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Comparative analysis of sustainability factors in greenhouse and open-field strawberry production in Guilan Province, Northwest Iran

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ABSTRACT
Considering the reduction of natural resources, increasing world population, and food security, the development of greenhouse production is necessary. This study aimed to investigate and compare the energy use patterns, economic indices, and associated greenhouse gas emissions by strawberry production in both greenhouse (GH) and open-field (OF) farms in Guilan Province, Northwest Iran. Energy use efficiency was calculated at 0.13 and 0.48 for GH and OF strawberry production, respectively. Applications of fertilizers, human labor, and diesel fuel energy inputs were significant in both production methods. Greenhouse sensitivity analysis showed that an increase of 1 MJ in each water input for irrigation, human labor, and chemical energy would lead to an additional yield increase of 4.13, 2.63, and 2.11 kg ha^{-1}, respectively. Although the mean technical efficiency in GHs is slightly higher than in OFs, the low mean values of technical efficiencies indicate ample room for improvement in operating practices to enhance energy use efficiency for both GH and OF strawberry producers. The benefit-to-cost ratios for strawberry production in the surveyed GHs and farms were calculated to be 1.74 and 1.49, respectively. Diesel fuel and electricity are the main contributors to greenhouse gas (GHG) emissions in GHs. Greenhouses consumed significantly more energy (18 times higher), GH gas emissions (78 times higher), and incurred a higher total cost of production (8.87 times higher). However, GHs were more beneficial for producers as they provided a 25.75-fold higher net return due to their ability to yield more production, producing off-season, and command premium prices. To achieve sustainable development of GHs, more efforts should be made in intelligent management and reducing the consumption of electricity, fuel, fertilizers, and chemicals.

Keywords: Econometric model, Energy productivity, Environmental analysis, GHG emissions, Renewable energy, Scale efficiency.
Article type: Research Article.

INTRODUCTION
Much of the strawberry cultivation in the western region of Iran is done through OF farming, with approximately 90% of the total production being grown in soil. Due to the increasing prevalence of strawberry sensitivity, hydroponic strawberry GHs are becoming more popular. This allows for the cultivation of strawberries in regions where the soil and climate are not suitable for traditional farming methods. Agriculture contributes just over 11% to the gross national product and employs one-third of the labor force. Horticulture is the leading sub-sector of agriculture in Iran. The production quantity of most horticultural crops is sufficient for both domestic consumption and export. Agriculture is the largest economic sector that uses the earth's land, as it occupies 38% of the total land area. Over 15 and 150 ha of GH and OF strawberry production units are active in the Guilan zones (Ministry of Jihad-e-Agriculture of Iran 2020) respectively. In recent decades, area under cultivation of GH crops and its share in the total production of agricultural products has increased significantly. Development of GH complex and the provision of facilities for the development of GHs in Guilan Province are being carried out quickly by the government. However, the indiscriminate use of chemical and diesel inputs in this cultivation system has made the sustainability of these units questionable. Nowadays, energy use in agricultural production in Iran is becoming increasingly intensive due to the use of energy-intensive inputs. Efficient use of energy resources is vital for

increasing agricultural production and competitiveness. Input-output analysis is commonly used to evaluate the energy efficiency and environmental impacts of production systems. Considerable research has been conducted on the energy usage patterns and cost analysis of field crops in agriculture (Dutt 1982, Yaldiz *et al.* 2005). Some studies have been conducted on fruit and vegetables (Gezer *et al.* 2003, Ozkan *et al.* 2004b), while others have focused on GH production (Mohammadi & Omid 2010, Banaeian *et al.* 2010). Particularly in the context of strawberry production, research has explored various aspects, including energy efficiency in GH production (Banaeian *et al.* 2010), energy and economic analysis of production (Salami *et al.* 2010, Banaeian *et al.* 2012, Loghmanpour *et al.* 2013), and comparative assessments of energy use and GH gas emissions in both GH and OF production (Khoshnevisan *et al.* 2014, Yildizhan 2018). The main objective of agricultural production is to increase yield while decreasing costs. The energy budget is important in this regard. In general, increasing agricultural production in a sustainable and cost-effective manner is vital for improving the economic situation of farmers (De *et al.* 2001). This comparative study investigates energy and cost consumption, energy use patterns, technical efficiency, and cost analysis in strawberry production under GH and OF conditions, with a focus on local market considerations. Yildizhan (2018) evaluated the energy utilization in strawberry production in OF and GH using a thermodynamic approach, finding that the energy required for strawberry production in an OF is higher than in a GH. The cumulative degree of perfection values for one ton of strawberry production in OF and GH were found to be 0.29 and 0.18, respectively. The exergy loss values for the production of one ton of strawberries in an open field and a GH were found to be 6163 MJ and 11598 MJ, respectively (Yildizhan 2018).
Khoshnevisan *et al.* (2014) conducted a study on energy usage and energy use efficiency for strawberries in Guilan Province, Iran, comparing results from both OF and GH cultivation. They calculated the levels of technical efficiency (TE), pure technical efficiency (PTE), and scale efficiency (SE) for both OF and GH production. They reported that the total average energy input and output for OF production was estimated at 35,092.4 and 10,405.9 MJ ha^{-1}, respectively. Similarly, for GH strawberry production, the energy input and output were estimated at 1,356,932.8 and 137,772.4 MJ ha^{-1}, respectively (Khoshnevisan *et al.* 2014). In this study, we not only determined the levels of technical efficiency (TE), pure technical efficiency (PTE), and scale efficiency (SE), but also utilized the Cobb-Douglas production function to examine the correlation between energy inputs and strawberry yield. The sensitivity of energy inputs was analyzed using MPP to understand how much variation in a single input would affect strawberry yield in both GH and OF production systems. We calculated the gross value of production, gross return, net return, benefit-to-cost ratio, and economic productivity of strawberry production to provide an economic comparison between GH and OF production. We also evaluated and compared the environmental impacts of both OF and GH production of strawberries. Table 1 provides a review of similar studies that have been conducted in this research area.

MATERIALS AND METHODS

Selection of case study and data collection

Open-field (OF) and greenhouse (GH) data were collected from GH holders who grew single-crop strawberries through face to face questionnaire performed in July-August 2021 in Guilan Province, using a random sampling method. For estimating the size of required sample, Cochran formula, is used that eventually statistical sample method was executed by 18 GHs and 43 farms (Mohammadi & Omid 2010; Banaeian *et al.* 2010; Zangeneh *et al.* 2010). Transplanting strawberries, both in open fields and GHs, typically begins in the autumn while the fields or beds are being prepared. Furrow irrigation in the field should be done once a week, whereas drip irrigation in the GH should be carried out three times a day, with each session lasting for 15 minutes. The OF strawberries were harvested 15 times during the limited period of July-August, while the GH strawberry production had 34 harvests during the January-June period. Raw strawberries are left on the shrub each time to be harvested later. After the harvest period ends, producers prepare for the upcoming planting season. Various inputs such as human labor, machinery, diesel fuel, electricity, fertilizers (including farmyard manure, nitrogen, phosphate, potassium, and micro-nutrients), chemicals, and water for irrigation have been utilized to calculate the energy consumption, efficiency, and production costs of strawberries.

Energy equivalents and energy equations

Energy equivalents of inputs and outputs for both GH and OF strawberry production were obtained from various sources (Table 2). Energy consumption was calculated by applying a conversion factor (e.g., 1 liter of diesel = 56.31 MJ) and reported as MJ per hectare (MJ ha^{-1}). The formula used to calculate machinery energy provided in Eq. 1 was obtained from sources (Ozkan *et al.* 2004a, Ozkan et al. 2007, Mohammadi & Omid 2010).

$$ME = \frac{[EG]}{T} \quad \textbf{(1)}$$

where ME represents the energy consumed by machinery (MJ ha^{-1}), E is a constant value of 62.7 MJ ha^{-1} for tractors, G is the weight of the tractor (kg), and T is the economic lifespan of the tractor (hours).

Table 1. Literature review on energy consumption in greenhouse strawberry production.

	Purpose	Location of study	Examined factors	Methods	References
1	Investigating the Efficiency of Energy Consumption in Greenhouse Strawberry Production	Tehran-Iran	Investigating technical efficiency in relation to fertilizer, labor, fuel, electricity, machinery and water	DEA	Banaeian *et al.* (2011)
2	Examining the energy consumption and efficiency patterns for economic analysis of strawberry production	Tehran-Iran	Estimation of energy rate, energy efficiency, specific energy, net energy, energy intensity, gross production value, gross income, net income, cost-to-profit ratio and efficiency	Cobb–Douglas (CD) production function	Banaeian *et al.* (2010)
3	Investigating energy, exergy, and carbon dioxide emissions in GH and open-farm production of strawberry	-	Cumulative energy consumption, cumulated exergy consumption, cumulated carbon dioxide production and cumulated degree of thermodynamic perfection	-	Yildizhan (2017)
4	Determination of Energy Consumption and Economic Analysis of Strawberry Production	Sanandaj-Iran	Investigating energy efficiency according to labor, machinery, fuel, fertilizer and product output	-	Salami *et al.* (2010)
5	Comparison of Energy Consumption and GH Gas Emissions in Field and GH Production of strawberry	Guilan-Iran	Energy consumption efficiency, energy efficiency, specific energy, net energy, technical efficiency, pure technical efficiency and scale efficiency	DEA	Khoshnevisan *et al.* (2013)
6	Determination of Energy Consumption and Economic Analysis of Strawberry Production	Babolsar-Iran	Energy consumption efficiency, energy efficiency, specific energy, net energy, gross value of the production and economic efficiency of the product	-	Loghmanpor *et al.* (2013)
7	Comparison of Energy Consumption in Conventional GH Strawberry Production versus Solar Technology	Alborz-Iran	Energy consumption, energy efficiency, net energy and specific energy	-	Hosseini-Fashami *et al.* (2019)
8	Investigating the environmental impact of strawberry production in both open-field and GH settings	Guilan-Iran	Environmental factors and gross product value, gross income, net income and cost-to-profit ratio	Artificial neural network	Khoshnevisan *et al.* (2013)
9	analyzing energy consumption and environmental impacts in GH strawberry production, considering the construction of two different types of GH structures (Quonset and Spanish)	Khuzestan-Iran	Human labor, diesel fuel, electricity, total energy consumption, human health index and ecosystem quality	LCA IMPACT World+	Mousavi *et al.* (2023)

Table 2. Energy equivalents of different input and output values used in different farming systems.

Particular	Energy equivalent (MJ $Unit^{-1}$)	References
A. Input		
Human labor (h)	1.96	(Singh *et al.* 2002; Omid *et al.* 2010)
Machinery (h)	13.06	(Ozkan *et al.* 2004a; Omid *et al.* 2010)
Diesel fuel (L)	56.31	(Singh *et al.* 2002; Zangeneh *et al.* 2010)
Fertilizers (kg)		(Ozkan *et al.* 2004a; Zangeneh *et al.* 2010)
Manure	0.3	(Ozkan *et al.* 2004a; Zangeneh *et al.* 2010)
Nitrogen (N)	66.14	(Yilmaz *et al.* 2005; Zangeneh *et al.* 2010)
Phosphate (P_2O_5)	12.44	(Yilmaz *et al.* 2005; Zangeneh *et al.* 2010)
Potassium (K_2O)	11.15	(Yilmaz *et al.* 2005; Zangeneh *et al.* 2010)
Micro	120	(Canakci & Akinci 2006)
Chemicals (kg)		
Pesticides (general)	199	(Ozkan *et al.* 2004a)
Electricity (kWh)	11.93	(Singh & Mittal 1992; Zangeneh *et al.* 2010)
Water for irrigation (m^3)	1.02	(Canakci & Akinci 2006; Omid *et al.* 2010)
B. Output		
Strawberry (kg)	1.9	(Singh & Mittal 1992)

Based on the energy equivalents of the inputs and outputs presented in Table 2, calculations were performed to determine the energy ratio (energy use efficiency), energy productivity, and net energy (Mandal *et al.* 2002; Zangeneh *et al.* 2010).

$$Energy\ use\ efficiency = \frac{Energy\ output\ (MJ/ha)}{Energy\ input\ (MJ/ha)} \quad \textbf{(2)}$$

$$Energy\ productivity = \frac{Strawberry\ output\ (kg/ha)}{Energy\ input\ (MJ/ha)} \quad \textbf{(3)}$$

$$Specific\ energy = \frac{Energy\ input\ (MJ/ha)}{Strawberry\ output\ (kg/ha)} \quad \textbf{(4)}$$

$$Net\ energy = Energy\ output\ \left(\frac{MJ}{ha}\right) - Energy\ input\ \left(\frac{MJ}{ha}\right) \quad \textbf{(5)}$$

The input energy was examined in terms of direct and indirect, renewable, and non-renewable forms. Although direct energy includes human labor, diesel fuel, water for irrigation, and electricity used in strawberry production, indirect energy encompasses the use of machinery, chemicals, and fertilizers. On the one hand, renewable energy sources include human power, water for irrigation, and farmyard manure. On the other hand, nonrenewable energy sources include machinery, diesel, electricity, chemicals, and fertilizers used during the production period (Mandal *et al.* 2002; Hatirli *et al.* 2005).

Econometric model estimation of energy inputs for strawberry production

The Cobb-Douglas production function provided better estimates in terms of statistical significance and expected signs of parameters for energy analysis. The Cobb-Douglas production function is expressed in Eq. 6.

$$Y = f(x)\exp(u) \quad \textbf{(6)}$$

This function has been utilized by multiple authors to analyze the correlation between energy inputs and yield (Rafiee *et al.* 2010; Mohammadi *et al.* 2010; Hatirli *et al.* 2010). Eq. 8 can be linearized and rewritten as shown in Eq. 7.

$$ln\, Y_i = \alpha_0 + \sum_{j=1}^{n} \alpha_j \ln(X_{ij}) + e_i \qquad i = 1,2,\ldots,n \quad \textbf{(7)}$$

where Y_i denotes yield the i^{th} orchard, x_{ij} the vector of energy inputs used in the production process, α_0 constant term, α_j represent coefficients of energy inputs which are estimated from the model and e_i is the error term.
Eq. 8 is expanded in accordance with the assumption that the yield is a function of energy inputs.

$$ln\, Y_i = \alpha_0 + \alpha_1\, ln\, X_1 + \alpha_2\, ln\, X_2 + \alpha_3\, ln\, X_3 + \alpha_4\, ln\, X_4 + \alpha_5\, ln\, X_5 + \alpha_6\, ln\, X_6 + \alpha_7 \ln X_7 + e_i \quad \textbf{(8)}$$

where X_i (i $= 1, 2, \ldots,$9) stand for input energies from diesel fuel (X_1),water for irrigation (X_2), human labor (X_3), fertilizers (X_4), chemicals (X_5), machinery (X_6) and electricity (X_7). With respect to this pattern, using Eq. 8 the impact of energy inputs on yield was studied. In the final stage of the research, the marginal physical productivity (MPP) method was used to analyze the sensitivity of energy inputs on strawberry yield. This method is based on the response coefficients of the inputs. MPP of a factor represents the change in total output resulting from a one-unit increase in the factor input, while holding all other factors constant at their geometric mean level. A positive value of MPP of any input variable indicates that the total output increases by an elevation in that input. Therefore, one should continue to increase the use of variable inputs as long as the fixed resource is not fully utilized. A negative value of MPP of any variable input indicates that each additional unit of input reduces the total output of previous units. Therefore, it is more beneficial to maintain a surplus of the variable resource rather than using it as a fixed resource. The MPP of the various inputs was calculated using the energy inputs using Eq. 9 (Singh *et al.* 2004, Rafiee *et al.* 2010, Mobtaker *et al.* 2010).

$$MPP_{xj} = \frac{GM(Y)}{GM(X_i)} \times \alpha_j \quad \textbf{(9)}$$

where MPP_{xj} is marginal physical productivity of j^{th} input, α_j regression coefficient of j^{th} input, $GM(Y)$, geometric mean of yield, and $GM(X_j)$, geometric mean of j^{th} energy on per hectare basis.

Data envelopment analysis technique

The main models of data envelopment analysis (DEA) have been described in detail by several authors (Charnes *et al.* 1978, Banker *et al.* 1984). Therefore, a comprehensive explanation will not be provided here. The first DEA model was developed by Charnes *et al.* in 1978, which assumes constant returns to scale (CRS). The efficiency score in the presence of multiple input and output factors is shown in Eq. 10 (Omid *et al.* 2010).

$$Efficiency = \frac{Weighted\ sum\ of\ outputs}{Weighted\ sum\ of\ inputs} \tag{10}$$

The concept of Constant Returns to Scale (CRS) suggests that a proportional increase in inputs would lead to a corresponding increase in outputs, resulting in a conical hull as the feasible region of the envelopment problem. A restriction on the intensity vectors of inputs and outputs does not impose any conditions on the allowable returns to scale, which are also known as variable returns to scale (VRS). Under these conditions, the performance frontier line is not restricted to passing through the origin. As a result, an increase in inputs may not necessarily lead to a proportionate elevation in outputs (Cooper *et al.* 2006). Due to convexity, the set of efficient Decision-Making Units (DMUs) forms a convex hull onto which all inefficient points are projected. Due to its greater flexibility and tighter data envelopment, the VRS yields a pure technical efficiency (PTE) score that is equal to or greater than the overall technical efficiency (TE) score obtained from the CRS. The relationship as shown in Eq. 11 can be used to measure the scale efficiency (SE) of GHs (Cooper *et al.* 2006; Nassiri & Singh 2009; Omid *et al.* 2010).

$$Scale\ Efficiency = \frac{Technical\ Efficiency}{Pure\ Technical\ Efficiency} = \frac{CRS\ Score}{VRS\ Score} \tag{11}$$

In summary, the most popular DEA models for efficiency computation are adopted here, including the CCR model for CRS (Charnes *et al.* 1978) and the BCC model for VRS (Banker *et al.* 1984), which were discussed earlier. The data analysis was conducted using the DEA solver software.

Economic equations

From a financial point of view, energy usually costs money. The output–input analysis was also applied in economic benefits analysis. The process was similar for energy balance analysis, with one hectare of experimental field serving as the basic unit for analysis. The economic inputs of these systems include both fixed and variable costs, while the output includes GH or OF products such as strawberries. The economic benefit analysis focuses on the total cost of production, gross value of production, output-to-input ratios, and net returns. In the final section of the research, the net and gross returns, as well as the benefit-cost ratio, were calculated (Gezer *et al.* 2003; Banaeian *et al.* 2010).

$$Gross\ value\ of\ production = \frac{Strawberry\ yield (kg/ha)}{Strawberry\ price\ (\$/kg)} \tag{12}$$

$$Gross\ return = Gross\ value\ of\ production\ \left(\frac{\$}{ha}\right) - Variable\ cost\ of\ production\ (\frac{\$}{ha}) \tag{13}$$

$$Net\ return = Gross\ value\ of\ production\ \left(\frac{\$}{ha}\right) - Production\ cost \left(\frac{\$}{ha}\right) \tag{14}$$

$$BC = \frac{Gross\ value\ of\ production\ \left(\frac{\$}{ha}\right)}{Production\ cost \left(\frac{\$}{ha}\right)} \tag{15}$$

$$Productivity = \frac{Strawberry\ yield (kg/ha)}{Production\ cost \left(\frac{\$}{ha}\right)} \tag{16}$$

Information regarding inputs and crop yield under various production conditions was inserted into Excel spreadsheets. Energy and cost values were then calculated and simulated using Shazam 9.0 software. The DEA

Solver 7.1 software was utilized to calculate constant and variable returns to scale (CRS and VRS) using radial distances to the efficient frontier, and to estimate efficiency.

Greenhouse gas emissions

The GH gas (GHG) emissions from various inputs in both OF and GH farming were calculated by multiplying the quantity per unit area (hectare) of each input by the corresponding emission coefficients provided in Table 3. The results are expressed in terms of kilograms of carbon dioxide equivalent per hectare (kg CO_2 eq. ha^{-1}). The data in Table 3 was collected by Rabiee *et al.* in 2021.

Table 3. Greenhouse gas (GHG) emission coefficients for different inputs used in strawberry production.

Inputs	GHG coefficient (kg CO_2 eq. ha^{-1})	Reference
Diesel fuel (L)	2.76	Khoshnevisan *et al.* (2014)
Machinery (h)	0.071	Nabavi-Pelesaraei *et al.* (2016)
Nitrogen (kg)	1.3	Nabavi-Pelesaraei *et al.* (2016)
Phosphate (kg)	0.2	Pishgar-Komleh *et al.* (2012)
Potassium (kg)	0.2	Khoshnevisan *et al.* (2014)
Pesticides (kg)	5.1	Kitani (1999)
Electricity (kWh)	0.608	Khoshnevisan *et al.* (2014)

RESULTS AND DISCUSSION

The energy indices in strawberry production

Energy use in GH and OF strawberry production

Quantity of inputs and outputs used in GH and OF strawberry production, energy equivalents, and the percentages contributed to the total energy input are illustrated in Table 4.

Table 4. Energy consumption and output for strawberry production.

Inputs/Outputs	**Open-field**		**Greenhouse**	
	Quantity per unit area(ha)	**Total energy equivalent (MJ ha^{-1})**	**Quantity per unit area (ha)**	**Total energy equivalent (MJ ha^{-1})**
Human labor (h)				
Land preparation	168.26	329.78	1536.47	30114.85
Common practice	504.78	989.36	4609.41	9034.45
Harvesting	1009.56	1978.73	9218.83	18068.91
Machinery (h)				
Land preparation	9.3	121.45	-	-
Common practice	1.4	18.28	50.86	664.31
Transportation	34.1	445.34	-	-
Electricity (kWh)	-	-	3076.78	36706.06
Diesel fuel (L)	73.1	4116.26	13192.48	742868.61
Fertilizers (kg)				
Farmyard manure	11024.8	3307.44	-	-
Nitrogen (N)	168.2	18446.45	612.57	40515.77
Phosphate (P_2O_5)	278.9	3469.51	918.86	10245.33
Potassium (K_2O)	-	-	1837.72	22861.33
Micro	3.7	444	51.04	6125.76
Chemicals (kg)				
Pesticides (general)	5.2	329.78	42.8	8530.46
Water for irrigation (m^3)	14756.2	15051.32	10940.53	11159.34
Total energy input		49047.77		909791.86
Strawberry (kg)	12720.1	24161.19	64153.33	121891.33
Total energy Output		24161.19		121891.33

The results revealed that the energy consumption of diesel fuel in OF cultivation (with a share of 8.27%) is 4116.26 MJ ha^{-1}, whereas it is higher than ten times in GHs. During the winter season, GHs require a significant amount of energy to maintain a warm temperature. Diesel fuel is commonly used for this purpose, with a consumption rate of 13192.48 MJ ha^{-1} and a high share of 81.65%. Chemical fertilizer production requires high energy consumption in both OF and GH systems. It ranks first in energy consumption (51.59%) in OF production and second (8.77%, after diesel) in GH production. The electricity usage in GHs was found to be 3076.78 kWh (36706.06 MJ ha^{-1}). On the other hand, the use of drip irrigation with a circulating system in GHs resulted in a reduction of 3815.67 m^3 of water consumption compared to OF irrigation. Water for irrigation and energy in OF ranked second in terms of energy input, accounting for 30.25% of the total energy input. However, in GH this share is only 1.24% of the total input energy. According to Table 4, using human labor, machinery, and chemicals accounted for 3.31%, 0.08%, and 0.93% of the total energy input for GH strawberry production, while in OF production, they accounted for 6.63%, 1.19%, and 2.07%, respectively. The most labor-intensive task in both GH and OF strawberry production is harvesting. The most mechanized operation in open fields was land preparation, which required 121.45 MJ ha^{-1}. In GHs, the only mechanized operation was common practices, specifically spraying. In general, the total energy inputs consumed per hectare in OF and GH cultivation were calculated to be 49,752.77 and 909,791.86 MJ ha^{-1}, respectively. The strawberry yield obtained was 12,720.1 and 64,153.33 kg ha^{-1}, respectively. It is possible that although GHs yield more strawberries and output more energy (97730.14 MJ ha^{-1}), they also consume 762308.95 MJ ha^{-1} more energy than OF producers in the case of energy cycle. The differences between GH and open field production of strawberries and share of each input in the total energy inputs are clearly depicted in Fig. 1.

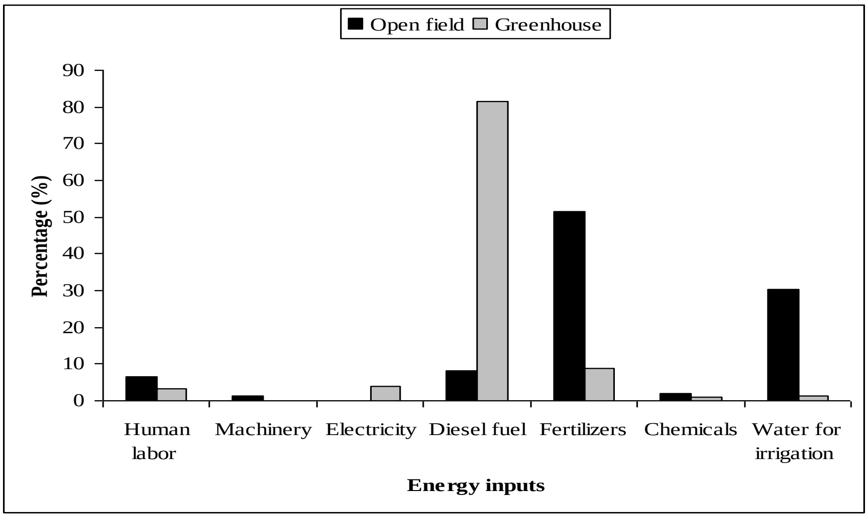

Fig. 1. Comparison of energy input shares between greenhouse and open-field strawberry production.

Energy input–output ratio in strawberry production

The energy use efficiency, energy productivity, specific energy, net energy, and energy intensity of strawberry production are presented in Table 5. Energy use efficiency, which is the ratio of output to input energy, was calculated to be 0.13 and 0.48 for GH and OF strawberry production, respectively. These values indicate inefficient energy use in both production methods. It has been concluded that the energy ratio can be increased by either increasing crop yield or reducing energy input consumption. Similar results have been reported for different crops, such as 0.74 for cotton (Yilmaz *et al.* 2005), 0.76 for cucumber and 0.61 for eggplant, and 0.99 for pepper (Canakci & Akinci 2006). Due to the low-calorie content of strawberries, the energy efficiency of strawberry production is lower than that of other fruits. Calculation of energy productivity rates is well-documented in the literature. For example, soybean (0.13; Jekayinfa *et al.* 2022), potato (0.35; Zangeneh *et al.* 2010), cucumber (2.19; Eskandari & Mosavian 2023), and apple (0.49; Rafiee *et al.* 2010) have all been studied. The average energy productivities of strawberries in GHs and open fields were 0.07 and 0.25 kg MJ^{-1}, respectively. This means that in the GH, 0.07 units of output were obtained per unit of energy, but in OF production, by consuming one megajoule of energy, an additional 0.18 kg of output (strawberries) can be gained. The specific energy, net energy, and energy intensity of GH strawberry production were 14.18 MJ kg^{-1}, -787900.54 MJ ha^{-1}, and 8.43 MJ $\$^{-1}$, respectively. In the case of OF production, the values were 3.91 MJ kg^{-1}, -25584.6 MJ ha^{-1}, and 4.08 MJ $\$^{-1}$ respectively. The negative net energy value indicates that energy is being lost during strawberry production. Regularly in energy intensive production systems like GHs net energy is negative (Banaeian *et al.* 2011). Compared to OF tomato production, GHs resulted in 6.4 times yield per unit area with 231 times energy, 18 times GH gas, and 0.74 times water footprints (Maureira *et al.* 2022).

Direct and indirect form of energy inputs

The total energy inputs, including direct and indirect, renewable, and non-renewable forms, for GH and OF strawberry production are presented in Table 5. It is evident that GH strawberry production consumes significantly more energy compared to the OF one. The total energy input required for GH strawberry production was 909,791.86 MJ ha^{-1}. Due to the high consumption of diesel fuel in GHs, 90.22% of the total energy input used in GH strawberry production was in the form of direct energy. The remaining portion of energy input usage (9.78%) was in the form of indirect energy. For OF strawberry production, a total of 49,752.77 MJ ha^{-1} of energy was consumed, of which 45.15% was direct energy and 54.85% was indirect. Direct energy includes human labor, diesel, water for irrigation, and electricity. Indirect energy includes fertilizers, manure, chemicals, and machinery.

Table 5. Energy analysis comparison between different products.

Product	Condition	Energy use efficiency	Energy productivity (Kg/MJ)	Specific energy (MJ/Kg)	Net energy (MJ/ha)	Direct Energy (MJ/ha)	Indirect Energy (MJ/ha)	Renewable Energy (MJ/ha)	Nonrenewable Energy (MJ/ha)	Energy intensiveness (MJ/$)	Reference
Strawberry	Open-field	0.48	0.25	3.91	-25584.6	22465.48	27287.29	21656.66	28096.11	4.08	Current study
	Greenhouse	0.13	0.07	14.18	-787900.54	820848.88	88942.99	41274.20	868517.67	8.43	
	Open-field	-	0.16	6.71	-24686.5	9659.3	25433.0	8382.4	26710.0	-	Khoshnevis *et al.* (2013)
	Greenhouse	-	0.06	20.39	-1219920.17	1226734.1	130198.8	68942.1	1287990.8	-	
Tomato	Open-field	0.59	0.74	1.35	-26657	24279.29	40966.66	-	-	-	Hosseinali Shamsabadi *et al.* (2017)
	Greenhouse	0.92	1.16	0.86	-8768	76610	40158	-	-	-	
	Greenhouse	1.48	1.38	0.72	63597.86	80459.99	50114.34	-	-	-	
	Greenhouse	0.99	1.24	0.81	-1225.43	42641.5	81478.84	-	-	-	
Cucumber	Open-field	0.33	0.41	2.38	-52171.93	54449.73	24026.6	11360.71	67115.63	-	Yousefi *et al.* (2012)
	Greenhouse	0.017	0.02	46.84	-11509452.43	11646798.96	62653.47	52794.67	11656657.76	-	

Renewable and non-renewable form of energy

The research results indicate that the total energy input used for both GH and OF strawberry production primarily relies on non-renewable energy sources. As shown in Table 5, the non-renewable form of energy accounted for 95.4% of the total energy input in GH strawberries and 56.47% in OF ones on average. Renewable energy is consistent of human labor, water for irrigation, and manure. Non-renewable energy includes diesel, electricity, chemical, fertilizers, and machinery. Table 5 also presents a comparison of all energy indicators among various products. Strawberry crops exhibit higher energy use efficiency and productivity in OF conditions compared to GH conditions. However, their specific energy is higher in GH conditions. The net energy balance for strawberries is negative in both OF and GH conditions. The amount of direct energy is higher in GH conditions, whereas the amount of indirect energy is higher in OF conditions. Renewable energy usage is higher in OF conditions, while nonrenewable energy consumption is higher in GH conditions. The energy intensity is higher in GH conditions. Tomato crops exhibit higher energy use efficiency and productivity when grown in GH conditions compared to OF conditions (Djević & Dimitrijević 2009; Ahmadbeyki *et al.* 2023). Their specific energy is higher in OF conditions. The net energy for growing tomatoes is negative in both OF and most GH conditions. GH conditions result in higher direct energy for tomatoes. Cucumber crops exhibit higher energy use efficiency and productivity in OF conditions compared to GH conditions (Yousefi *et al.* 2012; Eskandari *et al.* 2023). Their specific energy is higher in GH conditions. The net energy for cucumbers is negative in both OF and GH conditions. Both direct and indirect energy are higher in GH conditions, whereas renewable energy is higher in OF conditions. Nonrenewable energy is higher in GH conditions. In the case of grape crops, direct, indirect, and renewable energy are all higher in GH conditions while nonrenewable energy is higher in OF conditions (Ozkan *et al.* 2007). In summary, strawberry crops have higher energy use efficiency and productivity when cultivated in OF conditions while tomato crops demonstrate high energy use efficiency and productivity when grown in GH conditions. Cucumber crops compared to tomatoes exhibit low energy use efficiency and productivity regardless of the growing condition. GH-grown tomatoes have high productivity, while GH-grown cucumbers have a negative net energy with low productivity (Ahmadbeyi *et al.* 2023). The specific energy of crops varies depending on the crop type and growing condition.

Estimating the econometric model for energy inputs in strawberry production

To investigate the relationship between energy inputs and strawberry yield, we estimated the Cobb-Douglas production function using the Ordinary Least Squares (OLS) estimation technique. Therefore, it is assumed that the strawberry yield is an endogenous variable that depends on various exogenous ones, including human labor, machinery, diesel fuel, chemicals, fertilizers, water for irrigation, and electricity (in GH production).

Table 6 compares the impact of different inputs on strawberry yield in GH and OF cultivation, highlighting significant differences. In GHs, diesel fuel, human labor, fertilizers, and electricity significantly boost yield, with diesel fuel having the most substantial impact. In open fields, water for irrigation, fertilizers, diesel fuel, and human labor are crucial, with water being particularly influential.

Table 6. Econometric estimation and sensitivity analysis results of inputs for strawberry production (** Significant at 1% level; * Significant at 5% level).

	Greenhouse			Open-field		
Variables	**Coefficient**	**t-ratio**	**MPP**	**Coefficient**	**t-ratio**	**MPP**
Endogenous variable						
Yield (kg ha^{-1})	–	–	–	–	–	–
Exogenous variables						
Constant (α_0)	-1.94	-0.21 $^{n.s}$		-3.18	-2.54*	
Diesel fuel (α_1)	1.68	3.36**	2.63	0.21	2.01*	0.43
Water for irrigation (α_2)	-0.01	-0.08 $^{n.s}$	0.01	0.12	4.93**	2.48
Human labor (α_3)	0.15	2.42*	4.13	0.23	1.93*	1.04
Fertilizers (α_4)	0.21	3.18**	2.11	0.07	2.63**	0.47
Chemicals (α_5)	0.01	-0.02$^{n.s}$	0.01	-0.02	-0.07$^{n.s}$	0.02
Machinery (α_6)	-0.13	-0.36$^{n.s}$	0.03	0.08	0.19$^{n.s}$	0.07
Electricity (α_7)	1.23	3.21**	1.07	-	-	-
Durbin-Watson		1.54			2.09	
R^2		0.77			0.94	

As can be seen in Table 6, the impact of inputs on different cultivation methods varies significantly. The coefficient of determination (R^2) for the linear regression model in OF production was significantly higher than that of GH one, with values of 0.94 and 0.77, respectively. The regression results from Equation 8 in Table 6 indicate that using fertilizers, human labor, and diesel fuel significantly contribute to both methods of production. The impact of electricity in GHs and water for irrigation in OF farms were both significant, but separately. The estimated coefficients indicate that energy inputs have a positive impact on strawberry yield. Diesel fuel had the highest impact (1.68) among the other inputs in GH strawberry production, whereas in OF one, human labor displayed the highest value (0.23). Rafiee *et al.* (2010) estimated an econometric model for apple production in

Iran, reporting that human labor, chemicals, farmyard manure, electricity, and water for irrigation have a significant impact on the yield of apple production. Mohammadi *et al.* (2010) reported that human labor, machinery, total fertilizer, and water for irrigation had a significant impact on improving the yield of kiwifruit.

Sensitivity of energy inputs in strawberry production

The sensitivity of energy inputs was analyzed using the MPP, which is provided in the last column of Table 6. The higher MPP values in OF strawberry farms suggest that irrigation water and human labor were significant factors, with values of 2.48 and 1.04, respectively. As observed in strawberry GHs, the MPP of human labor, diesel fuel, and fertilizer inputs were found to be 4.13, 2.63, and 2.11, respectively. This indicates that an increase of 1 MJ in each input of water for irrigation, human labor, and chemical energy would lead to an additional yield increase of 4.13, 2.63, and 2.11 kg ha^{-1}, respectively. Exogenous parameters with large sensitivity coefficients have a significant impact on the endogenous variable. This indicates which variables should be identified and measured most carefully to assess the state of the environmental system, and which environmental factors should be managed preferentially (Drechsler 1998). The comparisons of the MPP values of the inputs are shown in Fig. 2. The sensitivity of water for irrigation is significant in open fields compared to its limited value in GHs. A similar situation exists for human labor, fertilizers, and diesel energy in GHs. Feasible diversity shows that each method of strawberry cultivation using inputs should be managed and carefully planned in a different way.

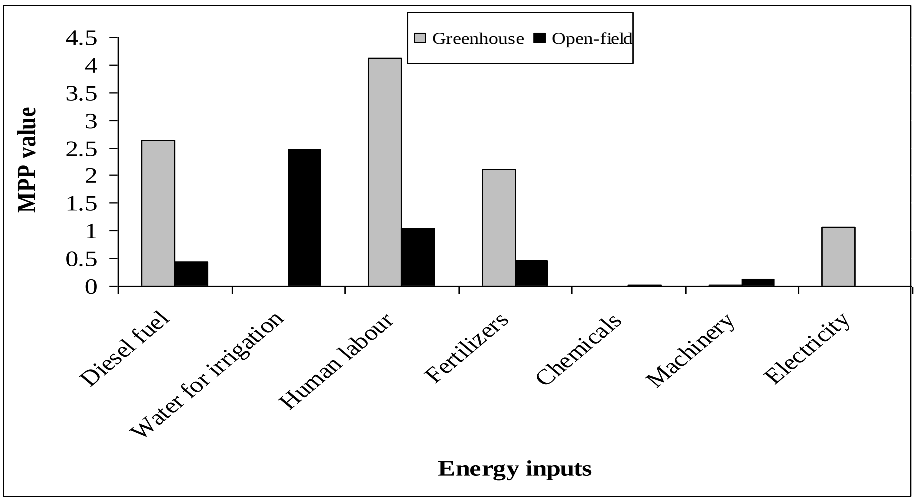

Fig. 2. Comparison of MPP energy inputs between greenhouse and open-field strawberry production.

The highest MPP values in GHs and strawberry farms were attributed to human labor (2.48) and irrigation water (1.04), respectively. In previous studies, sensitivity analysis of apple and barley production showed that human labor and water for irrigation both exhibited a high MPP value (Rafiee *et al.* 2010; Mobtaker *et al.* 2010).

Efficiency of strawberry production

Table 7 presents the descriptive statistics for the variables analyzed. The present study only utilizes source-specific data on energy use and yield, both in constant and variable return-to-scale models. The amount of input energy (in MJ ha^{-1}) used from primary sources such as human labor, diesel fuel, fertilizers, and water for irrigation are considered as inputs, while the yield (in kg ha^{-1}) is considered as the output. The average values of TE, PTE, and SE for all GHs and farms producing strawberries are summarized in Table 8. The average technical efficiency and pure technical efficiency values for strawberry producers were found to be 0.58 and 0.93, respectively, in GHs and 0.54 and 0.72 in open fields respectively. Therefore, cultivating strawberries in GHs resulted in an increase in the values of TE and PTE. Although the mean technical efficiency in GHs is slightly higher than in open fields, the low mean values of technical efficiencies indicate that there is ample room for improvement in operating practices to enhance energy use efficiency for both GH and OF strawberry producers. The average pure technical efficiency in OF farms is 0.72. This suggests that if inefficient farms were to use their inputs more efficiently, significant energy savings (28%) from various sources could be achieved without any need for changes in technological practices.

Table 7. Summary of inputs (source wise energy use, MJ ha^{-1}) and output (yield; kg ha^{-1}).

Particular	(I) Human labor	(I)Diesel fuel	(I) Fertilizers	(I)Water for irrigation	(O)Yield
1.Greenhouse					
Average	57218.21	742868.61	79748.19	11159.34	64153.33
SD	20341.21	25672.11	22347.21	2546.38	21390.57
2.Open-field					
Average	3297.87	4116.26	25223.4	15051.32	12720.1
SD	915.43	705.26	6245.01	7218.49	3405.67

Table 8. Average efficiencies of the producers.

Particular	Greenhouse		Open-field	
	Average	SD	Average	SD
Technical efficiency	0.58	0.13	0.54	0.16
Pure technical efficiency	0.93	0.05	0.72	0.10
Scale efficiency	0.62	0.14	0.75	0.17

Fig. 3 presents the distribution of efficiency scores for both methods of production. Although GH strawberry producers may be more efficient, their scale efficiency is lower than that of OF producers. The interpretation of the scale efficiency scores leads to some interesting observations. As shown in the Fig., the mean scale efficiency of strawberry GHs is 0.62, indicating that their average size is not optimal. If they were to adjust their GH operation to an optimal scale, an additional 38% productivity gain would be feasible, assuming no other constraining factors. Producers in open fields cultivate strawberries under low-efficiency conditions, but the scale of farms is closer to the optimum size.

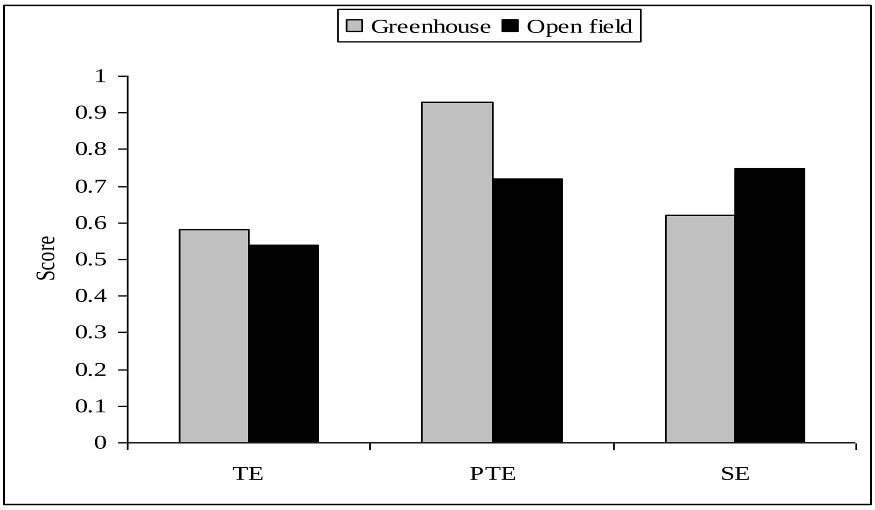

Fig. 3. Efficiency scores of strawberry producers.

The cost of strawberry production

The costs and returns of strawberry production for both GH and OF farms are presented in Table 9. The total cost of strawberry production and the gross value of production were calculated using equations 8-12. Our results revealed that the costs of production per hectare for GH and OF strawberry production were 107913.09 and 12164.74 USD ($) per hectare, respectively. The price of strawberries is highly seasonal and variable. The estimated cost of producing 1-kg strawberries in a GH is relatively high compared to OF one. Although the total cost of production in GHs is high, the high quality of strawberries, off-season production, and premium prices result in a higher net return. According to the results, the productivity of strawberries was calculated to be 0.59 kg per USD in OF production and 1.04 kg per USD in GH one. The benefit-to-cost ratio was calculated for the surveyed GHs and farms, resulting in ratios of 1.74 and 1.49 respectively. These findings are consistent with those reported by other authors, such as 2.37 for orange, 1.89 for lemon and 1.88 for mandarin (Ozkan *et al.* 2004a), 2.58 for cucumber (Omid *et al.* 2010), 0.86 for cotton (Yilmaz *et al.* 2005), and 1.97 and 2.09 for canola (Ghorbani *et al.* 2011) under organic and conventional farming systems, respectively. Additionally, apricots had ratios of 2.13 and 2.14 (Gezer *et al.* 2003) under the same farming systems respectively. The results of this study indicate that although strawberry production is a high-energy consumption, it is still a profitable agricultural operation. Although GH growers incur higher costs ($95,748.35 per hectare), they also generate higher gross returns (more profit per hectare than their counterparts. Productivity is expressed as kg per USD, indicating how much product is produced for each USD spent on strawberry production. In this study, productivity was 0.59 and 1.04 kg per USD in the GH and OF strawberry production respectively. Table 9 also provides an economic comparison between different products. GH-grown strawberries, chilies, and lettuce exhibit a higher yield and sale price per kilogram compared to crops grown in open fields, resulting in a higher net return and benefit-to-cost ratio (B/C ratio), despite the higher costs associated with GH production. GH-grown tomatoes have higher production costs and a lower B/C ratio compared to OF conditions, primarily due to lower productivity. Grapes have a higher yield and net return in OF conditions compared to other crops (Maureira *et al.* 2022).

Table 9. Economic analysis comparison between different products

Product	Condition	Yield (Kg ha^{-1})	Sale price ($ Kg^{-1})	Fixed cost ($ ha^{-1})	Variable cost ($ ha^{-1})	Total cost ($ ha^{-1})	Gross return ($ ha^{-1})	Net return ($ ha^{-1})	B/C ratio	Productivity (Kg $\$^{-1}$)	Reference
Strawberry	Open-field	12720.1	1.42	3392.48	8772.26	12164.74	18171.57	5897.80	1.49	1.04	Current study
	Greenhouse	64153.33	4.05	25568.18	82344.91	107913.09	177476.09	151907.91	1.74	0.59	
Tomato	Open-field	32000	0.17	39.57	4454.63	4494.20	926.54	886.96	1.20	7.12	Kuswardhani *et al.* (2012)
	Greenhouse	50400	0.45	11250.34	4508.43	15758.77	18092.46	6842.13	1.43	3.20	
Chili	Open-field	9000	0.56	39.57	4823.47	4863.05	221.37	181.79	1.04	1.85	
	Greenhouse	23400	0.90	11250.34	4627.65	15877.99	16358.90	5108.56	1.32	1.47	
Lettuce	Open-field	16500	0.11	32.29	1773.37	1805.66	76.41	44.12	1.02	9.14	
	Greenhouse	8000	1.68	11210.76	1319.58	12530.34	12133.34	922.58	1.07	0.64	
Grape	Open-field	10220	-	-	-	3368.60	7460.60	4092	2.21	-	Ozkan *et al.* (2007)
	Greenhouse	6220	-	-	-	6391.30	11693.60	5302.3	1.83	-	

Environmental impacts of strawberry production

Table 10 displays the greenhouse gas (GHG) emissions resulting from different inputs in OF and GH farming. The inputs include diesel fuel, machinery for land preparation, common practices, and transportation, fertilizers such as nitrogen, phosphate, and potassium, chemicals such as pesticides, and electricity. The calculation of GHG emissions involves multiplying the GHG coefficient by the quantity per unit area for each input. The table illustrates that nitrogen fertilizers are the primary source of GHG emissions in OF farming, whereas diesel fuel is the primary source of GHG emissions in GH ones. In OF farming, the total GHG emissions amount to 505.90 kg of carbon dioxide equivalent per hectare (CO_2 eq. ha^{-1}), whereas in GH farming, the total GHG emissions reach 39,851.48 kg CO_2 eq. ha^{-1}. According to the table, GH farming has significantly higher GHG emissions than OF one. In OF farming, the second highest source of GHG emissions is diesel fuel, while in GH one, the second highest source of GHG emissions is electricity. The common practice machinery produces the lowest GHG emissions in both GH and OF farming. Table 10 also indicates that GH farming requires significantly higher quantities of diesel fuel, nitrogen fertilizer, phosphate fertilizer, and potassium fertilizer per unit area compared to OF farming. This could be one of the reasons why GH farming has higher GHG emissions than OF one, as indicated by the Table. In comparison to other research, Yildizhan (2018) found that producing one ton of strawberries results in 506.07 kg of CO_2 emissions in GH production, primarily due to electricity consumed, compared to 243.06 kg CO_2 in OF production, mainly due to water for irrigation. This indicates that GH production emits twice as much CO_2. Similarly, Khoshnevisan *et al.* (2014) reported that total GHG emissions from OF strawberry production were 803.4 kg CO_2 eq. ha^{-1}, largely due to biocide use, while GH production emitted a significantly higher 35,083.5 kg CO_2 eq. ha^{-1}, mainly because of electricity consumption. GH cultivation would need to focus on both reducing the energy needs and shifting to cleaner sources to reduce environmental impacts and lead to sustainable intensification of food production (Maureira *et al.* 2022; ahmadbeyki *et al.* 2023).

Table 10. Greenhouse gas (GHG) emissions from various inputs in open-field and greenhouse farming.

Input		GHG coefficient (kg CO_2 eq. ha^{-1})	Open-field Quantity per unit area (ha)	Open-field GHG emissions (kg CO_2 eq. ha^{-1})	Greenhouse Quantity per unit area (ha)	Greenhouse GHG emissions (kg CO_2 eq. ha^{-1})
Diesel fuel (L)		2.76	73.1	201.756	13192.48	36411.24
	Land preparation	0.071	9.3	0.6603	0	0
Machinery (h)	common practice	0.071	1.4	0.0994	50.86	3.61106
	Transportation	0.071	34.1	2.4211	0	0
	Nitrogen (N)	1.3	168.2	218.66	612.57	796.341
Fertilizers (kg)	Phosphate (P_2O_5)	0.2	278.9	55.78	918.86	183.772
	Potassium (K_2O)	0.2	0	0	1837.72	367.544
Chemicals (kg)	Pesticides (general)	5.1	5.2	26.52	42.8	218.28
Electricity (kWh)		0.608	0	0	3076.78	1870.682

CONCLUSION

In this study, energy requirements of inputs and outputs for both GH and OF strawberry production analyzed. The results indicate a significant difference between these two kinds of production in terms of diesel fuel and electricity usage. It was found that GH strawberry production resulted in 18.2 times more energy use compared to OF ones. The main source of this difference is the ventilation systems used for winter heating and summer cooling in GHs. Eventually, GHs obtained a higher yield of strawberries (51433.23 kg ha^{-1}) and output energy (97730.14 MJ ha^{-1}) compared to OFs. However, they lost 762308.95 MJ ha^{-1} more than OFs in the energy cycle. The regression results revealed that the contributions of fertilizers, human labor, and diesel fuel are significant in both kinds of production. The estimated MPP for human labor energy in GHs and water for irrigation energy in OF farms were the highest among all energy inputs. An input-oriented DEA model has been applied to investigate the level of technical efficiency. Results show that the technical efficiency and pure technical efficiency of GH strawberry production were higher than those by OF ones. However, the scale efficiency of farms was higher, indicating that the scale of farms was closer to the optimum size. GHs can increase their productivity by 38% if they optimize their operations to an optimal scale. GH strawberry production provides a yield 5.04 times higher, a net return and 25.75 times higher, allowing producers to sell their products at premium prices 5 months earlier than traditional methods. GH farmers get a higher total cost of 95748.35 USD ha^{-1}, and also a higher gross return of 146010.11 USD ha^{-1} earning 50261.76 USD ha^{-1} more profit than OF cultivation. It was concluded that increased inputs in strawberry production resulted in a corresponding elevation in strawberry yield. The environmental hotspots were identified as diesel fuel, electricity, and chemical fertilizers, such as nitrogen and potassium, for GH production of strawberries, which had the highest environmental impacts. As for OF production, the hotspots were found to be nitrogen fertilizer, diesel fuel, potassium fertilizer, and pesticides, respectively. Based on the higher input requirements of GH production for strawberries, the environmental impacts of this method are significantly greater than those of OF ones.

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