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RESEARCH

Energy Use Efficiency and Greenhouse Gas Emissions in Plum (*Prunus domestica* L.) Production: Evidence from Central Türkiye

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Abstract

This research sought to study the amount of energy and the amount of greenhouse gas released in the plum growing in Akşehir, a district of Konya. The information was obtained from the farmers mentioned above, by means of questionnaires which were filled up during a part of the 2025 harvest. In order to ascertain the energy and emission values of all inputs, standard references available to workers in agricultural investigations were used. Total energy input was found to be 10,441.48 megajoules per hectare, while total energy output was 26,127.53 megajoules per hectare. This means that for one unit of energy put in, there is about 2.53 units received. Nearly one half of all energy used is in the form of electricity, which also has the greatest potential effect on the general appearance of the farm from the point of view of its energy economy. The total amount of greenhouse gases evolved was estimated to be about 1217 kg per hectare, in terms of equivalent CO, of which about three-fourths come from the use of electric energy. These results show that there is an efficient use of energy in the growing of plums in this region, but that it is rather limited in its possibilities for improvement in environmental quality on account of the rare use of renewable energy. The greatest possibilities for use of this renewable energy lies in the way of increased use of solar energy for irrigation and from the use of machinery that is more economical in energy used for that purpose. The general effect of this would be a decrease in cost of production which would mean greater opportunity for agricultural enterprise and at the same time an improved quality of the farm from the point of view of it being more happily located in a less polluted environment.

Keywords Plum (*Prunus domestica* L.) · Carbon footprint · Sustainable fruit production · Energy use efficiency

Introduction

Fruit production is becoming increasingly relevant in the context of sustainable agriculture, largely due to rising energy demands and growing environmental pressures. As the global population expands and consumption habits evolve, the need for efficient use of agricultural inputs has become more urgent (Tang et al. 2018). The energy used in farming not only influences how efficiently food is produced but also carries significant environmental consequences. Unchecked energy consumption contributes to major issues such as greenhouse gas emissions, soil degradation, and water pollution (Esengün et al. 2007; TURKSTAT 2023). For this reason, improving energy efficiency is widely seen as a core element of sustainable agricultural development (Singh et al. 1997; Mandal et al. 2002).

Energy lies at the heart of agricultural production and has long been tied to economic growth. But as farmland becomes more limited and producers face growing pressure to increase their earnings, the drive to boost yields per hectare has led to a heavier reliance on energy (Özbek et al. 2023). In fruit farming-especially crops like lemon, banana, and pomegranate-this often means greater use of chemical fertilizers, diesel fuel, and electricity, which together make up most of the energy consumed (Baran and Kadak 2025). One of the more troubling outcomes is the rise in nitrous oxide (N_2O) emissions, mainly from nitrogen-rich fertilizers, which significantly add to agriculture's carbon footprint (Lal 2004; Dyer and Desjardins 2006). In this context, taking a closer look at where and how energy is used in fruit

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production has become essential-not just for keeping farms economically viable, but also for reducing their impact on the environment.

With its diverse climate and rich ecological zones, Türkiye provides ideal conditions for cultivating a wide range of fruit species. Among these, plum (Prunus domestica L.) holds a special place due to its broad genetic variation and strong economic value. The presence of multiple varieties with different ripening periods allows for an extended harvesting season across the country (Karamürsel et al. 2023). Studies focusing on stone fruits have shown that choices around training systems and planting density can significantly shape energy efficiency, with denser planting often leading to more efficient use of resources (Tabatabaie et al. 2012; Bayav and Karlı 2020). In plum production, as in many other fruit crops, a large portion of total energy use comes from fertilization, irrigation, and electricity consumption (Gül et al. 2022; Kadakoğlu and Karlı 2022). These patterns highlight the need for a production approach that not only considers technical improvements but also aligns with site-specific conditions and input strategies to enhance sustainability.

In Türkiye, there have been several studies on the energy use in agriculture, production cost of a range of crops, and the environmental efficiency of alternative systems. For instance, Baran et al. (2017a) examined energy efficiency in walnut production and Karlı et al. (2017) economics of cotton production in Şanlıurfa. Gündüz et al. (2016) analyzed technical efficiency in Samsun tomato production, whereas Kadakoğlu and Karlı (2022) analyzed cost structure of potato farming in Afyonkarahisar. Some of the other research are Gökdoğan (2022), wherein energy consumption and profitability of kiwifruit production were analyzed in Mersin, and Gül et al. (2022), wherein economic performance of eggplant farming in Antalya was analyzed. Energy aspects associated with apple farming were studied by Yılmaz and Bayav (2022), and energy efficiency and emissions associated with lemon farming were studied by Özbek et al. (2023). Moreover, they investigated the energy and carbon emissions in products such as Apple (Demir 2024), cherry (Gökdoğan et al. 2024), orange (Ağizan et al. 2025), winegrapes (Güner and Candemir 2026), wolfberry (Oğuz et al. 2019), lavender (Demir et al. 2022), sunflower (Baran et al. 2016), cotton (Gokdogan et al. 2016), cumin (Yilmaz et al. 2021), vetch (Kokten et al. 2017), garlic (Baran et al. 2023), sudan grass (Tutar et al. 2025). The influence of good agricultural practices has been studied Baran (2022) in persimmon cultivation, and Aydın and Aktürk (2018) in peach and cherry cultivation. Plums, however, have been studied by Baran et al. (2017b) in terms of energy input-output balances, and Karamürsel et al. (2023) have investigated the influence of different training systems on yield and fruit quality. Although this body of literature is growing, the study of plum production remains general in its scope and fails to consider comparative analysis of the methods of production and energy profiles, and there remains a gap in the literature that needs to be addressed.

These include the energy use efficiency (EUE), specific energy (SE), energy productivity, and net energy (NE) that allow us to not only understand the way a production system works but also what its environmental impacts are. The configuration of inputs and the level of their use are determinant to these outcomes (Baran et al. 2017b; Mohammadi et al. 2008). Research on crops like banana, pomegranate and lemon has indicated that small adjustments in energy consumption can lead to substantial differences in terms of economic benefits as well as environmental footprints (Banaeian and Zangeneh 2011; Gündoğmus 2013). In this wider horizon, the study of energy and environmental efficiency in plum farming is a very useful point of view with which to reformulate sustainability in fruit growing.

Recent studies indicate that separation of direct from indirect energy use in fruit production- and retaining renewables as the dominant energy source-can improve efficiency significantly and reduce environmental footprint (Rafiee et al. 2010). While farms are weaned from fossil fuel with more dependency on local renewable resources, this also means a significant reduction in greenhouse gas emissions (Graefe et al. 2013; Houshyar et al. 2015). A deeper knowledge of where, and how, energy is being used in plum cultivation, therefore, can make a significant contribution towards establishing the baseline for more sustainable and climate-resilient operations in Türkiye's fruit sector.

Methodology

The research was carried out in Akşehir province in Konya city located in Türkiye's Central Anatolia Region. Aksehir, an important district in the Konya province of Türkiye with its favorable climate conditions fertile soils and well-organized irrigation facilities is known as a famous region for plum production. Data were gathered through face-to-face interviews with local farmers who were actively producing during the 2025 season. The questionnaire covered a range of topics including types of inputs used, energy consumption, farming practices, irrigation methods, and crop yields. The sample size was determined using the simple random sampling method outlined by Newbold (1995), which allows each farmer in the population an equal chance of being included in the study.

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

In this sampling method, n stands for the number of participants in the sample, p represents the estimated proportion of individuals with a given characteristic, and q is simply (1–p). When there's no prior information about the value of p, it's standard practice to use 0.5, as this yields the maximum required sample size. The margin of error is calculated using the formula d = percentage error × mean, and the appropriate t value is chosen based on whether the sample size is above or below 30. Using these guidelines, the study determined that a sample of 30 farmers would be sufficient. Surveys were carried out in the areas of Akşehir where plum cultivation is most concentrated, including both villages and neighborhoods.

In this study, energy inputs used in plum farming were calculated by multiplying the amount of each input by its corresponding energy equivalent. These coefficients were based on standard values commonly cited in the literature, including Singh (2002), Mandal et al. (2002), and Özkan et al. (2004). Each input-such as human labor, machinery use, fuel, fertilizers, irrigation water, and electricity-was evaluated individually, and total energy input was obtained by summing these components.

Greenhouse gas (GHG) emissions were estimated using emission coefficients linked to the energy content of each input, following reference values from Lal (2004), Dyer and Desjardins (2006), and Khoshnevisan et al. (2014). As shown in Tables 1 and 2, every input was matched with its corresponding emission factor. This allowed for the inclusion of both direct emissions (such as those from fuel, electricity, and water use) and indirect emissions (originating from fertilizers, machinery, and plant protection products), offering a complete view of the system's environmental impact.

In the energy use efficiency analysis, indicators developed by Mandal et al. (2002) and Singh et al. (2002) were used. Accordingly, energy use efficiency (EUE), energy productivity (EP), specific energy (SE), and net energy (NE) values were calculated using the following formulas:

$$\text{Energy use efficiency} = \frac{\text{Energy output}\left(\frac{\text{MJ}}{\text{ha}}\right)}{\text{Energy input}\left(\frac{\text{MJ}}{\text{ha}}\right)} \tag{1}$$

$$\text{Specific energy} = \frac{\text{Energy input}\left(\frac{\text{MJ}}{\text{ha}}\right)}{\text{Yield output}\left(\frac{\text{kg}}{\text{ha}}\right)} \tag{2}$$

$$\text{Energy productivity} = \frac{\text{Yield output}\left(\frac{\text{kg}}{\text{ha}}\right)}{\text{Energy input}\left(\frac{\text{MJ}}{\text{ha}}\right)} \tag{3}$$

$$\begin{aligned}&\text{Net energy} =\\&\text{Energy output}(\text{MJ ha}^{-1}) - \text{Energy input}(\text{MJ ha}^{-1})\end{aligned} \tag{4}$$

The greenhouse gas (GHG) emissions ($\text{kgCO}_{2\text{-eq}}\text{kg}^{-1}$) for producing 1 ha of plum were calculated using the method developed by Hughes et al. (2011). The calculation involves

Table 1 Standard coefficients to compute energy content of outputs and inputs in plum production

Inputs	**Unit**	**Energy equivalent ($\mathbf{MJ\ unit^{-1}}$)**	**References**
Labour	H	1.96	Mani et al. (2007); Karaağaç et al. (2011)
Machinery			
Tractor	H	25.4	Singh et al. (2002)
Plough	H	18.7	Singh et al. (2002)
Pesticides			
Insecticides	Kg	238	Khoshroo and Mulwa (2014); Candemir et al. (2025)
Fungicides	Kg	216	Khoshroo and Mulwa (2014); Bayramoğlu et al. (2025)
Organic fertilizers			
Farmyard manure	Kg	0.30	Singh et al. (2002)
Chemical fertilizers			
Nitrogen	Kg	60.60	Singh et al. (2002); Candemir et al. (2024)
Phosphorus	Kg	11.10	Mandal et al. (2002); Ozalp et al. (2018)
Others			
Diesel	L	56.31	Singh et al. (2002)
Electricity	kWh	3.60	Özkan et al. (2004); Candemir et al. (2025)
Transportation	MJ.t.km	4.5	Fluck and Baird (1982); Kitani (1999)
Output	**Unit**	**Energy equivalent ($\mathbf{MJ\ unit^{-1}}$)**	**Reference**
Plum	Kg	1.90	Singh and Mittal (1992)

Table 2 GHG emissions coefficients in production

Inputs	Unit	GHG equivalent ($kgCO_{2\text{-eq}}$ $unit^{-1}$)	References
Labour	H	0.36	Houshyar et al. (2015)
Machinery	MJ	0.071	Pishgar-Komleh et al. (2012); Eren et al. (2019)
Farmyard manure	Ton	0.005	Meisterling et al. (2009)
Insecticides	Kg	6.300	Graefe et al. (2013)
Fungicide	Kg	3.900	Graefe et al. (2013)
Nitrogen	Kg	1.300	Lal (2004); Candemir et al. (2025)
Phosphorus	Kg	0.200	Lal (2004); Ozalp et al. (2018)
Diesel	L	2.760	Dyer and Desjardins (2006); Ozalp et al. (2018)
Electricity	kWh	0.608	Khoshnevisan et al. (2014)
Transportation	Kg	0.150	Meisterling et al. (2009); Eren et al. (2019)

finding the sum, denoted by $\sum$, of the product of the application ratio of input i ($unit_{input}ha^{-1}$), denoted by R(i), and the GHG emission coefficient of input i ($kgCO_{2\text{-eq}}unit_{input}^{-1}$), denoted by EF(i). However, an index has been devised to measure the amount of $kgCO_{2\text{-eq}}$ emissions spread per kg yield, using the following formula proposed by Houshyar et al. (2015). In this formula, I_{GHG} represents the GHG ratio and Y refers to the yield in kg per ha (Eren et al. 2019).

$$GHG_{ha} = \sum_{i=1}^{n} R(i)\, x EF(i) \tag{5}$$

$$I_{GHG} = \frac{GHG_{ha}}{Y} \tag{6}$$

Discussion

As outlined in Table 3, energy consumption patterns in fruit production vary significantly depending on the crop. In the production of lemons, total energy input was 28,952.20 MJ per hectare, of which the greatest share came from chemical fertilizers (Özbek et al. 2023). Banana production, on the other hand, had enormously greater energy needs of 94,373.80 MJ per hectare, where diesel and fertilizer use was the prevailing structure of inputs (Candemir et al. 2025). In pomegranate cultivation, diesel and chemical fertilizers once more proved to be the major contributors to energy intensity. However, the introduction of renewable energy sources has been suggested as a way to improve overall system efficiency and reduce dependence on conventional inputs (Baran and Kadak 2025). These findings illustrate how each fruit type brings its own energy demands, emphasizing the importance of crop-specific strategies for sustainable resource management.

The findings from plum cultivation reinforce the broader trends observed in fruit production. Total energy input was calculated as 10,441.48 MJ per hectare, while energy output reached 26,127.53 MJ per hectare, resulting in an energy use efficiency (EUE) of 2.53. Electricity use alone made up nearly half of the total input, reflecting the strong influence of modern irrigation technologies on the energy profile. Chemical fertilizers contributed 20.14%, and farm manure accounted for 11.68% of total energy input. This combination suggests a system that not only operates with reasonable efficiency but also includes a notable share of renewable-based inputs, offering a degree of balance between productivity and sustainability.

The energy use results from plum cultivation align well with patterns reported for other fruit crops, confirming earlier research that highlights how intensive use of electricity and chemical fertilizers raises overall energy demand, while integrating renewable inputs can boost system efficiency (Mandal et al. 2002; Lal 2004; Rafiee et al. 2010). In that respect, the large EUE recorded in the production of plums reflects not only a technical achievement but also the result of the balanced input use and efficient energy management. Both these aspects support the robustness of the system to be able to produce sustainably.

There is an existing system which efficiently utilizes energy input with an efficiency use of energy (EUE) of 2.53 units in plum production (Table 4). The information can be considered as an evidence on the existence of corroboratory findings on various researches that show how energy can be efficiently used in the production of fruits. As pointed out by both Tang et al. (2018) and Bilgili (2012), energy efficiency not only symbolizes an intellectual concept. Energy efficiency has proven itself not just as a concept, it also acts as an important indicator of environmental performances which then becomes the base of agricultural sustainability. Contrarily, Soyler et al. (2022) emphasized that though there was an increase in energy consumption in fruit production, it can still be ecologically sustainable.

The values of specific energy (SE) = 0.80 MJ/kg and energy productivity (EP) = 1.33 kg/MJ reveal that plum farming in this particular case offers a substantial level of energy return. This reveals an efficient level of input-output. Mandal et al. (2002), as cited by Esengün et al. (2007), stated

Table 3 EUE in plum production

Inputs	**Unit**	**Energy equivalent (MJ unit^{-1})**	**Input used per hectare (unit ha^{-1})**	**Energy value (MJ ha^{-1})**	**Ratio (%)**
Labor	–	–	42.77	83.82	0.80
Pruning	H	1.96	5.39	10.56	0.10
Soil tillage (2 times)	H	1.96	4.54	8.91	0.09
Fertilizing (Chemical and Farmyard)	H	1.96	7.36	14.42	0.14
Spraying	H	1.96	7.00	13.72	0.13
Irrigation	H	1.96	1.92	3.76	0.04
Harvesting	H	1.96	13.46	26.39	0.25
Transportation	H	1.96	3.10	6.08	0.06
Machinery	–	–	18.87	983.33	9.42
Tractor	H	25.4	14.33	363.93	3.49
Plough (2 times)	H	18.7	4.54	84.98	0.81
Pesticides	–	–	2.48	627.22	6.01
Fungicide	Kg	216	1.00	215.78	2.07
Insecticide	Kg	278	1.48	411.44	3.94
Farmyard manure	Kg	0.3	4066.67	1220.00	11.68
Chemical fertilizers	–	–	55.50	2103.36	20.14
Nitrogen	Kg	60.6	30.05	1820.83	17.44
Phosphorus	Kg	11.1	25.45	282.53	2.71
Diesel	L	56.31	11.09	624.22	5.98
Electricity	kWh	3.6	1477.78	5320.00	50.95
Transportation	H	4.5	3.10	13.95	0.13
Total input	–	–	–	10,441.48	100.00
Output	**Unit**	**Energy equivalent (MJ/unit)**	**Output per hectare (unit ha^{-1})**	**Energy value (MJ ha^{-1})**	**Ratio (%)**
Plum fruit	Kg	*1.90*	13,751.33	26,127.53	*100.00*
Total output	–	–	–	26,127.53	100.00

that energy productivity is remarkably responsive to fertilization practices as well as the level of irrigation efficiency. Similar findings could also be seen in different agricultural systems. Regarding this issue, it was stated by Mohammadi et al. (2008), Banaeian and Zangeneh (2011) that labor employment, use of machinery, or optimal use of irrigation facilities all contribute substantially to efficiently utilize the energy input into crop production. The net energy of 15,686.05 MJ/ha indicates that this production system consumes less energy in comparison with its production energy, which is beneficial, of course. Rafiee et al. (2010), Graefe et al. (2013), showed that this result not only indicated economic viability but potentially healthy environment outcomes. Based on this scenario, it was found by Meisterling et al. (2009), Dyer and Desjardins (2006) that less energy-intensive agricultural production continues to make significant impacts on reducing greenhouse gas production on agricultural farms.

The findings achieved within the framework of the current research fit into the pattern of previous research concerning energy consumption in fruit production systems, which follows from both Tabatabaie et al. (2012) and Baran

Table 4 EUE calculations in plum production

Calculations	Unit	Values
Plum Fruit	kg ha^{-1}	13,751.33
EI	MJ ha^{-1}	10,441.48
EO	MJ ha^{-1}	26,127.53
EUE	–	2.53
SE	MJ kg^{-1}	0.80
EP	kg MJ^{-1}	1.33
NE	MJ ha^{-1}	15,686.05

Table 5 Energy inputs in the varieties of energy for plum production

Energy groups	Energy input (MJ ha^{-1})	Ratio (%)
DE	6028.04	57.73
IDE	4413.44	42.27
Total	*10,441.48*	*100.00*
RE	83.82	0.80
NRE	10,357.66	99.20
Total	*10,441.48*	*100.00*

Table 6 GHG emissions in plum 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 (%)
Labor	H	0.700	42.77	29.939	2.46
Machinery	MJ	0.071	983.33	69.81643	5.74
Farmyard manure	Ton	0.029	4066.67	117.93343	9.69
Insecticides	Kg	6.300	1.00	6.3	0.52
Fungicides	Kg	3.940	1.48	5.8312	0.48
Nitrogen	Kg	1.300	30.05	39.065	3.21
Phosphorus	Kg	0.200	25.45	5.09	0.42
Diesel	L	2.760	11.09	30.6084	2.52
Electricity	kWh	0.608	1477.78	898.49024	73.83
Transportation	kg	4.500	3.10	13.95	1.15
Total	–	–	–	1217.0237	100.00
GHG ratio (per kg)	–	–	–	0.09	–

et al. (2017b). Plant layout or design refers among the factors that undoubtedly affect energy performance, which follows from which, according to Bayav and Karlı (2020), plays an important role in the effectiveness of energy usage throughout all stages of the production process. In that respect, the large EUE recorded in the production of plums reflects not only a technical achievement but also the result of the balanced input use and efficient energy management. Both these aspects support the robustness of the system to be able to produce sustainably.

The higher share of direct energy in plum production (57.73%) than indirect energy (42.27%) indicates that production is strongly dependent on field operations, particularly the use of machinery, diesel fuel, irrigation, and electricity (Table 5). These operations are consistent with previous research explaining the fundamental structure of energy use in fruit growing (Özkan et al. 2004; Bilgili 2012; Pergola et al. 2013). The low share of renewable energy at 0.76% and the high share of non-renewable energy at 99.24% are like the energy profiles reported for lemon and banana production. The inclusion of electrical and chemical inputs as non-renewable energy is the primary factor explaining this high share. However, as noted by Vahid-Berimanlou and Nadi (2021) and Saltuk et al. (2022), increasing irrigation efficiency and expanding the use of organic fertilizers can improve environmental performance by increasing the share of renewable energy.

As shown in Table 6, total greenhouse gas emissions in plum production were calculated as 1217.02 kg CO_2-eq ha^{-1}, with 73.83% of the emissions originating from electricity use. This trend has also been observed in different fruit systems, and it has been reported that electricity-intensive processes are a determining factor in the carbon profile (Özbek et al. 2023; Oğuz et al. 2022; Saltuk et al. 2022). While emissions from diesel and nitrogen fertilizer are relatively low, the carbon intensity of fossil and synthetic inputs increases the total load. The results clearly indicate that optimizing energy inputs and incorporating renewable alternatives-especially in electricity use-can significantly contribute to lowering emissions in agricultural production (Gökduman et al. 2022; Yılmaz and Bayav 2022; Ekinci et al. 2020). This is further supported by findings from sour cherry cultivation, where improved energy efficiency and effective resource utilization have been shown to offer considerable potential for reducing the environmental impact of farming systems (Sarı and Gökdoğan 2024). These insights reinforce the role of energy planning in advancing more sustainable and climate-conscious agricultural practices.

Conclusion

This study contrasted the environmental sustainability of plum production in Türkiye in energy consumption efficiency, renewable energy ratio, and greenhouse gas emissions. The results show that almost half of the total input energy is received through the direct form of energy sources, mainly electricity and fuel, while the consumption of renewable energy is relatively low. The large share of electricity use means that irrigation activities are the dominant drivers of energy use and a key consideration for managing overall system environmental performance. The estimated efficiency of use of energy indicates that production inputs applied are used efficiently in aggregate but with some inefficiencies. Reducing the consumption of electricity and chemical fertilizers will make the process more energy efficient and lower the carbon footprint of the overall process.

Estimation of the emissions of the greenhouse gases suggested that the consumption of electricity accounts for a significant share of total emissions and thus the carbon footprint of energy-intensive irrigation systems is greater.

Application of cleaner technologies such as solar or low-pressure irrigation systems can enhance environmental performance and raise economic sustainability. Coordinated management of energy use and environmental efficiency is vital for meeting sustainability targets in plum production. In Türkiye, plum production relies heavily on direct sources such as electricity and fuel for energy consumption, which contributes significantly to the weight of electricity-based irrigation systems in total greenhouse gas emissions. These findings suggest that policy tools to enhance environmental sustainability should focus on irrigation infrastructure, energy pricing, and input use standards. The study's results provide a basis for policy and practice aimed at achieving more efficient and responsible resource use in agriculture.

Conflict of interest M. Bozdemir Akçil, S. Candemir, H.G. Doğan and Z. Bayramoğlu declare that they have no competing interests.

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