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Energy Use Efficiency and Agricultural Life Cycle Assessment in Table Grape Production in Siirt Province

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Abstract
This study aimed to determine energy use efficiency in table grape production in Siirt Province, Türkiye, and to assess the environmental impacts of the production process using the life cycle assessment (LCA) approach. The primary data were collected through surveys of 179 table grape farms. The sample size was determined using the proportional sample size formula, based on a 99% confidence level and a 10% margin of error. Energy equivalents of inputs, including labor, machinery, fuel, fertilizers, pesticides, irrigation water, and electricity, were calculated. Energy use efficiency, energy productivity, specific energy, and net energy were evaluated. The results showed that total energy input and output were 35,374.97 MJ/ha and 87,635.06 MJ/ha, respectively. Fuel consumption accounted for the largest share of total energy input (34.93%), followed by fertilizer use (27.56%). Energy use efficiency was calculated as 2.48, energy productivity as 0.21 kg/MJ, specific energy as 4.76 MJ/kg, and net energy as 52,260.09 MJ/ha. Direct and indirect energy sources accounted for 53.18% and 46.82% of total energy input, respectively. 81.46% of total energy consumption was derived from non-renewable sources. The LCA results indicated that environmental impacts were mainly associated with irrigation practices, energy consumption, and chemical inputs. Higher impacts were observed in marine ecotoxicity, eutrophication, and freshwater ecotoxicity categories. In conclusion, table grape production was found to be energy-efficient; however, it remained highly dependent on non-renewable energy sources and chemical inputs. Optimizing energy use, promoting renewable energy sources, and adopting environmentally friendly agricultural practices are therefore essential for sustainable table grape production.
Keywords: Energy balance, energy use efficiency, table grape, life cycle assessment

Introduction

The agricultural sector is a strategic sector that extends well beyond food production: it underpins rural development, generates employment, and interacts strongly with agro-based industries. In recent years, the integration of technological advances into production processes, the diffusion of modern farming practices, and public support and incentive schemes have accelerated the structural transformation of the sector and strengthened its competitiveness (İstikbal 2022). Today, the emphasis in agriculture is no longer solely on increasing output; reducing production costs and ensuring the efficient use of resources have become equally prominent objectives. In this context, the growing share of energy-intensive inputs (fuel, electricity, chemical fertilizers, and mechanization) in production costs has made the efficiency of energy use increasingly critical. Excessive or injudicious use of energy inputs in agricultural production raises costs while simultaneously amplifying environmental impacts. Conversely, the optimal and balanced use of inputs not only improves farm profitability but also contributes to the conservation of natural resources and the development of sustainable production systems. The high degree of import dependence for many agricultural inputs further necessitates their more rational and efficient use (Eksik 2026).

Energy flow analysis is one of the most important approaches used to evaluate the development of agricultural production systems and to reveal the sustainability of their production structure. By examining the energy relationship between the inputs used and the outputs obtained in agricultural production, such analyses make it possible to characterize and compare production systems in terms of their energy consumption. Accordingly, improving productivity and preventing unnecessary input use require a careful analysis of the energy equivalents of all inputs used in the production process and of the products obtained (Baran et al. 2019). The joint assessment of energy use and environmental impacts in agricultural production is of great importance both for improving production efficiency and for developing sustainable farming systems. The combined use of energy balance and life cycle assessment methods therefore allows agricultural production systems to be analyzed through a more comprehensive and holistic approach and offers important contributions to the improvement of production processes.

Studies on the determination of energy use and greenhouse gas emissions in agriculture include those conducted on strawberry (Yılmaz et al. 2026), citrus (Ertekin and Comart 2024), berry (Ertekin et al. 2024), pomegranate (Ozalp et al. 2018; Baran and Kadak 2025), cherry (Gökdoğan et al. 2024), fig (Oğuz et al. 2022), pistachio (Gökdoğan et al. 2022), wolfberry (Oğuz et al. 2019), wheat (Demirel et al. 2024), apple (Gökdoğan and Uysal 2024), maize (Kokten et al. 2018), corn silage (Barut et al. 2011), sesame (Baran and Gokdogan 2017), bitter vetch (Kokten et al. 2017), and lavender (Demir et al. 2022), among others.

The main objective of this study was to determine the energy equivalents of the inputs used in table grape production in Siirt Province, to analyze the energy use structure of the production process, and to establish energy use efficiency on the basis of the resulting findings. To this end, the energy equivalents of the principal inputs used in the production process—human labor, machinery, fuel, fertilizers, pesticides, irrigation water, and electricity—were calculated, total energy input and output were determined, and the key energy indicators of energy use efficiency, energy productivity, specific energy, and net energy were evaluated. In addition, the distribution of the energy used in production across direct and indirect, and renewable and non-renewable, energy sources was analyzed so that the energy structure of the production system could be addressed holistically.

A further important aim of the study was to determine the environmental impacts of the table grape production process using the agricultural life cycle assessment (LCA) approach. Within this scope, the environmental burdens, greenhouse gas emissions, and resource use levels associated with the inputs used in production were analyzed in order to reveal the environmental sustainability dimension of production. Furthermore, the stages at which the environmental impacts of the production system are concentrated were identified, with the aim of contributing to the development of more sustainable production strategies.

Materials and Methods

Materials

The main material of the study consisted of data obtained through a questionnaire survey of table grape producers in Siirt Province. The study was conducted on farms operating in the central district of Siirt and in the districts of Baykan, Eruh, Kurtalan, and Pervari, together with their villages, where grape production is concentrated. In addition, data from the relevant public institutions and organizations, chiefly the records of the Siirt Provincial Directorate of Agriculture and Forestry, were used. Statistical data from national and international organizations such as the Turkish Statistical Institute (TurkStat) and the Food and Agriculture Organization of the United Nations (FAO) were also employed. Finally, the findings of previous scientific studies on the subject conducted in Türkiye and in other countries, together with the relevant literature, were reviewed.

Methods

Sampling procedure

According to data obtained from the Siirt Provincial Directorate of Agriculture and Forestry, the total number of grape producers registered in the Farmer Registration System was 1237. The study was conducted on farms in the central district of Siirt and in the districts of Baykan, Eruh, Kurtalan, and Pervari, together with their villages, where grape production is concentrated.

Rather than including all producers, it was considered more appropriate to select a specified number of producers by sampling. Accordingly, the proportional sample size formula (Newbold 1995) was used to determine the sample size, which was calculated as 179 at a 99% confidence level and a 10% margin of error (Eq. 1). The number of producers to be surveyed in each district was determined in proportion to the share of each district in the total number of producers, and the sample was allocated accordingly.

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

where:

n = sample size

N = total number of grape producers

p = proportion of grape-producing farms (taken as 0.50 to obtain the maximum sample size)

σ_{px}^2= variance

Data collection

The direct and indirect energy inputs used in grape production were determined through questionnaire surveys conducted with producers in 2025. Producers were asked questions designed to establish, for each cultivation activity they carried out, the quantity applied, the number of applications, the duration of each application, and the number of persons involved. Specifically, the questionnaire recorded the number of tillage, fertilization, and spraying operations, their duration, and the number of workers engaged in these activities. The number and duration of irrigation events, the duration of harvesting, and the amount of labor employed during harvest were also determined. In addition, data on the fuel consumed by the machinery and equipment used in production were obtained through the survey.

Data analysis

The data obtained through the questionnaires were coded and transferred to a computer environment. To calculate energy equivalents, the quantities of the inputs used in grape production were determined. These input data were then converted into energy values by multiplying them by the corresponding energy equivalent coefficients, which were drawn from previous studies in the literature (Table 1). All energy equivalents of the input items were expressed in megajoules (MJ).

Table 1 Energy equivalents used for the inputs and output of grape production

Inputs and outputs	Unit	Energy equivalent (MJ)	References
Inputs			
Human labor	h	1.96	Mani et al. (2007)
Machinery	h	64.80	Kızılaslan (2009); Singh (2002)
Chemical fertilizers			
Nitrogen (N)	kg	60.60	Singh et al. (2002)
Phosphorus (P_2O_5)	kg	11.10	Singh et al. (2002)
Sulfur (S)	kg	1.12	Nagy (1999)
Micronutrients	kg	120	Singh (2002)
Farmyard manure	kg	0.3	Singh et al. (2002)
Pesticides			
Fungicide	kg	92	Helsel (1992)
Insecticide	kg	199	Helsel (1992)
Diesel fuel	L	56.31	Demircan et al. (2006); Singh (2002)
Water	m^3	1.02	Azizi and Heidari (2013)
Electricity	kWh	3.60	Özkan et al. (2004)
Outputs			
Fruit (grape)	kg	11.80	Özkan et al. (2007)

Energy efficiency calculations are based on comparing the energy equivalents of the inputs used and the outputs obtained on the farms. These calculations make it possible to evaluate how efficiently the resources used in the production process are employed and how effectively these inputs are converted into product. The equations for the main indicators used to determine energy efficiency are given below (Baran 2022).

$$Energy\ output/input\ ratio = \frac{\text{Energy output (MJ/ha)}}{\text{Energy input (MJ/ha)}} \quad (2)$$

$$Energy\ productivity = \frac{\text{Grape yield (kg/ha)}}{\text{Energy input (MJ/ha)}} \quad (3)$$

$$Specific\ energy\ = \frac{\text{Energy input (MJ/ha)}}{\text{Grape yield (kg/ha)}} \quad (4)$$

$$Net\ energy = Energy\ output\ (MJ/ha)\ - Energy\ input\ (MJ/ha) \quad (5)$$

The energy inputs were classified into direct, indirect, renewable, and non-renewable forms of energy, following the classification widely used in the literature (Mandal et al. 2002). This classification allows the nature of the energy sources used in the production process to be characterized more systematically. Renewable energy sources denote forms of energy that are capable of self-renewal in nature and are regarded as sustainable; they comprise inputs such as human labor, farmyard manure, and water. Non-renewable energy sources, in contrast, denote forms of energy with finite reserves that tend to be depleted with use; they comprise fuel, electricity, chemical fertilizers, pesticides, and machinery. Details of this classification are presented in Table 2.

Table 2 Energy forms

Energy form	Unit	Description
Direct energy	MJ	Human labor, fuel, electricity, water
Indirect energy	MJ	Chemical fertilizers, farmyard manure, machinery, pesticides
Renewable energy	MJ	Human labor, farmyard manure, water
Non-renewable energy	MJ	Chemical fertilizers, fuel, pesticides, machinery, electricity

Agricultural Life Cycle Assessment

The agricultural life cycle assessment was carried out in four stages. In the first stage, the goal and scope were defined. The primary goal of the study was stated as the determination of the environmental impacts arising from the grape production process. Accordingly, system boundaries were defined to identify the processes to be

considered in the analysis, and the stages of the production process were delimited as shown in Fig. 1. The functional unit was defined as 1 kg of grapes produced, so that the environmental impacts arising from the table grape production process could be determined.

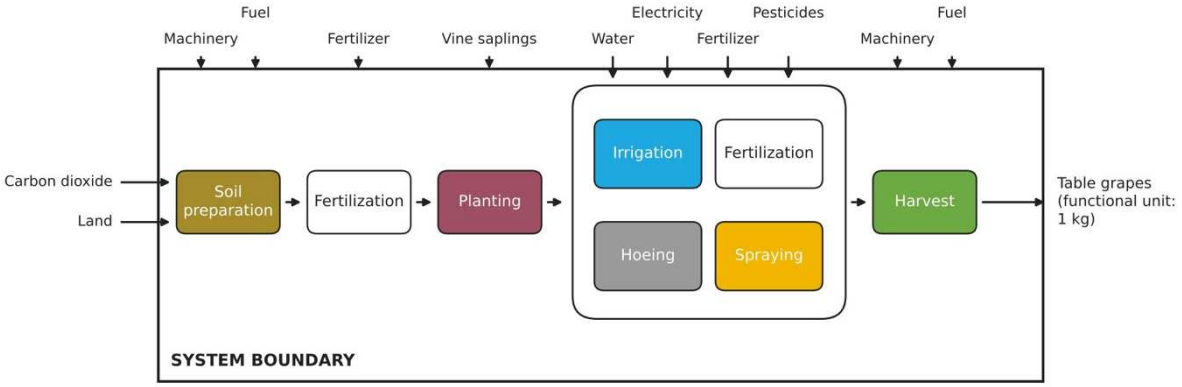


Fig. 1 Agricultural life cycle assessment of grape production

In the second stage, the agricultural life cycle inventory was compiled. Several basic assumptions were made in order to establish the inventory of the table grape production system. The agricultural land on which production takes place was assumed to be level and arable. Production was assumed to be carried out under irrigated conditions, and basic soil properties such as clay content, humus content, and the potential rooting depth of the crop were taken into account. The soil erodibility factor (K factor) of the land was, however, excluded from the assessment. Fertilization was assumed to be practiced, but no machinery use aimed at preventing ammonia losses or soil erosion was assumed. On the basis of these assumptions, the agricultural life cycle inventory of the grape production system was established according to the framework presented in Table 3. The inventory calculations were performed using the equations developed by Eren (2011).

Table 3 Agricultural life cycle inventory

Direct field emissions	Emissions to air	Ammonia (NH_3) Nitrous oxide (N_2O) Nitrogen oxides (NO_x)
	Emissions to water	Nitrate (NO_3^-) leaching Phosphorus (P) emissions Heavy metal emissions (Cd, Cr, Cu, Pb, Hg, Ni and Zn)
	Energy content	
	CO_2 sequestration	
Agricultural machinery	Machinery manufacture	
	Fuel consumption	
	Emissions to air (from fuel combustion)	HC- (NMVOC), NO_x-, CO, CO_2, SO_2, Pb, CH_4, C_6H_6, $PM_{2.5}$, Cd, Cr, Cu, N_2O, Ni, Zn, $C_{20}H_{12}$, NH_3, Se, PAH
	Emissions to soil (from tyre wear)	Zn, Pb, Cd
	Waste heat	

In the third stage, the agricultural life cycle impact assessment was carried out. The data obtained in the life cycle inventory stage were transferred to the licensed SimaPro 8.0.5.13 Analyst software, and impact assessment was performed using the CML-IA baseline method (Table 4).

Table 4 Impact categories and characterization units according to the CML-IA baseline model

Impact category	Characterization unit
Abiotic depletion	kg Sb-eq
Global warming (GWP100)	kg CO_2-eq
Stratospheric ozone depletion	kg CFC-11-eq
Human toxicity	kg 1,4-DCB-eq
Photochemical oxidation	kg C_2H_4-eq
Acidification	kg SO_2-eq
Eutrophication	kg PO_4-eq

In the fourth stage, the agricultural life cycle interpretation was carried out. The life cycle inventory analysis and impact assessment results for the grape production system were considered jointly and interpreted.

Results and Discussion

In this section, the energy equivalents of the inputs were calculated within the framework of the energy analysis of grape production, the energy efficiency indicators were determined, and the forms of energy input were examined under the direct, indirect, renewable, and non-renewable classifications. Finally, a life cycle assessment was carried out to reveal the environmental dimension of the production process, and the environmental impacts of production activities were evaluated. The findings are discussed and interpreted in the light of the literature.

Energy Balance of Grape Production

Energy equivalents of inputs in grape production

The energy equivalents of the inputs used in table grape production in Siirt Province and their distribution within total energy input are presented in Table 5. Total energy input was determined to be 35,374.97 MJ/ha, and this energy varied considerably among input groups. Total energy output amounted to 87,635.06 MJ/ha, indicating that the energy equivalent of the product obtained exceeded that of the inputs.

Fuel accounted for the largest share of energy inputs. Fuel consumption of 219.45 L/ha corresponded to 12,357.23 MJ/ha, or 34.93% of total energy input. Fertilizer use ranked second, with a 27.56% share of total energy input. Nitrogen fertilizer in particular, with an energy equivalent of 5584.29 MJ/ha, accounted for 15.79% of total input—the largest share among the fertilizer inputs. While the energy equivalents of phosphorus, sulfur, and micronutrients remained lower, farmyard manure, with an energy equivalent of 3070.28 MJ/ha, was notable with a share of 8.68%. Machinery accounted for 11.00% of total energy input, corresponding to an energy consumption of 3890.59 MJ/ha, and was concentrated in harvesting (3.66%), tillage (2.75%), and spraying (2.73%).

Pesticide inputs accounted for 8.26% of total energy. Fungicide use, with an energy equivalent of 2299.08 MJ/ha, had a share of 6.50%, whereas insecticide use remained lower (1.76%). Irrigation water and electricity also occupied an important place among the energy inputs: irrigation water, with an energy equivalent of 2769.93 MJ/ha, accounted for 7.83% of the total, and electricity, at 2965.90 MJ/ha, for 8.38%. The energy equivalent of human labor totaled 719.46 MJ/ha, constituting only 2.03% of total energy input. Although labor use was concentrated in harvesting (1.00%) and pruning (0.44%), its share of the total in terms of energy equivalent was very small.

Energy inputs in table grape production thus consisted largely of energy-intensive inputs such as fuel, fertilizers, and machinery, whereas the energy share of labor remained limited. Moreover, the fact that total energy output (87,635.06 MJ/ha) was considerably higher than total energy input (35,374.97 MJ/ha) points to a favorable picture in terms of energy efficiency in production.

Table 5 Input quantities and energy equivalents in grape production

Input	Input quantity (unit/ha)	Energy equivalent (MJ/ha)	Share of total (%)
Human labor (h)		*719.46*	*2.03*
Tillage	15.02	29.44	0.08
Fertilization	27.72	54.33	0.15
Pesticide application	29.75	58.31	0.16
Irrigation	34.80	68.21	0.19
Pruning	79.34	155.51	0.44
Harvest	180.44	353.66	1.00
Machinery (h)		*3890.59*	*11.00*
Tillage	15.02	973.30	2.75
Fertilization	10.12	655.78	1.85
Pesticide application	14.91	966.17	2.73
Harvest	19.99	1295.35	3.66
Fertilizers (kg)		*9749.91*	*27.56*
Nitrogen (N)	92.15	5584.29	15.79
Phosphorus (P_2O_5)	40.28	447.11	1.26
Sulfur (S)	29.14	32.64	0.09
Micronutrients	5.13	615.60	1.74
Farmyard manure	10,234.25	3070.28	8.68
Pesticides (kg)		*2921.95*	*8.26*
Insecticide	3.13	622.87	1.76
Fungicide	24.99	2299.08	6.50

Fuel (L)	219.45	12,357.23	34.93
Irrigation water (m^3)	2715.62	2769.93	7.83
Electricity (kWh)	823.86	2965.90	8.38
Total energy input (MJ)	-	35,374.97	100.00
Output (grape yield) (kg)	7426.70		
Total energy output (MJ)		87,635.06	

The findings on table grape production in Siirt Province are broadly consistent with many studies in the literature in terms of energy use structure and efficiency. In particular, the finding that total energy input derives largely from fuel and fertilizer use is in line with studies showing that energy-intensive inputs play a decisive role in grape production. Koçtürk and Engindeniz (2009) and Rajabi Hamedani et al. (2011) likewise found chemical fertilizers and fossil fuels to be the dominant energy inputs. Similarly, Rasouli et al. (2014) reported that chemical fertilizers accounted for more than 51% of energy inputs, and Karimi and Moghaddam (2018) identified nitrogen fertilizer as the largest energy input. The shares of 34.93% for fuel and 27.56% for fertilizers determined in Siirt Province are therefore consistent with the literature. The fact that fuel had the largest share in the present study reveals the decisive effect of mechanization on energy consumption in production. This finding parallels Malwe et al. (2022), who identified diesel fuel as the largest energy input at 29%, and Say et al. (2024), who found fuel consumption to be concentrated in tillage and harvesting. In some studies, however, fertilizer inputs have a larger share than fuel. Such differences may stem from regional production techniques, levels of mechanization, and fertilization practices.

Energy efficiency indicators

The energy efficiency indicators presented in Table 6 provide a holistic picture of the energy use performance of table grape production in Siirt Province. Total energy input per hectare was 35,374.97 MJ and total energy output 87,635.06 MJ. The energy output/input ratio (energy use efficiency) of 2.48 indicates that approximately 2.48 units of energy output were obtained for every unit of energy entering the system.

Energy productivity, at 0.21 kg/MJ, expresses the amount of product obtained per unit of energy used and indicates that energy conversion in production took place at a certain level of efficiency. Specific energy, in turn, was calculated as 4.76 MJ/kg; this value expresses the amount of energy expended to produce 1 kg of grapes and provides an important indicator of the energy intensity of the production process. Net energy was determined to be 52,260.09 MJ/ha, representing the difference between total energy output and total energy input. Table grape production in Siirt Province thus exhibited a strong performance in terms of energy efficiency, although the structure of the energy inputs used (particularly fuel and chemical fertilizers) increased energy intensity.

Table 6 Energy efficiency indicators in grape production

Energy efficiency indicator	Unit	Mean
Total energy input	MJ/ha	35,374.97
Total energy output	MJ/ha	87,635.06
Energy output/input ratio (energy use efficiency)	-	2.48
Energy productivity	kg/MJ	0.21
Specific energy	MJ/kg	4.76
Net energy	MJ/ha	52,260.09

The energy productivity (0.21 kg/MJ) and specific energy (4.76 MJ/kg) values also differ from those reported in the literature. For example, Uzun and Baran (2022) reported a higher energy productivity of 0.92 kg/MJ, whereas Khoshroo et al. (2018) calculated energy productivity as 0.35 kg/MJ. These differences may arise from yield levels, the quantities of inputs used, the production system (organic or conventional), and regional conditions. The relatively high specific energy in Siirt Province indicates that the inputs used in production are highly energy-intensive and that fuel and fertilizer use in particular increase this value.

Energy input forms

The findings presented in Table 7 detail the distribution of the energy used in table grape production in Siirt Province by energy form and allow a more comprehensive evaluation of the energy structure of the production system. Of the total energy input of 35,374.97 MJ/ha, 53.18% (18,812.52 MJ/ha) consisted of direct energy and 46.82% (16,562.45 MJ/ha) of indirect energy sources. The considerable magnitude of indirect energy input (16,562.45 MJ/ha) reveals that inputs such as fertilizers, pesticides, and machinery and equipment give rise to substantial indirect energy consumption during their manufacture, transport, and use.

Examination of the renewable/non-renewable distinction yields more striking results regarding the sustainability dimension of the production system. Only 18.54% (6559.67 MJ/ha) of total energy input was supplied from renewable energy sources, whereas 81.46% (28,815.30 MJ/ha) derived from non-renewable sources.

Table 7 Energy input forms in grape production

Energy form	Energy input (MJ/ha)	Share of total (%)
Direct energy	18,812.52	53.18
Indirect energy	16,562.45	46.82
Total energy input	35,374.97	100.00
Renewable energy	6559.67	18.54
Non-renewable energy	28,815.30	81.46
Total energy input	35,374.97	100.00

The close balance between direct and indirect energy indicates that the production system has a mixed energy structure. This finding is similar to the direct and indirect energy use ratios reported by Koçtürk and Engindeniz (2009) and Ağızan et al. (2024). At the same time, the high share of non-renewable energy use (81.46%) confirms the dependence on fossil fuels and chemical inputs that is frequently emphasized in the literature; Veisi et al. (2025) and Akdemir (2022) likewise reported that non-renewable energy use was dominant.

Life Cycle Assessment of Grape Production

On the basis of the life cycle inventory data derived from the inputs and outputs of grape cultivation in Siirt Province, life cycle impact assessment was performed in the SimaPro 8.0.5.13 Analyst software according to the CML-IA baseline model. The resulting characterization values are given in Table 8, and the percentage distribution of the cultivation inputs and cultural practices across the impact categories is shown in Fig. 2.

The abiotic depletion potential was calculated as 9.20E-06 kg Sb-eq/kg, with pesticide use during cultivation as its hotspot. The abiotic depletion potential (fossil fuels) was calculated as 4.87 MJ/kg. The global warming potential was 0.53 kg CO_2-eq/kg, with irrigation during cultivation as its hotspot. The ozone layer depletion potential was calculated as 2.17E-07 kg CFC-11-eq/kg, with pesticide use during cultivation as its hotspot. The human toxicity potential was calculated as 0.33 kg 1,4-DCB-eq/kg, with irrigation as its hotspot. The freshwater ecotoxicity potential was calculated as 0.13 kg 1,4-DCB-eq/kg, again with irrigation as its hotspot.

The marine ecotoxicity potential was calculated as 374.00 kg 1,4-DCB-eq/kg, with irrigation during cultivation as its hotspot. The terrestrial ecotoxicity potential was calculated as 1.31E-03 kg 1,4-DCB-eq/kg, likewise with irrigation as its hotspot. The photochemical oxidation potential was calculated as 1.17E-04 kg C_2H_4-eq/kg, with irrigation as its hotspot. The acidification potential was calculated as 4.27E-03 kg SO_2-eq/kg, with the grape crop itself (direct field emissions) as its hotspot; SO_2 and NO_x emissions arising from agricultural activities and energy consumption can cause acidification at the regional scale. The eutrophication potential was calculated as 4.05E-03 kg PO_4-eq/kg, with irrigation during cultivation as its hotspot.

Table 8 Characterization values obtained from the life cycle assessment of 1 kg of grape production in Siirt Province and hotspots

Impact category	Unit	Value per kg	Hotspot
Abiotic depletion	kg Sb-eq	9.20E-06	Pesticides
Abiotic depletion (fossil fuels)	MJ	4.87E+00	Irrigation
Global warming	kg CO_2-eq	5.29E-01	Irrigation
Ozone layer depletion	kg CFC-11-eq	2.17E-07	Pesticides
Human toxicity	kg 1,4-DCB-eq	3.29E-01	Irrigation
Freshwater ecotoxicity	kg 1,4-DCB-eq	1.34E-01	Irrigation
Marine ecotoxicity	kg 1,4-DCB-eq	3.74E+02	Irrigation
Terrestrial ecotoxicity	kg 1,4-DCB-eq	1.31E-03	Irrigation
Photochemical oxidation	kg C_2H_4-eq	1.17E-04	Irrigation
Acidification	kg SO_2-eq	4.27E-03	Grape crop
Eutrophication	kg PO_4-eq	4.05E-03	Irrigation

The life cycle assessment findings are also broadly consistent with studies in the literature. In particular, the identification of irrigation as the hotspot in many impact categories—abiotic depletion (fossil fuels), global warming, human toxicity, freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, and eutrophication—is in agreement with studies revealing the decisive role of energy-intensive irrigation practices in environmental impacts. In a study conducted in Iran, Mohseni et al. (2018) similarly calculated a global warming potential of 0.51 kg CO_2-eq/kg and emphasized the decisive role of irrigation in environmental impacts. The value of 0.53 kg CO_2-eq/kg obtained in Siirt Province is very close to the results

reported in the literature, demonstrating that irrigation-related energy use in particular has a substantial effect on greenhouse gas emissions in grape production.

Fig. 2 shows that the environmental impacts stem largely from irrigation practices, pesticide use, and fertilizer inputs. Irrigation in particular was found to have the dominant effect in the global warming, human toxicity, freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, and eutrophication categories. This indicates that the electricity used for irrigation and the emissions associated with energy consumption play a decisive role in environmental impacts.

Another notable feature of Fig. 2 is the large share of pesticide use in the abiotic depletion and ozone layer depletion categories. The intensive use of energy and chemicals in the manufacture, transport, and application of pesticides increases these impact categories, underscoring the importance of judicious pesticide use and integrated pest management practices in grape cultivation.

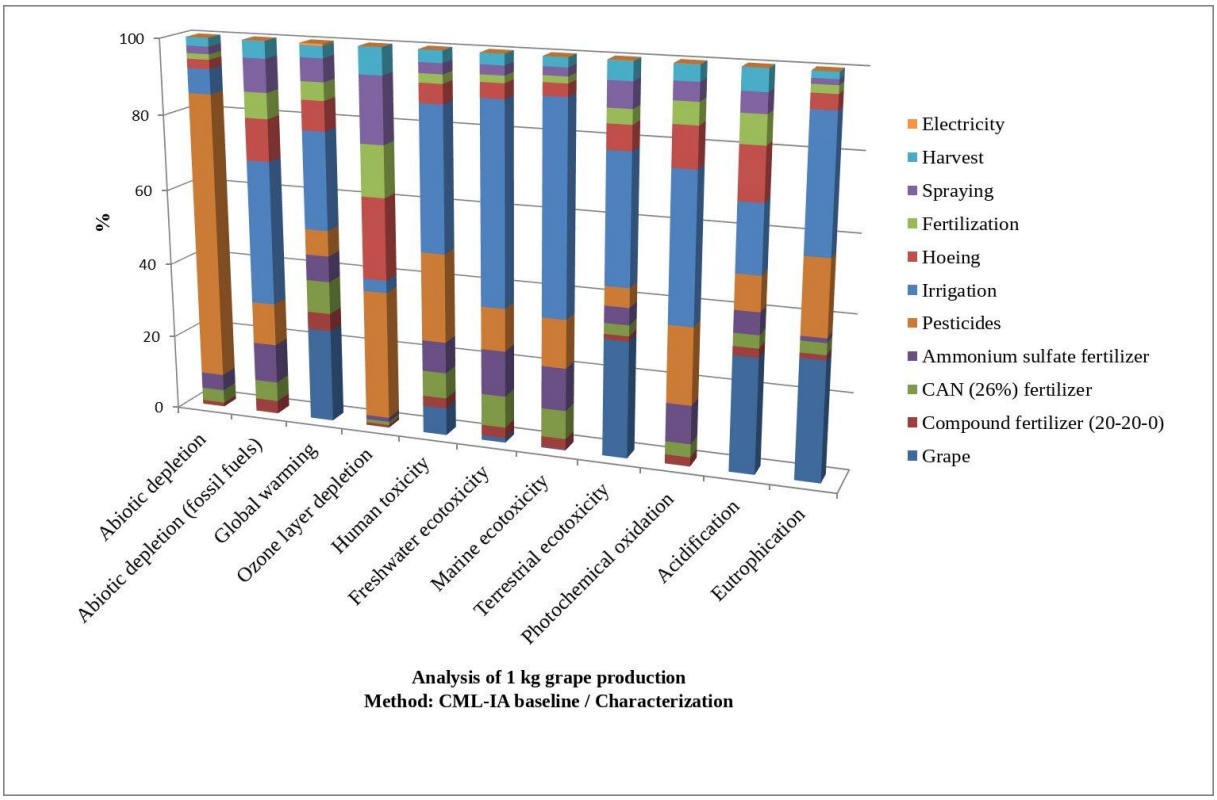


Fig. 2 Distribution of the characterization values obtained from the life cycle assessment by process

The ozone layer depletion potential of 2.17E-07 kg CFC-11-eq/kg, together with the identification of pesticide use as the hotspot in this category, highlights the importance of pesticide-related emissions for environmental impacts. The value obtained in Siirt Province is lower than the 3.10E-07 kg CFC-11-eq/kg reported by Mohseni et al. (2018), which may be attributable to differences between production systems and in the quantities of inputs used.

Table 9 shows that the eutrophication impact is high relative to many other impact categories, indicating that the use of nitrogen- and phosphorus-containing fertilizers in grape cultivation is of particular environmental significance. The abiotic depletion (fossil fuels), global warming, and acidification categories were also found to be at notable levels relative to the other impact categories, demonstrating that energy consumption and fossil fuel use play an important role in the environmental impacts of grape cultivation.

Table 9 Normalization values obtained from the life cycle assessment of 1 kg of grape production in Siirt Province

Impact category	Value (E-12)
Abiotic depletion	0.1086
Abiotic depletion (fossil fuels)	0.1550
Global warming (GWP100)	0.1053
Ozone layer depletion	0.0024
Human toxicity	0.0424
Freshwater ecotoxicity	0.2582

Marine ecotoxicity	3.2092
Terrestrial ecotoxicity	0.0270
Photochemical oxidation	0.0138
Acidification	0.1515
Eutrophication	0.3072

Fig. 3 shows that the marine ecotoxicity category has a considerably higher value than all other impact categories. Once normalization rendered the environmental impacts comparable with one another, the dominance of marine ecotoxicity within the total environmental burden became more pronounced.

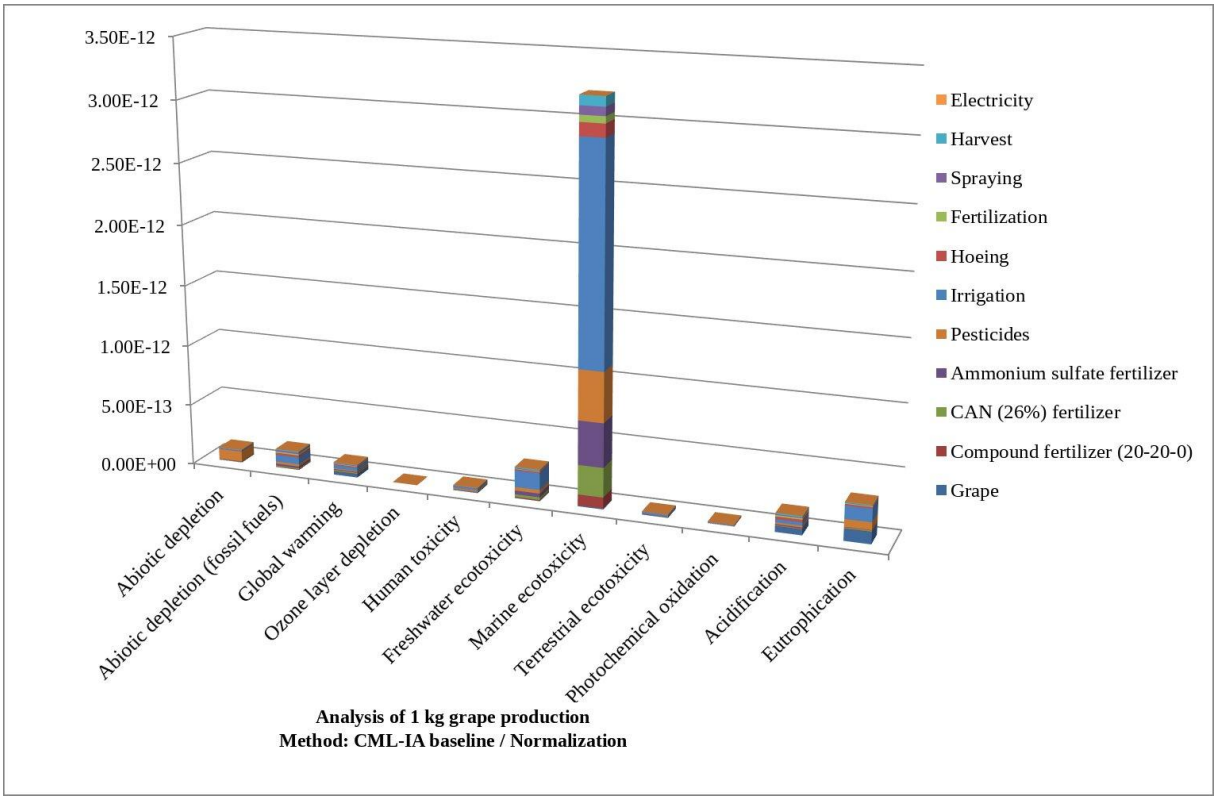


Fig. 3 Comparison of the normalization values obtained from the life cycle assessment by impact category

When the environmental impacts of producing 1 kg of grapes in Siirt Province were compared with one another (Fig. 4), the largest impact was found to occur at the local level (87.75%), followed by impacts at the global (8.48%) and regional (3.77%) levels. The concentration of the majority of environmental impacts at the local scale indicates that grape cultivation exerts pressure particularly on water resources and local ecosystems. The transport of agrochemicals into the environment with the surface runoff generated by irrigation is thought to contribute to the high level of local impacts.

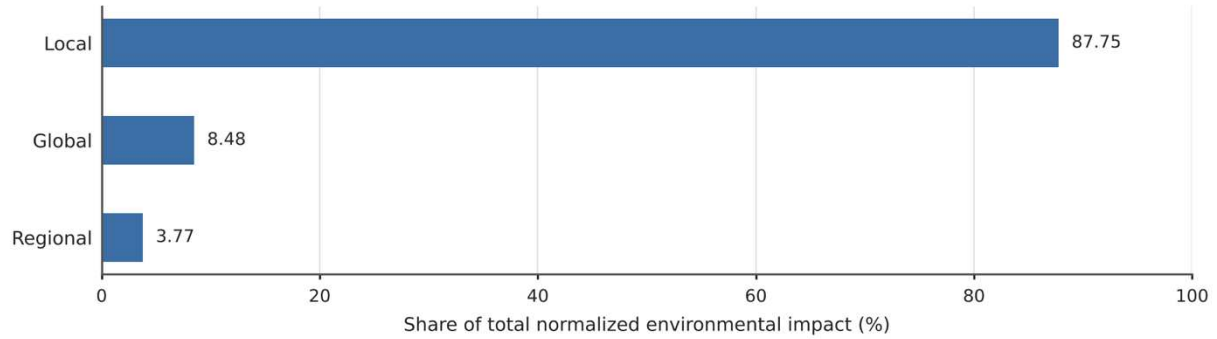


Fig. 4 Comparison of the impact categories

Local impacts

When the impact categories contributing to local impacts were compared with one another (Fig. 5), marine ecotoxicity was found to be high (83.49%). Since there is no sea in the vicinity of Siirt Province, this impact may be disregarded in practical terms. Emissions arising from energy consumption, irrigation practices, and the manufacture of chemical inputs are thought to increase this impact category. Marine ecotoxicity was followed by eutrophication (7.99%). Fig. 5 shows that local environmental impacts are concentrated largely in impact categories related to water resources, underscoring the significance of the environmental pressure generated by irrigation practices in grape cultivation. Nutrients and agrochemicals carried with post-irrigation drainage water can have adverse effects on aquatic ecosystems.

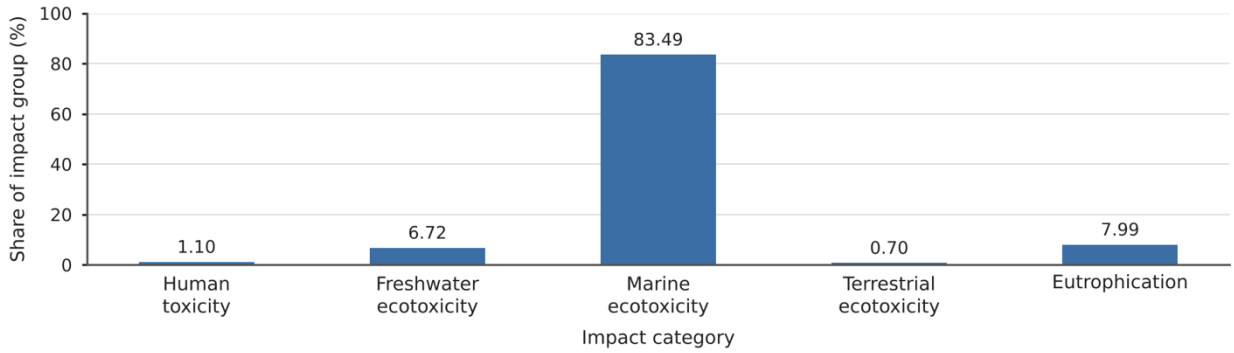


Fig. 5 Distribution of the impact categories contributing to local impacts

Global impacts

When the impact categories contributing to global impacts were compared with one another (Fig. 6), abiotic depletion (fossil fuels) was found to be high (41.74%). Electricity consumption during irrigation is thought to contribute to the increase in abiotic depletion (fossil fuels); in particular, the fact that the electricity used in irrigation systems is generated largely from fossil energy sources raises this impact. Fig. 6 shows that fossil fuel consumption has the largest share among global impacts, demonstrating that energy use is an important element of environmental sustainability in grape cultivation. The global impact of ozone layer depletion was found to be at negligible levels; nevertheless, pesticide use and the emissions generated during agricultural activities may have indirect effects on the ozone layer.

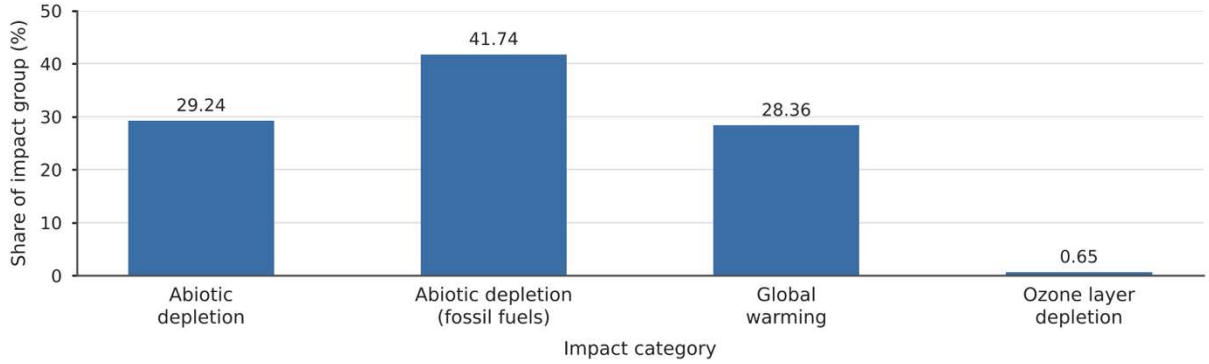


Fig. 6 Distribution of the impact categories contributing to global impacts

Regional impacts

When the impact categories contributing to regional impacts were compared with one another (Fig. 7), acidification was found to be high (91.63%). Fig. 7 shows that regional environmental impacts stem largely from acidification. SO_2 and NO_x emissions arising from energy consumption, irrigation practices, agricultural mechanization, and the use of chemical inputs are thought to be responsible for the high acidification impact. Through various chemical reactions in the atmosphere, these gases can give rise to acid rain and the associated environmental effects.

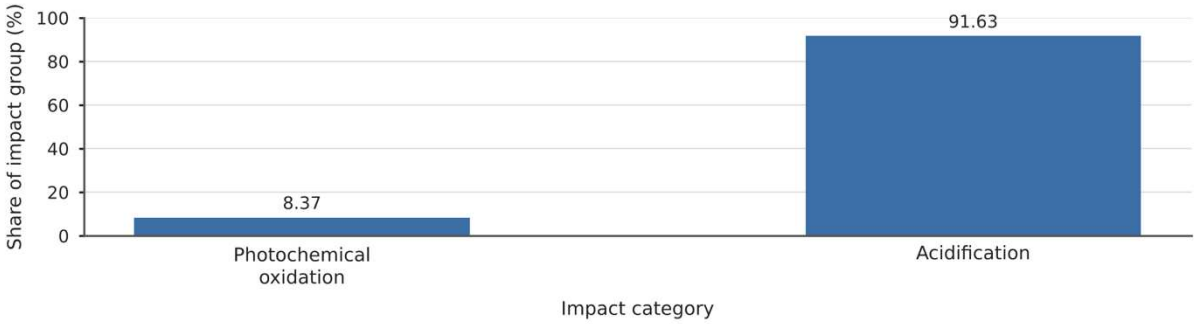


Fig. 7 Distribution of the impact categories contributing to regional impacts

Conclusions

This study evaluated the energy use efficiency of table grape production in Siirt Province through a holistic approach. The energy balance results reveal that a substantial part of total energy input in table grape production consists of energy-intensive inputs such as fuel, fertilizers, and electricity. The high share of fuel in particular clearly demonstrates the dependence of the production system on fossil fuels. Similarly, the considerable share of chemical fertilizers—especially nitrogen fertilizer—in total energy consumption shows that energy-intensive inputs dominate the production process. The high level of electricity used for irrigation stands out as a further important factor increasing the energy dependence of production.

The energy efficiency indicators reveal that the production system has an overall positive energy balance. The energy output/input ratio of 2.48 shows that the energy used in the production process is efficiently converted into product. The relatively high specific energy value, however, indicates that energy consumption per unit of product needs to be reduced. Although the positive and high net energy value shows that production is energetically profitable, the sustainability of this situation depends on the structure of the energy sources used.

Examination of the energy input forms showed that the production system relies largely on non-renewable energy sources. The very high share of non-renewable energy use poses significant risks to both economic and environmental sustainability in the long term. In particular, fossil fuel use and the indirect energy consumption associated with chemical inputs may increase greenhouse gas emissions and intensify pressure on natural resources. Although the current production structure is successful to a certain extent in terms of energy efficiency, there are therefore important aspects that need to be improved from a sustainability perspective.

The life cycle assessment results reveal that the environmental impacts of table grape production in Siirt Province stem largely from irrigation practices, energy consumption, and chemical inputs. The identification of irrigation as the hotspot in many impact categories—abiotic depletion (fossil fuels), global warming, human toxicity, freshwater ecotoxicity, marine ecotoxicity, and eutrophication—shows that the production system is energy-intensive and generates environmental pressure. Because the electricity used for irrigation is generated largely from fossil sources, it increases greenhouse gas emissions and natural resource consumption. In addition, the influence of pesticide use on the abiotic depletion and ozone layer depletion categories reveals that chemical inputs constitute a significant risk factor for environmental sustainability.

The normalization and interpretation results indicate that environmental impacts are concentrated largely at the local scale. The high values found for marine ecotoxicity, freshwater ecotoxicity, and eutrophication in particular show that production activities exert considerable environmental pressure on water resources. Given that Siirt Province lies within the Tigris Basin, one of the region's major catchment areas, the transport of agrochemicals and nutrients into water bodies with post-irrigation surface runoff is considered an important environmental concern requiring attention. In addition, regional impacts such as acidification and photochemical oxidation show that emissions from energy consumption and agricultural activities also affect air quality.

On the basis of these findings, several recommendations are put forward to improve energy efficiency and ensure environmental sustainability in table grape production.

First, optimizing the quantity of chemical fertilizer used in production on the basis of soil analysis will both reduce energy consumption and help to limit environmental impacts. The wider adoption of controlled fertilization practices is particularly important for mitigating environmental impacts such as eutrophication and acidification. Similarly, given the decisive role of pesticide use in environmental impacts, integrated pest management methods should be promoted and judicious pesticide use encouraged.

Authors contribution

This article is derived from the MSc dissertation of Süleyman Eksik, " Energy use efficiency and agricultural life cycle assessment in table grape production in Siirt Province." The authors received no support from any organization. The data supporting the findings are available upon request from the corresponding author. The authors express gratitude to the grape growers who participated in this study.

Declaration

Competing interests

S. Eksik, MF. Baran and B. Doğan Öz declare that they have no competing interests.

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