

Article

Sustainable Agriculture through Reduced Emission and Energy Efficiency: Estimation of Input–Output Energy and GHG Emission under Tunnel Cultivation of Tomato

Qamar Ali ¹, Azhar Abbas ^{2,*} , Muhammad Tariq Iqbal Khan ³, Salim Bagadeem ⁴ , Bader Alhafi Alotaibi ^{5,*} , Muhammad Tariq ⁶  and Abou Traore ⁷ 

¹ Department of Economics, Virtual University of Pakistan, Faisalabad 38000, Pakistan; qamarali2402@gmail.com

² Institute of Agricultural and Resource Economics, University of Agriculture, Faisalabad 38040, Pakistan

³ Department of Economics, Government Graduate College, Jaranwala 37200, Pakistan; tariqiqbal88@yahoo.com

⁴ Faculty of Business Administration, Arab Open University, Riyadh 11681, Saudi Arabia; bagadeem@arabou.edu.sa

⁵ Department of Agricultural Extension and Rural Society, College of Food and Agriculture Sciences, King Saud University, Riyadh 11451, Saudi Arabia

⁶ Department of Livestock Management, University of Agriculture, Sub-Campus, Toba Tek Singh 36050, Pakistan; tariqlm@uaf.edu.pk

⁷ Department of Community Sustainability, College of Agriculture and Natural Resources, Michigan State University, 328 Natural Resources Building, East Lansing, MI 48824, USA; traoreab@msu.edu

* Correspondence: azhar.abbas@uaf.edu.pk (A.A.); balhafi@ksu.edu.sa (B.A.A.)



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Abstract: Tomato production under tunnel structures has shown promising returns in recent years in Pakistan. However, the energy use and GHGs dynamics remain largely unknown for tomato production under controlled conditions. This study estimates the energy budgeting and GHG emission in off-season (tunnel-farming) tomato production. Study data were gathered from 70 tunnel tomato growers through a simple random sampling technique. Energy use efficiency, energy productivity, and net energy along with covariates of energy output were estimated through Cob–Douglas regression. The results indicate that the total input energy consumption and production were 91,376.38 MJ ha^{−1} and 56,764.64 MJ ha^{−1}, on average, respectively. The contribution of fertilizers (60.78%) was higher in total input energy followed by diesel and chemicals. The value of energy use efficiency was 0.652, which was higher for small farms (0.678) and lower (0.604) for large farms. Energy productivity (0.815 kg MJ^{−1}), specific energy (1.355 MJ Kg^{−1}), and net energy (−34,611.743 MJ ha^{−1}) were also estimated. The total greenhouse gas emission was 3426.66 kg CO₂ eq. ha^{−1}, which is low for large farms (3197.57 kg CO₂ eq. ha^{−1}). The contribution of farmyard manure to total GHG emissions was high. The results show the inefficient use of inputs, responsible for GHG emissions. Fertilizers were a major contributor both in total input energy and GHG emission. The efficient utilization of agricultural inputs is a solution to reduce GHGs emissions in crop production. Therefore, the agriculture department should play its role to ensure the optimal or efficient use of agricultural inputs. The Department of Extension is working to guide farmers about crop production at each stage. Thus, regular visits from extension staff are recommended to guide vegetable producers about efficient input use.

Keywords: carbon dioxide; energy budget; energy ratio; energy forms; off-season tomato

1. Introduction

The sustainable feeding of the global population is an immense challenge for the entire world. Energy in different forms is needed in the production of various types of foods to feed the ever-increasing population [1]. The GHGs have increased in the atmosphere from

several agricultural inputs (i.e., irrigation, fertilizers, pesticides, seeds, and farm operations). These agricultural inputs are categorized into several energy forms which play a key role in crop production. However, high energy utilization causes an environmental burden which in turn leads to poor environment and low economic returns. Thus, a reduction in energy use from several inputs leads to a decrease in GHG emissions from the agriculture sector [2]. Environmental degradation is accountable for several diseases such as stroke, heart disease, respiratory diseases, and lung cancer; thus, it is responsible for the loss of human lives [3]. Thus, investigating the utilization and management of energy inputs in agriculture are the main research challenges that can help in ensuring sustainable production. This is because energy use is directly linked with the environment, having many implications both for agriculture and society. More importantly, the efficient use of agricultural inputs is required to ensure environmental safety and energy savings [4]. Scientists agree that global warming will be the main environmental problem in the future, having wide-ranging implications for agriculture and allied sectors. Global warming is a gradual increase in temperature due to an increase in greenhouse gases (GHGs). GHGs are a result of human activities and naturally occurring phenomena. Agriculture-related GHG emissions contribute about 10% to 12% of total man-made GHG emissions [5]. Different activities, including production, storage, transportation, input distribution, and their application with machinery result in fossil fuel combustion and energy use from substitute sources, responsible for GHG emissions. Therefore, an understanding of GHG emissions from various tillage operations, pesticides, fertilizers, irrigation, and harvesting is useful for the identification of substitutes, such as bio-fuel and renewable energy sources [5].

Protected agriculture is a cultivation practice in which farmers grow crops under an extended favorable climate (i.e., sophisticated heating, lighting, and cooling) to obtain higher crop yields as compared to open farming. In this practice, the crop is protected from meteorological adversities, pests, and diseases [6]. However, protected cultivation is responsible for the excessive use of different agricultural inputs such as pesticides and fertilizers [7]. Due to this, input–output energy estimation is useful for the development of a complete policy for the utilization and management of inputs in protected agriculture [4]. Energy is vital in agriculture which is used for ensuring food security, enhancing productivity, and rural development. The efficient use of energy is required for sustainable production in agriculture. The rapid population increase, scarcity of arable land, and improvements in the living standards were responsible for the increased use of energy in agriculture. Energy utilization in agriculture has also increased due to the intensive use of chemical fertilizers, fossil fuel, machinery, electricity, and pesticides. However, the excessive use of energy also causes some environmental and health problems. Therefore, the efficient utilization of inputs is important for the reduction in environmental problems as well as an increase in production and economic growth [8]. The excessive use of undesirable inputs is evident due to the limited technical knowledge of farmers [9].

Therefore, an input–output analysis of crops is important for policymakers for the evaluation of energy use in this sector [10] including production, the use of agricultural inputs, and machinery involved in fuel combustion, which emits GHGs. Energy use from different sources was responsible for GHGs [11]. In this context, it is clear that the estimation of energy is difficult in agriculture as compared to the industrial sector, but energy budgeting is also important in agriculture [8]. Agricultural production under a protected structure can control the cultivation environment and optimize the growth and development of crops. Figure 1 shows the tunnel structure in which farmers can cultivate fruits, vegetables, and flowers [12].



Figure 1. Tunnel structure in Punjab, Pakistan.

In vegetables, tomato (*Lycopersicon esculentum Mill*) is ranked second after potato in the world with a production of 124.75 million tons. It is an indispensable component of the diet due to its usefulness in raw and cooked forms. It provides different vitamins, calcium, iron, fiber, and potassium. Lycopene is also found in tomatoes, which is useful for cancer patients [13].

In Pakistan, 20.9% of the GDP comes from agriculture, involving 43.5% of the labor force. In 2013–2014, in Pakistan, 63,200 ha of land was used to grow tomato with 599,700 tonnes of production, while in Punjab, 7800 ha of land was used to grow tomato with 100,100 tonnes of production [14]. Punjab province is located between 24–37° N and 62–75° E in the alluvial land of five south-flowing rivers named Chenab, Jhelum, Indus, Sutlej, and Ravi [15]. The climate of Punjab is adequate for growing vegetables in normal conditions as well as in the off-season. In tunnel farming, vegetables are grown under tunnels covered with plastic sheets that control the temperature and save solar energy. The area under plastic tunnels showed an increase due to an expansion in season and yield [14].

Thus, this study contributes to the literature in three ways: (a) by estimating the energy forms, energy ratios, and GHG in tomato cultivation under the tunnel structure, (b) estimating the energy forms, energy ratio, and GHG for three sub-groups according to operational landholding, and (c) exploring the regression results for energy output and various energy inputs in tomato cultivation under tunnels.

2. Literature Review

There are published reports available from different countries about energy estimation for crops such as tomato, cucumber, eggplant, pepper, cotton, greenhouse tomato, stake-tomato, cherries, melon, watermelon in Turkey [8,10,15–20], tomato, cucumber, garlic, wheat, strawberry in Iran [21–24], cotton in Greece [25], coriander, radish, lettuce, spinach in Colombia [26], tomato, onion, sweet pepper, hot pepper in Nigeria [27], and lettuce in Serbia [28]. Literature about GHG emissions for different crops is available for hazelnut, greenhouse cucumber, potato, and greenhouse and open-field strawberry cultivation in Iran [5,11,29,30]. Tunnel farming is different from a conventional greenhouse structure, and it is more profitable than open-field production, but the literature was not available on energy calculation in tomato cultivation under the tunnel structure in Pakistan. Additionally, no study was available about output–input energy analysis and GHGs in off-season/tunnel farming tomato production in Pakistan, an agriculture-based country.

In a study carried out in Turkey, Esengun et al. [31] explored energy utilization in open-field tomatoes ($96,957.36 \text{ MJ ha}^{-1}$), finding that 42% of energy comes from diesel, while the contribution of fertilizers and machinery remained around 38%. The ratio of input and output energy was found to be 0.80, while the value of energy productivity was $1.00 \text{ kg MJ ha}^{-1}$. The share of non-renewable energy was 76%, and renewable energy was about 22%. It was believed that the intensive use of inputs could spearhead a higher yield of tomatoes, but it can also create problems related to global warming and pollution of the environment. Similarly, Heidari and Omid [23] performed energy analysis for vegetables grown in the greenhouse, and the highest total input energy was estimated for cucumber ($141,493.51 \text{ MJ ha}^{-1}$), followed by tomato ($131,634.19 \text{ MJ ha}^{-1}$). Likewise, Nabavi-Pelesaraei et al. [29] reported the input energy use (1284 GJ ha^{-1}), output energy (125 GJ ha^{-1}), and GHG emissions ($82,724 \text{ kg CO}_2 \text{ eq. ha}^{-1}$) in greenhouse cucumber. Similarly, Khoshnevisan et al. [11] found that the total GHG was $803.4 \text{ kg CO}_2 \text{ eq. ha}^{-1}$ (open-field) and $35,083.5 \text{ kg CO}_2 \text{ eq. ha}^{-1}$ (greenhouse) in strawberry cultivation. The total greenhouse gas emission was $803.4 \text{ kg CO}_2 \text{ eq. ha}^{-1}$ and $35,083.5 \text{ kg CO}_2 \text{ eq. ha}^{-1}$ in the open-field and greenhouse production, respectively. Ali et al. [32] estimated the GHG emission in cucumber cultivation under tunnels. The GHG emission was higher for large farms ($19.63 \text{ kg CO}_2 \text{ eq. for } 1000 \text{ kg production}$). The larger share of GHGs came from diesel fuel followed by fertilizer and machinery. Thus, the current study was designed to check the input energy, output energy, and GHG in tunnel farming tomato production. It also explored different energy ratios and energy forms. All empirical analyses were performed for three farm size categories.

3. Methodology

This study was based on the collection of primary data, collected from off-season tomato farmers in Punjab, Pakistan, using a structured questionnaire. The questionnaire was divided into different sub-sections, containing different questions about (a) tunnel structure, (b) land preparation, (c) seed transplantation, (d) hoeing, (e) fertilization, (f) irrigation, (g) chemicals, (h) labor, and (i) tomato output. The average time an interview took was 30 min, and major problems were (a) finding tomato farmers and (b) transportation costs. An agricultural farm, called Mian Shadi agriculture farm, located in tehsil Mamunkanjan, district Faisalabad, was considered the pioneer in vegetable cultivation under tunnels in Punjab. Faisalabad is ranked as the second biggest city in Punjab and has a large vegetable market. Kamalia, district Toba Tek Singh is a center of off-season vegetable production in Punjab. Thus, this study selected two districts named Faisalabad and Toba Tek Singh. Farmers were personally surveyed about input use and output with simple random sampling. The formula for sample size determination [8,13,22] is:

$$n = \frac{N \times s^2 \times t^2}{(N - 1)d^2 + s^2 \times t^2} \quad (1)$$

where n shows the required sample size, N represents the total targeted population, s^2 shows the variance in the targeted population, t shows the t -value, which is 1.96 at the 5% significance level, and d is the 5% acceptable error [13]. The calculated sample size was 65 but it was increased to 70 for better results. The total farmers engaged in the cultivation of tomatoes under tunnel structures were further distributed into three sub-groups according to the operational land of farmers and producers. Farmers with 5 ha or less fell in the first category, while farmers with more than 5 ha and less than 12 fell in the second sub-group. Farmers having more than 12 ha were classified in the third category [10,13]. Data were analyzed using SPSS-15 and Microsoft Excel. To calculate the energy consumption in tomatoes under the tunnel structure, first, the average use of each input was estimated in the standard units, using a structured questionnaire. All inputs were estimated per ha, and the quantities of inputs were multiplied by their energy equivalent (Table 1). The sum of energy values for each input gave the total input energy. The amount of total tomato production was multiplied by the energy equivalent of tomato to find the total output energy. Energy ratios were estimated using the following expressions [13]:

$$\text{Energy use efficiency} = \frac{\text{energy output (MJ ha}^{-1}\text{)}}{\text{energy input (MJ ha}^{-1}\text{)}} \quad (2)$$

$$\text{Energy productivity} = \frac{\text{off – season tomato output (Kg ha}^{-1}\text{)}}{\text{energy input (MJ ha}^{-1}\text{)}} \quad (3)$$

$$\text{Specific energy} = \frac{\text{energy input (MJ ha}^{-1}\text{)}}{\text{off – season tomato output (Kg ha}^{-1}\text{)}} \quad (4)$$

$$\text{Net energy} = \text{energy output (MJha}^{-1}\text{)} - \text{energy input (MJha}^{-1}\text{)} \quad (5)$$

Moreover, the total amount of input energy was further distributed into various forms, including direct, indirect, renewable, non-renewable, commercial, and non-commercial. Conventional agriculture faced three challenges: (a) an energy deficit, (b) a reduction in profitability, and (c) the deterioration of natural resources. Therefore, it is beneficial to concentrate on several forms of energy used in crop production [32]. Direct energy is obtained from water, diesel, and human labor. On the other hand, indirect energy is obtained from plastic, machinery, chemicals, seeds, fertilizer, and farmyard manure. Renewable energy is obtained from human labor, seeds, water, and manure. Non-renewable energy means the energy from plastic, chemicals, diesel, machinery, and fertilizers. According to Bórawski et al. [33], the promotion of renewable energy sources could reduce the fossil fuel demand, thus playing a favorable role in environmental protection. The development of renewable energy sources is also beneficial for the economy and energy security. Commercial energy is energy from plastic, chemicals, seeds, diesel, fertilizers, water, and machinery. On the other hand, non-commercial energy means energy from farmyard manure and human labor [13]. The GHG emission was measured in kg CO₂ eq. by using the coefficient of GHG for each agricultural input (Table 1). Quantities of inputs were multiplied by their respective GHG coefficient to find total GHG emissions. The GHG ratio was calculated with the expression [11,13]:

$$\text{GHG ratio} = \frac{\text{KgCO}_2\text{eq.ha}^{-1}}{\text{Off – season tomato output (t ha}^{-1}\text{)}} \quad (6)$$

Table 1. Energy and GHG equivalents of agricultural input and output.

Type	Source	Energy Equivalent (MJ Unit ⁻¹)			GHG Emission Coefficient (kg CO ₂ eq. Unit ⁻¹)		
		Unit	Energy eq.	Reference	Unit	GHG Coef.	Reference
Inputs	1—Plastic (polyethylene and mulch)	kg	158	[32]		-	
	2—Chemicals	kg	101.2	[20]	kg	2.47	[34]
	3—Labor	h	1.96			-	
	4—Machinery	h	62.7	[23]	MJ	0.071	[11]
				5-Fertilizer			
	Nitrogen	kg	66.14		kg	1.3	
	Phosphorus	kg	12.44	[23]	kg	0.2	[11]
	Potassium	kg	11.15		kg	0.2	
	Farmyard manure	kg	0.3		kg	0.126	[30]
	6—Seeds	kg	1	[31]		-	
7—Irrigation water	m ³	0.63			-		
	8—Diesel	L	56.31	[20]	l	2.76	[11]
Output	Tomato	kg	0.8			-	

4. Results and Discussion

4.1. Agronomic Practices in Off-Season Tomato Production

Table 2 depicts the agronomic practices and their time period during off-season tomato production. Sahel and Dollar were the main seed varieties in off-season tomato production. The total number of seedlings was 32,526 ha⁻¹, and those were planted double-side on a bed/ridge of 2.5 feet in width. In the initial stage, a one-month nursery was prepared for off-season tomato production. The first operation in off-season tomato production was ploughing and was performed in September or October. Commonly, MF-240 and Fiat NH-480 were used in the preparation of land along with different agricultural equipment. Tomato is a water-intensive crop, and irrigation was performed for almost the whole time period with different intervals depending upon the type of crop. Variations exist in the use of chemical spray, but farmers performed 24.99 sprays on average depending upon the type and intensity of disease attack. Some farmers started picking in February, but mostly, three-month picking was performed from March to May. A complete description of agronomic practices in off-season tomato production is given in Table 2.

Table 2. Agronomic application in tomato production under tunnel structure.

Name of the Agronomic Application	Off-Season Tomato
Names of varieties	Dollar, Fantom, Sahel
Number of seedlings (ha ⁻¹)	32,526.08
The tractor used for the preparation of land: 240 MF 47 hp and Fiat NH-480 55 hp	Disc plough, disc harrow, cultivator, rotavator, ridger, land leveler
Land preparation period/nursery sowing	September–October
Average ploughing number	6
Planting/transplanting period	October–November
The average number of tunnels (ha ⁻¹)	35
The average number of ridges (ha ⁻¹)	86.66
Fertilization period	October–March
Average fertilization (No.)	23.62
Hoeing period	January–March
Average hoeing (No.)	3.42
Irrigation period	November–May
Average irrigation (No.)	29.11
Spraying period	December–May
Average spraying (No.)	24.99
Picking period	March–May
Average picking (No.)	32.19

4.2. Input–Output Energy in Off-Season Tomato

Table 3 reveals the physical quantities and energy of different inputs and outputs with respect to three farm size groups. It shows that 529.82 kg of plastic sheet, 0.26 kg of seed, 3039.41 h of human labor, 697.13 kg of nitrogen, 454.61 kg of phosphorus, 60.63 kg of potassium, 10.343 tonnes of farmyard manure, 81.51 kg of chemicals, 59.96 h of machinery, 7446.54 m³ of irrigation water, and 234.02 L of diesel were used for the per ha production of tomatoes. Labor is used in different farm operations, such as land preparation, nursery sowing, plant transplantation, hoeing, irrigation, fertilization, spraying, and picking. Thus, the number of labor hours increases with farm size. Large farmers preferred chemical fertilizers N, P, and K over farmyard manure. The per hectare production of off-season tomato was 68,013.59 kg, 72,453.29 kg, and 72,525.32 kg for the small to large farm size categories, while the weighted average was 70,955.80 kg ha⁻¹. Tomato yield lay within the range of tomato yield showed in the literature, i.e., 22,392.9 kg ha⁻¹ [20], 40,000 kg ha⁻¹ [17], 45,358.7 kg ha⁻¹ [10], 156,185.64 kg ha⁻¹ [23], 159,685.7 kg ha⁻¹ [19], and 200,000 kg ha⁻¹ [16] under different growing conditions (open, glasshouse, and greenhouse).

Table 3. Input usage and energy consumption in off-season tomato production.

Inputs	Input–Output Quantities (ha ⁻¹)				Input–Output Energy (MJ ha ⁻¹)				
	Farm Size Groups (ha)			Weighted	Farm Size Groups (ha)			Weighted	Average
	0.1–5.0	5.1–12.0	12.1+	Average	0.1–5.0	5.1–12.0	12.1+	Quantity	
Plastic (polyethylene and mulch) (kg ha ⁻¹)	519.54	499.10	568.29	529.82	82,087.05	78,857.16	89,789.83	83,712.89	47.81
Seed (kg ha ⁻¹)	0.25	0.28	0.24	0.26	0.25	0.28	0.24	0.26	0
Labor (hours ha ⁻¹)	2960.17	3058.39	3101.26	3039.41	5801.94	5994.44	6078.47	5957.25	3.4
Fertilizer (kg ha ⁻¹)	12,861.87	13,059.56	8870.35	11,555.48	53,207.17	48,810.75	64,048.04	55,542.31	31.72
Nitrogen	665.95	601.87	815.63	697.13	44,045.8	39,807.63	53,945.55	46,108	26.33
Phosphorus	409.78	386.33	562.04	454.61	5097.69	4805.9	6991.72	5655.37	3.23
Potassium	48.65	53.07	79.54	60.63	542.43	591.74	886.83	676.01	0.39
Farmyard Manure (tonne ha ⁻¹)	11.737	12.018	7.413	10.343	3521.25	3605.49	2223.95	3102.93	1.77
Chemicals (kg ha ⁻¹)	83.75	76.96	83.43	81.51	8475.82	7788.55	8443	8248.57	4.71
Machinery (h ha ⁻¹)	54.81	68.65	57.14	59.96	3436.65	4304.09	3582.48	3759.27	2.15
Diesel (L ha ⁻¹)	213.45	268.87	222.63	234.02	12,019.22	15,140.29	12,536.31	13,177.41	7.53
Water (m ³ ha ⁻¹)	7257.32	8321.01	6834.15	7446.54	4572.11	5242.24	4305.51	4691.32	2.68
Total input energy (MJ ha ⁻¹)			-		169,600.2	166,137.8	188,783.9	175,089.3	100
Off-season tomato yield (kg ha ⁻¹)	68,013.59	72,453.29	72,525.32	70,955.8			-		
Total output energy (MJ ha ⁻¹)			-		54,410.87	57,962.63	58,020.25	56,764.64	-

Table 3 shows the energy consumption and output in off-season tomato production. A maximum of 47.81% of total input energy come from plastic sheets, which is a basic component of protected agriculture. A plastic sheet is used for mulching and covering tunnel structures. About 31.72% of total input energy came from fertilizers. The contribution of nitrogen was the maximum (26.33%), followed by phosphorus (3.23%). Farmyard manure contributed 1.77% of total input energy. The third-largest source of input energy was diesel (7.53%), followed by chemical (4.71%), labor (3.4%), water (2.68%), and machinery (2.15%) inputs. The average input energy was 175,089.3 MJ ha⁻¹, and the total output energy was 56,764.64 MJ ha⁻¹.

Table 4 reveals different energy ratios and energy forms in off-season tomato cultivation under a tunnel structure. On average, the energy use efficiency or output–input energy ratio was 0.332, which shows a decreasing trend with farm size. Energy use efficiency lay between the range of previous studies such as 0.10 [27], 0.30 [20], 0.70 [17], 0.80 [31], 0.80 [10], 1.20 [19], 1.26 [16], and 1.48 [23]. Energy productivity was 0.416 Kg MJ⁻¹,

which had a reciprocal association with farm size, which reasonably agrees with values reported in the literature: 0.09 Kg MJ⁻¹ [19], 0.12 Kg MJ⁻¹ [27], 0.36 Kg MJ⁻¹ [20], 0.99 Kg MJ⁻¹ [10], and 1.38 Kg MJ⁻¹ [23]. The value of specific energy was 2.577 MJ Kg⁻¹, while the net energy was −118,324.633 MJ ha⁻¹. The specific energy was 1.14 MJ Kg⁻¹ [17] and 1.82 MJ Kg⁻¹ [23]. According to Heidari and Omid [23], the net energy in tomato production was also negative (−44,137.91 MJ ha⁻¹). The share of commercial energy (94.83%) was more than the share from non-commercial energy (5.17%). The share of non-renewable energy (92.15%) was more than renewable energy (7.85%). The share of indirect energy (86.39%) was more than direct energy (13.61%). The share of indirect, commercial, and non-renewable energy was higher for large farm sizes.

Table 4. Input–output energy ratios and energy forms in off-season tomato production.

Inputs	Farm Size Groups (ha)			Weighted Average	
	0.1–5.0	5.1–12.0	12.1+	Quantity	%
Energy ratios					
Energy use efficiency	0.334	0.356	0.309	0.332	-
Energy productivity (Kg MJ ⁻¹)	0.418	0.445	0.387	0.416	-
Specific energy (MJ Kg ⁻¹)	2.584	2.394	2.738	2.577	-
Net energy MJ ha ⁻¹	−115,189.326	−108,175.158	−130,763.626	−118,324.633	-
Energy forms (MJ ha ⁻¹)					
Direct energy	22,393.26	26,376.96	22,920.29	23,825.98	13.61
Indirect energy	147,206.94	139,760.83	165,863.59	151,263.29	86.39
Renewable energy	13,895.55	14,842.44	12,608.17	13,751.75	7.85
Non-renewable energy	155,704.65	151,295.35	176,175.72	161,337.52	92.15
Commercial energy	160,277.01	156,537.87	180,481.47	166,029.1	94.83
Non-commercial energy	9323.18	9599.93	8302.41	9060.18	5.17

4.3. Greenhouse Emission in Off-Season Tomato

Table 5 exposes the GHG (kg CO₂ eq. ha⁻¹) in off-season tomato production. GHG emissions were higher in the case of farmyard manure (38.03%) followed by nitrogen (26.45%), diesel (18.85%), machinery (7.79%), chemicals (5.88%), phosphorus (2.65%), and potassium (0.35%). In the literature, only Pishgar-Komleh et al. [30] used farmyard manure for GHG analysis in agriculture. On average, 3426.66 kg CO₂ eq. ha⁻¹ GHG was recorded in off-season tomato cultivation. The share of GHG emissions was higher for chemical fertilizer (37.27%) in potatoes [5], diesel fuel (61%) in greenhouse cucumber [30], nitrogen (35%) in open-field strawberries [11], and diesel fuel (33.84%) in hazelnut [29]. The GHG emissions in off-season tomato production were greater than the GHG emissions (77.66 kg CO₂ eq. ha⁻¹) in hazelnut [29] and potato (992.88 kg CO₂ eq. ha⁻¹) [5], and they were less than the GHG emissions in greenhouse strawberry (35,083.5 kg CO₂ eq. ha⁻¹) [11] and greenhouse cucumber (82,724 kg CO₂ eq. ha⁻¹) [30]. The GHG ratio was 64.46 kg CO₂ eq. t⁻¹ in off-season tomato production, which shows that the emissions of GHG were 64.46 kg CO₂ eq. for 1000 kg tomato production.

Table 6 shows the econometric results between GHG emissions and energy imbalance and energy inputs in tomato cultivation under the tunnel structure. It also explores the coefficient of pairwise correlation between the variables. This model was good according to R² (0.756). A significant F-stat indicates the overall reliability of the regression model. The impact of an increase (of 1%) in energy imbalance is positive (0.09%) and significant on GHG emissions. A positive and significant increase in GHG was also observed for a 1% rise in the value of farmyard manure and diesel. A significant and negative impact on GHG emissions was observed in the case of chemicals and machinery. These figures are generally accepted, as the tunnel structure would potentially adsorb the emissions as well

as curtail the energy imbalance by capturing the potential leakages as well as improving its efficiency [35,36].

Table 5. GHG (kg CO₂ eq. ha⁻¹) in off-season tomato production.

Inputs	Farm Size Groups (ha)			Weighted Average	
	0.1–5.0	5.1–12.0	12.1+	Quantity	%
1—Chemicals (kg)	206.87	190.09	206.07	201.32	5.88
2—Machinery (MJ)	244	305.59	254.36	266.91	7.79
3—Fertilizer					
Nitrogen (kg)	865.73	782.43	1060.32	906.27	26.45
Phosphorus (kg)	81.96	77.26	112.41	90.92	2.65
Potassium (kg)	9.73	10.62	15.91	12.13	0.35
Farmyard Manure (kg)	1478.92	1514.3	934.05	1303.23	38.03
4—Diesel (L)	589.11	742.09	614.46	645.88	18.85
Total GHG emission (kg CO ₂ eq.ha ⁻¹)	3476.33	3622.39	3197.57	3426.66	-
GHG ratio (kg CO ₂ eq.t ⁻¹)	67.5	65.72	60.26	64.46	-

Table 6. Econometric result of GHG emission (endogenous variable: lnGHG).

Exogenous Variables	Cobb-Douglas Model			Pairwise Correlation
	Coefficient	t-Value	Prob.	
Model 1: $\ln Y_i = a_1 \ln X_1 + a_2 \ln X_2 + a_3 \ln X_3 + a_4 \ln X_4 + a_5 \ln X_5 + a_6 \ln X_6 + a_7 \ln X_7 + a_8 \ln X_8 + e_i$				
1. Energy Imbalance (MJ ha ⁻¹)	0.092 **	2.387	0.020	0.515
2. Farmyard manure (kg ha ⁻¹)	0.09 ***	7.3	0.000	0.721
3. Nitrogen (kg ha ⁻¹)	0.01	0.089	0.929	0.140
4. Phosphorus (kg ha ⁻¹)	-0.097	-1.068	0.290	-0.052
5. Potassium (kg ha ⁻¹)	-0.014	-0.666	0.508	-0.196
6. Chemicals (kg ha ⁻¹)	-0.162 **	-2.28	0.026	0.041
7. Machinery (h ha ⁻¹)	-4.97 ***	-10.201	0.000	0.478
8. Diesel (L ha ⁻¹)	5.129 ***	11.935	0.000	0.48
R ²		0.756		
Adjusted-R ²		0.728		
F-stat		22.94 ***		

***, ** shows significance at 1% and 5%, respectively.

5. Conclusions and Policy Implications

The analysis of energy and GHG emissions is very important to contribute to the analysis of the actual environmental condition of critical/productive areas of the world. The current study was designed to estimate the energy use, production, and emissions of GHG in per ha off-season/tunnel farming tomato production in Punjab, Pakistan. A total of 70 respondents were distributed into three sub-groups according to farm size. On average, the total input energy was 175,089.3 MJ ha⁻¹, while the total output energy was 56,764.64 MJ ha⁻¹ in off-season tomato production.

The use of plastic sheets contributed most (47.81%) to the total input energy followed by fertilizers (31.72%), diesel (7.53%), chemicals (4.71%), labor (3.4%), irrigation water (2.68%), and machinery (2.15%). The total output energy showed an increasing trend with farm size, while energy use efficiency showed a decreasing trend with farm size. Energy use efficiency was 0.332, which was less than a sufficient level (0.80), as pointed out by [10]. Energy use efficiency was higher for medium farm size groups (0.356) and lower (0.309) in the case of large farm size groups, which shows that medium farmers made better use of energy resources. On average, the energy production was 0.416, which indicates 0.416 kg production of tomatoes by using 1 MJ of energy inputs. On average, the specific energy was 2.577 MJ Kg⁻¹ in off-season tomato production, which shows that input energy use was 2.577 MJ for 1 kg production of off-season tomato. The net energy was negative

($-118,324.633 \text{ MJ ha}^{-1}$), which shows that the energy output was lower than the energy inputs. These energy parameters related to efficiency as well as emission figures point toward a massive intervention to curb the energy wastage that too is harmful in terms of excessive emissions of GHGs at the farmers' fields.

All these energy calculations paint different views of the same picture which indicate the margin of increasing output energy or decreasing input energy use. The use of indirect energy (86.39%) was more than direct energy (13.61%). Similarly, the use of non-renewable energy (92.15%) and commercial energy (94.83%) was higher than their counterparts. The estimation of greenhouse gases is very important in agricultural production to check to what extent the growth of a crop damages the environment. GHG emissions were higher from farmyard manure (38.03%) followed by nitrogen (26.45%), diesel (18.85%), machinery (7.79%), chemicals (5.88%), phosphorus (2.65%), and potassium (0.35%). The total GHG emissions were lower for large farm size groups ($3197.57 \text{ kg CO}_2 \text{ eq. ha}^{-1}$) due to less use of farmyard manure. The GHG ratio showed that the GHG was $64.46 \text{ kg CO}_2 \text{ eq. for } 1000 \text{ kg}$ tomato production.

The findings of the study pointed out the inefficient use of inputs with respect to energy and GHG emissions. Fertilizers were found to be the leading element both in energy input consumption and GHG emissions. This shows that fertilizers were unconsciously used by the farmers, but they are harmful to the environment. The efficient utilization of energy resources is important for sustainable agriculture and the cleaning of the environment. The econometric impact of diesel was higher as compared to other inputs. The government should introduce some environmentally friendly fuel for use in machinery. The GHG emissions showed a reduction due to the increase in machinery. It is the responsibility of agriculture extension personnel to conduct regular meetings with vegetable producers and guide them on the efficient use of energy inputs. The government should ensure the availability of extension staff by organizing training programs.

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