit high antioxidant properties (İzgi and Bulut, 2023).

The sesame plant has a high total temperature demand, ranging from 2700 to 3500 ºC. It is a short-day plant that is typically grown as a summer crop in hot climate regions (Baydar and Erbaş, 2014). For optimal sesame cultivation, it is preferred that the soil be sandy-loamy, deep structure, with high organic matter, and an average pH of 5.5-8.0. The first flowers that bloom on the sesame plant develop into capsules earlier and so ripen earlier. According to Arıoğlu (2014), harvesting sesame capsules at different times can lead to problems and yield losses. Sesame is commonly grown as a second crop in southern and southern Anatolia, where the Mediterranean climate prevails, and it significantly contributes to the national economy.

Agricultural production is among the sectors most affected by global drought and climate change. The continuity of agricultural activities and the ability to meet basic nutritional needs, and thus food security, are affected by climate change (Şahin Suci and Kalender, 2022). Efficient use of inputs is crucial for sustainable agricultural production as increased energy consumption can lead to significant environmental issues, such as negative impacts on human health and increased greenhouse gas emissions. The use of machinery, diesel fuel, chemical fertilisers and electricity causes greenhouse gas emissions in agricultural production. As energy input increases, so do greenhouse gas emissions (Karaağaç et al., 2019).

It would be beneficial for researchers to establish databases of greenhouse gas emissions at the country level for each agricultural product. Studies have been conducted on the energy balance of agricultural products. For instance, studies have been conducted on the energy efficiency of various crops such as maize (Konak et al., 2004), wheat (Gökdoğan and Sevim, 2016), legumes (Ertekin et al., 2010) and chickpea (Marakoğlu et al, 2010), sunflower (Bayhan, 2016; Akdemir et al. 2017), sesame (Baran and Gokdogan, 2017). And also research has been carried out on the GHG of cotton (Pishgar-Komleh et al., 2012a), potato (Pisghar-Komleh et al., 2012b), lavender (Demir et al., 2022), wheat (Khoshnevisan et al., 2013), garlic (Baran et al., 2023), watermelon (Demir, 2023), rice (Maraseni et al., 2018), onion (Ozbek et al., 2021) etc. The energy efficiency analysis and GHG emission of sesame production in Manavgat-Antalya has not been investigated. The aim of this research is to determine the inputs used in sesame production in Manavgat district and their energy equivalents in 2023 was conducted.

Materials and Methods

Manavgat is situated approximately 75 km to the east of Antalya city centre, a well-known tourism destination, and about 60 km to the west of the Alanya district. The district is located at a latitude of 36.783 and a longitude of 31.433, with an altitude of 9 meters above sea level. The terrain is characterized by flat plains suitable for cultivation, as well as rugged terrain as one moves from the coast towards the inland areas. The Eynif Plain, nestled amidst the Taurus Mountains, is particularly renowned. Furthermore, the historic city of Side, which is renowned worldwide, is situated in the same area. The district is known for its Mediterranean climate, which is characterized by hot and arid summers and mild and rainy winters (Akış and Kaya, 2018).

This study was conducted in the Manavgat district of Antalya province, Türkiye, during the 2022-2023 production season. The production area covered 20 hectares, and a randomized complete-block design with three replications was employed in a working area of 0.1 hectares. To determine fuel consumption, the full-tank method was utilized. The tank was filled for a specific area and then refilled to its initial level using a calibrated container after the machine completed its task. The fuel consumption per unit area was determined by measuring the area of operation and the amount of fuel filled (Göktürk 1999; El Saleh 2000; Sonmete and Demir 2007). For the purpose of time measurements and area work efficiency calculations, a set of three stopwatches was utilized (Sonmete, 2006). The work efficiencies of the area were calculated as effective area work efficiency. The work efficiency (ha h^{-1}) was determined by using the effective working time spent during the cultivation of trial plots (Güzel, 1986; Özcan, 1986; Sonmete, 2006).

In sesame production, energy inputs such as human labor, machinery, chemical pesticides, chemical fertilizers, diesel fuel, seeds, and irrigation water (Table 1) were quantified in terms of their usage per hectare. The total energy inputs were calculated by multiplying the usage of inputs per hectare by their respective energy equivalents. Sesame was obtained as the output. The energy balance of sesame production was obtained by combining the inputs and outputs in the table. Energy use efficiency, specific energy, energy productivity, and net energy in sesame production were calculated using the following formulas (Mandal et al., 2002; Mohammadi et al., 2008; Mohammadi et al., 2010). According to Koctürk and Engindeniz (2009), various forms of energy input are involved in sesame production, including direct, indirect, renewable, and non-renewable sources.

$$EUE = \frac{\text{Energy output }(\frac{MJ}{ha})}{\text{Energy input }(\frac{MJ}{ha})} \quad (1)$$

$$SE = \frac{\text{Energy input }(\frac{MJ}{ha})}{\text{Sesame output }(\frac{kg}{ha})} \quad (2)$$

$$EP = \frac{\text{Sesame output }(\frac{kg}{ha})}{\text{Energy input }(\frac{MJ}{ha})} \quad (3)$$

$$NE = \text{Energy output (MJ ha}^{-1}) - \text{Energy input (MJ ha}^{-1}) \quad (4)$$

Greenhouse gas emissions per hectare in sesame production were calculated by multiplying the inputs with their respective greenhouse gas equivalent emission values. Using the calculations provided in Table 2, a greenhouse gas emission table was constructed for sesame production, and the greenhouse gas emission rate was determined. To determine greenhouse gas emissions, the formula adapted from Hughes et al. (2011) and Karaağaç et al. (2019) was utilized.

The greenhouse gas emissions per hectare are calculated using the formula:

$$GHG_{ha}=\sum i=1nR(i)\times EF(i)$$

Where:

GHG_{ha}: the greenhouse gas emissions ($kgCO_{2eq}$ ha^{-1}).

R(i): the application rate of input i (input unit ha^{-1}).

EF(i): the greenhouse gas emission equivalent of input i ($kgCO_{2\text{-}eq}/input_{unit}^{-1}$).

The GHG ratio is an index defined as the amount of GHG emissions per kilogram of yield. In the calculation of the GHG ratio, the formula adapted from Houshyar et al. (2015) and Khoshnevisan et al. (2014) and adopted by Karaağaç et al. (2019) is utilized.

$$I_{GHG} : \frac{GHG_{ha}}{Y} \quad (6)$$

I_{GHG} : GHG ratio ($kgCO_{2\text{-}eq}$ kg^{-1})

Y : Yield (kg ha^{-1})

Table 1. Energy equivalents in agricultural production

Inputs	Unit	Energy equivalent (MJ unit^{-1})	References
Human labour	h	1.96	Singh et al., 2001; Ozalp et al.,2018
Tractor	h	25.40	Singh, 2002; Akbolat et al.,2014
Plough	h	18.70	Singh, 2002; Akbolat et al.,2014
Cultivator	h	14.00	Singh, 2002; Akbolat et al.,2014
Disc harrow	h	19.60	Singh, 2002; Akbolat et al.,2014
Combined grain drill	h	33.30	Alluvione et al., 2011
Roller	h	17.90	Alluvione et al., 2011
Centrifugal fertilizer spreader	h	11.00	Alluvione et al., 2011
Boom-type sprayer	h	9.20	Alluvione et al., 2011
Trailer	h	64.10	Singh, 2002; Akbolat et al.,2014
Herbicide	kg	288	Kitani, 1999; Ekinci et al., 2020
Insecticide	kg	363.60	Pimentel, 1980; Ekinci et al., 2020
N	kg	60.60	Singh, 2002; Demircan et al., 2006
P	kg	11.10	Singh, 2002; Demircan et al., 2006
K	kg	6.70	Singh, 2002; Demircan et al., 2006
Diesel Fuel	l	56.31	Singh, 2002; Demircan et al., 2006
Irrigation water	m^3	0.63	Yaldiz et al.,1993; Ertekin et al., 2010
Seed	kg	30.356	Baran and Gokdogan (2017)
Output	Unit	Energy equivalent (MJ unit^{-1})	Reference
Sesame	kg	30.356	Baran and Gokdogan (2017)

Table 2. Greenhouse gas emission (GHG) equivalents in agricultural production

Inputs	Unit	GHG equivalent (kgCO_{2-eq} unit^{-1})	References
Tractor and Machinery	MJ	0.071	Dyer ve Desjardins, 2006; Ekinci et al., 2020
Herbicide	kg	6.300	Lal, 2004; Ekinci et al., 2020
Insecticide	kg	5.100	Lal, 2004; Ekinci et al., 2020
N	kg	1.300	Lal, 2004; Ozalp et al.,2018
P	kg	0.200	Lal, 2004; Ozalp et al.,2018
K	kg	0.200	Lal, 2004; Ozalp et al.,2018
Diesel fuel	l	2.760	Dyer ve Desjardins, 2006; Ozalp et al., 2018

Results and Discussion

Table 3 presents the energy balance of sesame production. The total energy input for sesame production is calculated as 12079.15 MJ ha^{-1}, while the energy output is 30052.44 MJ ha^{-1}. The energy inputs consist of 6642.3 MJ ha^{-1} (54.99%) from chemical fertilizer energy, 4206.36 MJ ha^{-1} (34.82%) from diesel fuel energy, 416.7 MJ ha^{-1} (3.45%) from chemical pesticide energy, 344.67 MJ ha^{-1} (2.85%) from tractor and machinery energy, 230.63 MJ ha^{-1} (1.91%) from human labor energy, 147.42 MJ ha^{-1} (1.22%) from irrigation water energy, and 91.07 MJ ha^{-1} (0.75%) from seed energy. The output energy is calculated as 30052.44 MJ ha^{-1}. Similarly, Baran and Gokdogan (2017) calculated the chemical fertilizer input in sesame production as 57.25%, Konak et al. (2004) estimated the chemical fertilizer input in maize production as 48.27%, Karaağaç et al. (2011) as 65.93% in wheat production, Vural and Efecan (2012) as 51.47% in maize production, and Gökdoğan and Sevim (2016) as 43.84% in wheat production.

Table 4 presents the calculations for energy input, output, use efficiency, specific energy, efficiency, and net energy for sesame production, based on the production of 990 kg of sesame. The total energy input was 12079.15 MJ ha^{-1}, while the total energy output was 30052.44 MJ ha^{-1}. The energy use efficiency was calculated to be 2.49, with a specific energy of 12.20 MJ kg^{-1}, an energy productivity of 0.08 kg MJ^{-1}, and a net energy value of 17973.29 MJ ha^{-1}. In previous studies, various values for energy use efficiency in sesame and maize production have been reported. Akpınar et al. (2009) calculated the efficiency as 1.80 and 1.40 for main and double cropping sesame, respectively, while Ibrahim (2011) reported a value of 5.20, Baran and Gokdogan (2017) obtained a value of 1.52 for sesame production, Konak et al. (2004) calculated energy use efficiency in maize production as 3.68.

The energy inputs in sesame production have been classified into four categories: direct, indirect, renewable, and non-renewable (as shown in Table 5). The direct energy inputs in sesame production have been calculated to be 4584.41 MJ ha^{-1} (37.95%), while the indirect energy inputs have been calculated to be 7494.74 MJ ha^{-1} (62.05%). Additionally, renewable energy inputs have been calculated to be 469.12 MJ ha^{-1} (3.88%), and non-renewable energy inputs have been calculated to be 11610.03 MJ ha^{-1} (96.12%). Similarly, in studies on sesame, wheat, maize, chickpea, and cotton production, it has been found that non-renewable energy inputs exceeded renewable energy inputs (Baran and Gokdogan, 2017; Tipi et al., 2009; Vural and Efecan, 2012; Karaağaç et al., 2019; Baran et al., 2021).

Table 3. Energy balance of sesame production

Inputs	Unit	Energy equivalent (MJ unit^{-1})	Input used per hectare (unit ha^{-1})	Energy value (MJ ha^{-1})	Ratio (%)
Human labour	h	1.96	117.67	230.63	1.91
Tractor and Machinery				344.67	2.85
Tractor	h	25.40	7.51	190.75	1.58
Plough	h	18.70	2.50	46.75	0.39
Cultivator	h	14.00	1.17	16.38	0.14
Disc harrow	h	19.60	1.00	19.60	0.16
Combined grain drill	h	33.30	1.17	38.96	0.32
Roller	h	17.90	0.83	14.86	0.12
Centrifugal fertilizer spreader	h	11.00	0.17	1.87	0.02
Boom-type sprayer	h	9.20	0.50	4.60	0.04
Trailer	h	64.10	0.17	10.90	0.09
Herbicide	kg	288	0.50	144.00	1.19
Insecticide	kg	363.60	0.75	272.70	2.26
Chemical fertilizers				6642.3	54.99
N	kg	60.60	103.00	6241.80	51.67
P	kg	11.10	22.50	249.75	2.07
K	kg	6.70	22.50	150.75	1.25
Diesel fuel	l	56.31	74.70	4206.36	34.82
Irrigation water	m^3	0.63	234	147.42	1.22
Seed	kg	30.356	3.00	91.07	0.75
Total				12079.15	100
Outputs	**Unit**	**Energy equivalent (MJ unit^{-1})**	**Output per hectare (unit ha^{-1})**	**Energy value (MJ ha^{-1})**	**Ratio (%)**
Sesame	kg	30.356	990.00	30052.44	100
Total	kg	30.356	990.00	30052.44	100

Table 4. EUE calculations in sesame production

Calculations	Unit	Values
Sesame	kg	990.00
Energy input	MJ ha^{-1}	12079.15
Energy output	MJ ha^{-1}	30052.44
EUE	-	2.49
SE	MJ kg^{-1}	12.20
EP	kg MJ^{-1}	0.08
NE	MJ ha^{-1}	17973.29

Table 5. Energy inputs in the forms of energy for sesame production

Energy groups	Energy input (MJ ha^{-1})	Ratio (%)
DE[a]	4584.41	37.95
IDE[b]	7494.74	62.05
Total	12079.15	100
RE[c]	469.12	3.88
NRE[d]	11610.03	96.12
Total	12079.15	100

[a]Human labour, diesel fuel, irrigation water; [b]Machinery, chemicals, chemical fertilizers, seed; [c]Human labour, irrigation water, seed; [d]Machinery, chemicals, chemical fertilizers, diesel fuel

Table 6. GHG emissions in sesame production

Inputs	Unit	GHG coefficient (kg CO_{2eq} unit^{-1})	Input used per area (unit ha^{-1})	GHG emissions (kg CO_{2eq} ha^{-1})	Ratio (%)
Tractor and Machinery	MJ	0.071	344.67	24.47	6.43
Herbicide	kg	6.300	0.50	3.15	0.83
Insecticides	kg	5.100	0.75	3.83	1.01
N	kg	1.300	103.00	133.90	35.19
P	kg	0.200	22.50	4.50	1.18
K	kg	0.200	22.50	4.50	1.18
Diesel fuel	l	2.760	74.70	206.17	54.18
Total				380.52	100
GHG ratio (per kg)				0.38	

According to greenhouse gas emission calculations of inputs in sesame production, 206.17 kg CO_{2eq} ha^{-1} (54.18%) diesel, 133.90 kg CO_{2eq} ha^{-1} (35.19%) N, 24.47 kg CO_{2eq} ha^{-1} (6.43%) tractor/machine, 4.5 kg CO_{2eq} ha^{-1} (1.18%) P, 4.5 kg CO_{2eq} ha^{-1} (1.18%) K, 3.83 kg CO_{2eq} ha^{-1} (1.01%) insecticide and 3.15 kg CO_{2eq} ha^{-1} (0.83%) herbicide and the total greenhouse gas emission is 380.52 kg CO_{2eq} ha^{-1}. The greenhouse gas emission rate was calculated as 0.38 kg CO_{2eq} ha^{-1}. In other studies, Khoshnevisan et al. (2013) calculated total GHG emission in wheat production as 2711.58 kg CO_{2eq} ha^{-1}, Imran and Ozcatalbas (2012) calculated total GHG emission in wheat production as 592.12 kg CO_{2eq} ha^{-1}, Karaağaç et al. (2019) calculated total GHG emission in chickpea production as 1638.85 kg CO_{2eq} ha^{-1}, Ozbek et al. (2021) calculated GHG emission in onion production as 2920.73 kg CO_{2eq} ha^{-1}, Baran et al. (2021) calculated GHG emission in cotton production as 6482.36 kg CO_{2eq} ha^{-1}.

Conclusion

This study calculated the energy use efficiency, specific energy, energy efficiency, net energy values, greenhouse gas emissions, and greenhouse gas emission rate of sesame production.

The total energy input in sesame production was 12079.15 MJ ha^{-1}, while the energy output was 30052.44 MJ ha^{-1}

On average, 990 kg of sesame was produced per hectare. Based on the energy use efficiency calculations, the energy use efficiency was determined to be 2.49, with specific energy at 12.20 MJ kg^{-1}, energy efficiency at 0.08 kg MJ^{-1}, and net energy value at 17973.29 MJ ha^{-1}.

For sesame production, direct energy inputs accounted for 37.95% (4584.41 MJ ha^{-1}), while indirect energy inputs accounted for 62.05% (7494.74 MJ ha^{-1}). Renewable energy inputs were 3.88% (469.12 MJ ha^{-1}), and non-renewable energy inputs were 96.12% (11610.03 MJ ha^{-1}).

The total greenhouse gas emissions are 380.52 kg CO_{2eq} ha^{-1}, with a calculated emission rate of 0.38 kg CO_{2eq} ha^{-1}.

In terms of energy use efficiency, sesame production is profitable as of the 2022-2023 production season data.

To further increase efficiency, it is recommended to use farm manure instead of chemical fertilisers, which constitute the highest input at 6642.3 MJ ha^{-1} (54.99%), in order to increase the ratio of renewable energy inputs in sesame production.

It is important to increase the use of renewable energy sources to reduce greenhouse gas emissions. Additionally, organic or renewable energy sources should be used in inputs instead of chemical fertilisers.

This study is the first to examine sesame energy balance and greenhouse gas emissions in the region, and will contribute to future studies and literature.

The agriculture sector both consumes and produces energy. The demand for food has led to an increase in energy usage in agriculture. The excessive use of energy in crop production poses a threat to both energy security and the environment's sustainability. Sustainable agriculture and environments are interdependent; therefore, efficient energy use in crop production is a prerequisite for sustainable agriculture (Imran and Ozcatalbas,, 2012).

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