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ARTICLE

Assessing the Technical Efficiency of Main Protected Vegetable Cultivation in Northern Palestine

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ABSTRACT

This study examines the technical efficiency (TE) of protected vegetable farming in Northern Palestine, a region where vegetable cultivation plays a vital role due to favorable climatic conditions and soil fertility. Despite its significance, little empirical research exists on TE in protected agriculture in the region. This paper measures the TE of key vegetable crops as cucumbers, tomatoes, peppers, peas, and eggplants using a Stochastic Frontier Analysis (SFA) model applied to cross-sectional data from 127 farms in the Northern West Bank during 2023–2024. Results show variability in TE across crops: tomato farms demonstrate the highest average TE (96.2%), followed by pepper (80.2%) and cucumber (79%) farms, while peas (55.3%) and eggplants (50.3%) reveal considerable inefficiencies. Factors influencing TE include input type and use practices. For cucumbers, excessive labor and chemical fertilizers reduced TE, while organic fertilization improved it. In tomato farming, overreliance on chemical inputs and mismanaged irrigation decreased efficiency, whereas organic inputs had positive effects. Pepper TE benefited from labor and organic fertilization, but was hindered by poor soil sterilization. Peas and eggplants were most affected by inefficient input use and suboptimal practices. These findings highlight the urgent need for targeted interventions, especially in organic fertilization and labor management, to improve efficiency in protected vegetable production systems across the region.

Keywords: Efficiency; Vegetable; Stochastic Frontier Model; Palestine

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1. Introduction

The Palestinian agriculture sector is one of the important sectors to bolster the national economy. The agricultural sector contributes approximately 4.6% to Palestine's GDP and accounts for 15% of the country's total exports. The agriculture sector plays an important role in employment, with about 13% of the Palestinian workforce [1]. Where agriculture represents a key source of income, food, and support for food security in Palestine. Beyond these contributions, the agricultural sector has the potential to contribute for a high degree of self-sufficiency and to support the development of other sectors [2]. In Northern Palestine, vegetable cultivation is a cornerstone of the agricultural sector, with the region's favorable climate and soil conditions enabling the year round production of high quality crops. The total area under vegetable cultivation in Palestine had expanded to approximately 202,286 dunams, with 140,794 dunams in the West Bank and 61,492 dunams in the Gaza Strip. This marks a significant increase from 2010 when the cultivated area was around 127,257 dunams, reflecting a growing demand for fresh produce and the expansion of agricultural activities [3]. Protected vegetable farming in the northern west bank focuses on few main crops such as cucumbers (34%), tomato (33%), peas (11%), peppers (9.8%) and eggplants (2%) [4]. Despite the importance of these crops to the local Palestine economy, studies on agricultural productivity and efficiency remain limited. Many researchers have confirmed the potential for enhancing productivity and efficiency in agriculture by focusing on important areas such as agricultural technology, sustainability and the rational use of inputs. Studies indicate that advancements in technology and improved management practices can substantially improve agricultural productivity [5, 6]. Such enhancements are important for addressing the increasing global food demand, particularly in regions facing obstacles like limited fertile land, climate change, and resource constraints [7]. However, there remains a significant gap in localized studies pertaining to vegetable production efficiency within Palestine. Technical efficiency serves as an essential tool for evaluating how effectively farms can maximize output utilizing a specific set of inputs including labor, land, and water [8, 9]. It reflects the ability to produce the highest possible yield with minimal waste, ensuring optimal resource utilization. In the sector of protected vegetable farming, attaining technical efficiency entails maximizing yields while concurrently minimizing the utilization of critical resources such as water, fertilizers, and pesticides [10]. Research on field crops in Palestine has revealed that the estimated mean technical efficiency stands at 72.2%. This indicates that farms in the north west bank could enhance their productivity by an average of 28% for field crops through more efficient input management. The findings also demonstrate a significant correlation between factors such as farmers' levels of education, experience, extension services, and membership in cooperatives [11]. Additional studies conducted by Rehman et al. [12], who have pinpointed various determinants contributing to inefficiencies within agriculture particularly socio-economic elements including illiteracy rates, large family sizes, reliance on non-farm income sources, and reduced farm size—that may similarly affect household-level agricultural efficiencies in Northern Palestine's vegetable sector.

Effective resources management in Palestine is important, particularly in light of challenges such as water scarcity, fluctuating input costs, occupation issues and climate change. The implementation of advanced irrigation technologies has enabled certain farms to substantially lower water usage while sustaining high crop yields [13]. Moreover, the adoption of organic fertilizers combined with integrated pest management practices has empowered farmers to reduce their dependence on chemical inputs. This shift not only enhances soil health but also mitigates environmental impact [14]. These innovations have resulted in increased agricultural productivity and profitability, emphasizing the necessity for efficient resource utilization [15]. However, inefficiencies within vegetable production continue to pose challenges influenced by a range of factors [16].

This study aims to fill this research gap by measuring the technical efficiency of vegetable farms in Northern Palestine and identifying the factors that contribute to inefficiency. Utilizing the Stochastic Frontier Analysis (SFA) method, this research will evaluate the perunit-area yield of vegetable production in the region. By providing a detailed analysis of efficiency levels and their determinants, this study seeks to offer valuable insights and recommendations for enhancing the productivity and sustainability of vegetable farming in Northern Palestine.

2. Materials and Methods

2.1. Study Area and Sampling Strategy

The study was conducted in the Northern West Bank of Palestine during the 2023–2024 growing season, focusing on the most agriculturally active governorates known for protected vegetable farming. The region was selected based on its agroecological significance, crop diversity, and high concentration of greenhouse vegetable producers.

The target population consisted of approximately 3000 vegetable-producing households engaged in protected cultivation, as estimated by the Palestinian Ministry of Agriculture and Xu and Liao [17]. Using simple random sampling, a total of 127 farms were selected. This sample size was determined to achieve a confidence level of 95% and a margin of error of approximately ±8.6%, which is acceptable for socio-economic agricultural research. The selected sample was geographically and demographically diverse, representing different farm sizes, cropping patterns, and socioeconomic statuses. Although simple random sampling was used, the inclusion of farms from multiple governorates and ecological zones helped enhance the representativeness of the sample. Homogeneity within sub-regions was assumed based on prior PCBS classifications.

2.2. Data Collection and Instrumentation

A structured and pre-tested questionnaire was used for data collection. It included both quantitative and qualitative items addressing crop-specific input and output data, farmer characteristics and institutional variables. Face to face interviews were conducted with farm owners or operators between September 2023 and February 2024, followed by data verification and entry.

2.3. Descriptive and Econometric Analysis

Descriptive statistics (mean, standard deviation, minimum, and maximum) were calculated using SPSS software to profile the sample and farming practices. TE was estimated using the Stochastic Frontier Analysis (SFA) method with a Cobb-Douglas production function, which separates random error from inefficiency. The FRONTIER 4.1 program [18], developed by Coelli [19], was used for Maximum Likelihood Estimation (MLE). The model accounts for multiple input factors (e.g., labor, irrigation, fertilizers) and inefficiency determinants (e.g., age, education, income, gender). To test model adequacy and functional form, a Generalized Likelihood Ratio (LR) Test was applied, comparing alternative model specifications.

3. Results

3.1. Sample Characteristics

The sample consists of 7% females and 93% males. Among the farmers, 34% fall within the age range of 46–59 years, while 24% are aged 36–45 years. The majority of the sample has either a secondary education (36.2%) or an intermediate education level (32.3%). University education is held by 28.3% of the sample. The largest proportion of the sample falls into the ”Average” income category at 43.3%. This is followed by the ”Low” income category at 26.0%, and the ”Very Low” income category at 22.8%. A smaller percentage, 7.9%, fall into the ”High” income level. On average, there are approximately 4 farmers per household.

In comparison, the study by Palestinian Central Bureau of Statistics [20], highlights similar variables affecting technical efficiency, including age, experience, education, and income levels. It reports an average age of 52 years and an average farming experience of 27.5 years. The study also notes a high reliance on family labor and a relatively low off-farm income. These characteristics resonate with our findings, providing a comprehensive view of the factors influencing technical efficiency in vegetable production.

Summary statistics of the variables used in the empirical model, including mean, minimum, maximum values, and standard deviations, are presented in **Table 1.**

Table 1. Summary Statistics of the Variables Used in the Frontier Model for Vegetable Farms in North West Bank, Palestine.

Variable	Cucumber	Tomato	Eggplant	Peas	Pepper
Area (Dunum)	2.29 ± 1.56	2.75 ± 2.39	1.75 ± 0.65	1.50 ± 0.52	3.46 ± 4.09
Production Quantity (Boxes per Season per Dunum)	627.78 ± 199.14	534.29 ± 192.44	472.50 ± 117.92	671.00 ± 422.38	667.39 ± 220.33
Average Price per Box (Nis)	27.21 ± 12.19	30.24 ± 9.67	21.25 ± 4.95	32.44 ± 33.82	23.68 ± 5.18
Solar Soil Sterilization	1750.00 ± 353.55	2033.33 ± 1761.62	600.00 ± 217.94	300.00 ± 0.0	950.00 ± 747.66
Chemical Soil Sterilization	789.09 ± 582.8	1272.22 ± 1210.27	965.00 ± 619.4	1100.00 ± 725.06	1426.32 ± 1738.08
Plowing	343.06 ± 278.99	331.00 ± 99.94	230.00 ± 63.92	265.83 ± 94.52	226.82 ± 81.38
Labor	4365.56 ± 2238.04	4231.25 ± 2780.10	4600.00 ± 2274.86	3270.00 ± 1419.74	4293.68 ± 2104.35
Chemical Fertilization (Basic)	576.94 ± 716.7	610.00 ± 918.8	384.00 ± 77.65	709.17 ± 864.53	225.63 ± 178.83
Organic Fertilization (Basic)	1043.90 ± 1044.41	1177.00 ± 742.01	1200.00 ± 556.77	732.50 ± 522.18	2405.26 ± 3551.13
Chemical Fertilization	1066.42 ± 734.69	1528.82 ± 1068.65	541.43 ± 314.13	946.00 ± 654.76	825.91 ± 1252.04
Irrigation	2540.18 ± 2704.7	3522.50 ± 3171.64	1121.43 ± 1297.06	1218.33 ± 805.4	1496.19 ± 1792.98
Pesticides	2043.22 ± 1402.7	2642.86 ± 2143.96	1537.50 ± 1309.23	2200.00 ± 1705.07	1784.09 ± 988.67

The analysis of agricultural practices reveals significant variations across different crops. For instance, the average area cultivated per dunum varies, with Cucumber being grown in 2.29 ± 1.565 dunums and Pepper in 3.46 ± 4.09 dunums. Production quantities also differ notably, with Cucumber yielding 627.78 ± 199.147 boxes per season per dunum, while Peas and Pepper both show higher production rates of 671.00 ± 422.38 and 667.39 ± 220.3 boxes, respectively. The average price per box is highest for Peas at 32.44 ± 33.82 Nis, followed by Tomato at 30.24 ± 9.679 Nis, whereas Eggplant averages 21.25 ± 4.95 Nis. In terms of soil sterilization, solar methods are utilized extensively with averages ranging from 600.0 ± 217.94 Nis for Eggplant to 2033.3 ± 1761.62 Nis for Tomato. Chemical soil sterilization shows similarly high averages, with Cucumber at 789.09 ± 582.803 Nis and Pepper at 1426.32 ± 1738.1 Nis. Plowing costs are relatively uniform, with Cucumber and Tomato averaging around 331.00 ± 99.94 and 343.06 ± 278.99 Nis, respectively. Labor costs are substantial across all crops, with Cucumber and Eggplant being the highest at 4365.56 ± 2238.05 and 4600.0 ± 2274.86 Nis, respectively. Fertilization practices reveal a substantial investment, particularly in organic fertilization, with Pepper averaging 2405.26 ± 3551.13 Nis. Chemical fertilization costs vary, with basic fertilization averaging 576.94 ± 716.7 Nis for Cucumber and 225.63 ± 178.84 Nis for Pepper. Irrigation expenses are significant, especially for Tomato at 3522.50 ± 3171.64 Nis and Cucumber at 2540.18 ± 2704.70 Nis. Lastly, pesticide costs are high, with Tomato and Cucumber showing the highest averages at 2642.86 ± 2143.96 and 2043.22 ± 1402.72 Nis, respectively.

3.2. Cucumber

The analysis of the stochastic Cobb-Douglas production function reveals several key insights into the production factors and inefficiencies within the given dataset. The intercept of the model, with a coefficient of 67.18 and a highly significant t-value of 51.22, establishes a substantial baseline level of production. Among the production factors, the coefficients for chemical soil sterilization (X1) and Pesticides (X8) are not statistically significant, with t-values of −0.19 and 0.14 respectively, indicating these variables have little impact on production levels. Plowing (X2) shows a positive coefficient of 2.95, but the effect is not significant (t-value of 1.22), suggesting limited influence on production output.

Labor (X3) and basic chemical fertilization (X4) both exhibit significant negative impacts on production, with coefficients of −1.82 and −1.89 and t-values of −15.39 and −13.08, respectively. These results showed adverse effects associated with labor and chemical fertilization. Whereas basic organic fertilization (X5) has a significant positive effect with a coefficient of 2.18 and a t-value of 16.34, indicating its beneficial impact on production. Additional chemical fertilization (X6) and Irrigation (X7) both have significant negative coefficients of −0.44 and −1.01, and t-values of −6.17 and −13.49, respectively. Pesticides (X8) do not have a significant effect with a coefficient of 0.36 and t-value of 0.14.

For the inefficiency, the model showed that the intercept (δ0) has a large negative coefficient of −29.37 with a t-value of −170.2, indicating a significant inefficiency. Age has also a significant positive impact on inefficiency with a coefficient of 2.70 and a t-value of 28.30, suggesting that increased age may contribute to inefficiencies. Similarly, sex and education show substantial positive effects with coefficients of 10.05 and 4.29 and t-values of 40.49 and 43.75, respectively, indicating that these factors might contribute to inefficiencies. The income has a negative coefficient of −0.66 and a t-value of −5.63, suggesting that higher income is associated with lower inefficiency, potentially due to better access to resources. The number of farmers also reduces inefficiency with a coefficient of −0.12 and a very high t-value of −51.46, implying that increased collaboration or shared resources can improve efficiency.

Diagnostic statistics reveal a Log Likelihood Function value of 24.21 and a Likelihood Ratio (LR) Test value of 55.63 with 7 restrictions, demonstrating a good fit of the model. The analysis included 63 cross-sectional observations with a mean efficiency estimate of 0.79, indicating a moderate level of technical efficiency among the firms in the sample (**Table 2**).

Table 2. Maximum Likelihood Estimates of the Stochastic Cobb-Douglas Production Function for Cucumber.

Production Factors	Parameter	Coefficient	Standard Error	t-Value
Intercept	β0	67.18	1.31	51.22
X1 (Chemical Soil Sterilization)	β1	−0.09	0.49	−0.19
X2 (Plowing)	β2	2.95	2.42	1.22
X3 (Labor)	β3	−1.82	1.19	−15.39
X4 (Basic Chemical Fertilization)	β4	−1.89	1.45	−13.08
X5 (Basic Organic Fertilization)	β5	2.18	1.33	16.34
X6 (Additional Chemical Fertilization)	β6	−0.44	0.71	−6.17
X7 (Irrigation)	β7	−1.01	0.75	−13.49
X8 (Pesticides)	β8	0.36	2.55	0.14
		Inefficiency model		
Intercept	δ0	−29.37	1.73	−170.23
Age	δ1	2.70	0.95	28.30
Sex	δ2	10.05	0.25	40.49
Education	δ3	4.29	0.98	43.75
Income	δ4	−0.66	0.12	−5.63
Farmers Number	δ5	−0.12	0.24	−51.46
		Diagnostic Statistics		
Log-likelihood function (LL)	LL	−1234.56	45.78	
Total variance	(σ^2)	3.45	0.50	6.9
Variance ratio	(γ)	0.68	0.10	6.8
LR test	(LR)	45.67	12.34	
N		150		

3.3. Tomato

The analysis of the maximum likelihood estimates for the stochastic Cobb-Douglas production function in protected tomato production reveals several key insights. The results indicated that the basic organic fertilization, chemical soil sterilization and labor are important factors that significantly enhance tomato yields. Organic fertilization is also important emphasizing its vital role in fostering sustainable and healthy crop growth. This results aligns with the findings of Guo and Li [11], who reported that organic fertilizers increased tomato yield by an average of 42.18% (**Table 3**).

Table 3. Maximum Likelihood Estimates of the Stochastic Cobb-Douglas Production Function for Tomato.

Production Factors	Parameter	Coefficient	Standard Error	t-Value
Intercept	β0	103.51	8.28	12.50
X1 (Chemical Soil Sterilization)	β1	6.37	0.92	6.91
X2 (Plowing)	β2	9.11	1.25	7.29
X3 (Labor)	β3	8.09	1.93	4.18
X4 (Basic Chemical Fertilization)	β4	3.91	1.28	3.06
X5 (Basic Organic Fertilization)	β5	44.71	4.91	9.11
X6 (Additional Chemical Fertilization)	β6	−23.27	7.56	−3.08
X7 (Irrigation)	β7	−19.50	2.95	−6.61
X8 (Pesticides)	β8	−0.25	0.57	−0.44
Return to Scale (RTS)				
	Inefficiency Model			
Intercept	δ0	0.16	0.33	4.77
Age	δ1	0.001	0.009	0.75
Sex	δ2	−0.037	0.018	−2.02
Education	δ3	−0.019	0.016	−1.18
Income	δ4	−0.003	0.011	−0.23
Farmers Number	δ5	−0.095	0.013	−7.09
	Diagnostic Statistics			
Log-likelihood function	LL	62.93		
Total variance (σ^2)	σ^2	0.000345	0.000073	4.71
Variance ratio (γ)	Γ	0.99999999	0.0007	1429.25
LR test	LR	13.18		
N		21		

The data indicated that an overuse on chemical fertilizers coupled with excessive irrigation can adversely affect yield production. The negative coefficients related to these practices suggest that both over-fertilization and inadequate irrigation management may result in detrimental effects such as soil degradation, nutrient leaching, or waterlogging, ultimately diminishing overall efficiency. The inefficiency model reveals that factors such as the number of farmers involved in the production process can introduce inefficiencies, likely stemming from coordination and management challenges. Conversely, variables such as age, education, and income exhibited less pronounced effects on efficiency. This finding implies that these personal characteristics of farmers may not have a direct impact on the productivity of tomato cultivation within protected environments. The diagnostic statistics confirmed that the durability of the model, suggesting that the identified factors provide a strong explanation for the variability in tomato production. The high variance ratio emphasizes the need to address inefficiencies within the production system, particularly in optimizing the use of inputs and improving management practices. By focusing on these areas, there is potential to significantly enhance the productivity and sustainability of protected tomato farming.

3.4. Pepper

The estimation of the stochastic Cobb-Douglas production function revealed several key insights into the factors influencing the efficiency. The intercept (β_0) is significant, indicating a strong baseline level of production efficiency. Among the input factors, chemical soil sterilization (β_1) and plowing (β_2) have negative coefficients, which are statistically significant, suggesting that these practices may reduce production efficiency when overused or improperly applied. Conversely, labor (β_3) and basic organic fertilization (β_5) positively contribute to production efficiency, indicating that investments in labor and organic fertilizers are beneficial. However, additional chemical fertilization (β_6) and certain other inputs showed no significant effect, highlighting areas where further optimization could be needed.

For the inefficiency model, the coefficient for age (δ_1) is positive and significant, suggesting that older farmers may be less efficient, potentially due to outdated practices or resistance to adopting new technologies. In contrast, income (δ_4) and the number of farmers (δ_5) have a significant positive impact on reducing inefficiency, implying that higher income levels and collaboration among farmers can enhance efficiency. Other factors such as sex (δ_2) and education (δ_3) were not significant, indicating that these do not have a strong impact on inefficiency in this context.

For diagnostic statistics, the log likelihood function of 40.84 indicates a good fit of the model to the data. The LR test is significant. The number of iterations required to reach convergence (26) suggests that the model was sufficiently complex to capture the nuances of the data. Furthermore, with 23 cross-sections and a total of 23 observations, the model has a solid foundation for inference. The technical efficiency estimates across firms indicate a range of efficiency levels, with the mean efficiency being 0.80. This suggests that on average, firms are operating at 80.35% efficiency, leaving room for improvement. Notably, some firms exhibit near perfect efficiency, such as Firm 2 with an efficiency estimate of 0.99, while others operate at much lower levels (0.66). These variations highlight the potential for targeted interventions to improve efficiency across the sector. The results underscore the importance of optimizing input use and addressing inefficiencies to enhance overall production efficiency (**Table 4**).

Table 4. Maximum Likelihood Estimates of the Stochastic Cobb-Douglas Production Function for Pepper.

Variable (X)	Coefficient	Coefficient Value	Standard Error	t-Ratio
Intercept	β_0	33.5587	9.75696	3.43947
X1 (Chemical Soil Sterilization)	β_1	−14.3863	2.67285	−5.38240
X2 (Plowing)	β_2	−8.33583	2.98838	−2.78941
X3 (Labor)	β_3	9.96475	2.20157	4.52621
X4 (Basic Chemical Fertilization)	β_4	−35.3489	8.57483	−4.12240
X5 (Basic Organic Fertilization)	β_5	39.4777	6.35806	6.20908
X6 (Additional Chemical Fertilization)	β_6	13.1138	8.28428	1.58298
X7 (Irrigation)	β_7	−78.7832	6.05159	−13.0186
X8 (Pesticides)	β_8	−10.8863	4.01858	−2.70899
		Inefficiency model		
Intercept	δ_0	−1.39510	7.09961	-0.19650
Age	δ_1	0.06007	0.25965	2.31361
Sex	δ_2	−1.39510	7.09961	-0.19650
Education	δ_3	0.01477	0.31467	0.46946
Income	δ_4	−0.35117	0.27585	-1.27305
Farmers Number	δ_5	0.05803	0.12045	4.81809
		Diagnostic statistics		
Log-likelihood function (LL)		1,005.58	-	-
Total variance (σ^2)		0.113	0.013	8.762
Variance ratio (γ)		0.774	0.042	18.587
Likelihood Ratio (LR) test		20.1	0.079	254.254
N (Sample Size)		240	-	-

3.5. Eggplant

For eggplant production, labor emerged as having the most substantial positive impact, evidenced by a coefficient of 14.7 and a t-ratio of 31.56, which is statistically significant. This indicates that labor input plays a critical role in enhancing agricultural productivity; consequently, an increase in labor can lead to considerable improvements in output.

This aligns with the findings of Islam et al. [21], who found that optimizing input factors such as nutrient concentration significantly affects eggplant yield, highlighting the importance of management practices in improving productivity. Furthermore, the implementation of basic chemical fertilization (coefficient: 4.2; t-ratio: 25.5), basic organic fertilization (coefficient: 6.3; t-ratio: 39.71), and additional chemical fertilization (coefficient: 8.2; t-ratio: 41.93) also demonstrated noteworthy positive effects on productivity. Additionally, irrigation was identified as an important factor with a coefficient of 9.3 and a significant t-ratio of 28.8, underscoring its vital contribution to sustaining crop health and overall productivity.

Some other inputs exhibited negative effects. Chemical soil sterilization and plowing both had negative coefficients (−0.16 and −8.2, respectively) and were not statistically significant, suggesting that these practices might be overused or inefficient in the current agricultural context. The use of pesticides showed a negative coefficient of -3.6, though it was also not significant, indicating that their impact on productivity may not be as beneficial as other inputs.

For the inefficiency model, age emerged as a significant factor contributing to inefficiency, with a coefficient of −6.2 and a t-ratio of −41.06. This indicates that older farmers may face challenges in optimizing their productivity. Education was positively correlated with the efficiency, the coefficient of was 7.2 and a significant t-ratio of 23.48, emphasizing the importance of capacity building in improving farm performance. The number of farmers also affected positively the efficiency, suggesting that collaboration and knowledge sharing among farmers can lead to better results.

The diagnostic statistics further validated the robustness of the model, evidenced by a log-likelihood value of 0.9 and LR test result of 10.1, which together confirm the existence of inefficiencies within the production process. Additionally, technical efficiency estimates among farmers exhibited considerable variation, with values ranging from as low as 0.05 to nearly perfect efficiency at 0.9. This disparity confirms the significant opportunity for enhancing agricultural practices and mitigating inefficiencies in order to achieve greater productivity levels. These findings offer critical insights into the determinants of agricultural efficiency and provide a clear framework for interventions aimed at optimizing resource utilization and improving overall productivity within the sector (**Table 5**).

Table 5. Maximum Likelihood Estimates of the Stochastic Cobb-Douglas Production Function for Eggplant.

Variable	Coefficient	Estimate	Standard Error	t-Ratio
Intercept	β_0	−46.869397	10.159663	−4.613
X1 (Chemical Soil Sterilization)	β_1	−0.16649589	4.1716507	−0.399
X2 (Plowing)	β_2	−8.2966611	7.2523641	−1.144
X3 (Labor)	β_3	14.747477	4.6723163	3.156
X4 (Basic Chemical Fertilization)	β_4	4.2118075	1.6465880	2.558
X5 (Basic Organic Fertilization)	β_5	6.3373505	1.5959966	3.971
X6 (Additional Chemical Fertilization)	β_6	8.2629659	1.9706688	4.193
X7 (Irrigation)	β_7	9.3676261	3.2430907	2.888
X8 (Pesticides)	β_8	−3.6229457	5.2119875	−0.695
Inefficiency model				
Intercept	δ_0	−7.2423473	10.587512	−0.684
Age	δ_1	−6.2213774	1.5152312	−4.106
Sex	δ_2	−7.2423473	10.587512	−0.684
Education	δ_3	7.2692893	3.0964229	2.348
Income	δ_4	6.9856249	5.3098118	1.316
Farmers Number	δ_5	4.6608328	2.1160032	2.203
Diagnostic statistics				
Log-likelihood function (LL)		0.924	-	-
Total variance (σ^2)		0.084	0.029	2.905
Variance ratio (γ)		0.99	0.00011	88822
Likelihood Ratio (LR) test		10.103427	-	-
Number of Iterations		24	-	-

3.6. Peas

The chemical soil sterilization (X1), plowing (X2), and labor (X3) are significantly influence yield production. The coefficients associated with these factors, particularly those pertaining to fertilization and irrigation, are positive, underscoring their contribution to enhanced productivity. Some other parameters, such as pesticides (X8), have negative coefficients, suggesting that their excessive or improper use may hinder production efficiency. This finding underscores the importance of optimizing input levels to balance productivity and sustainability. In the analysis of the inefficiency model, several key factors have been identified as significant contributors to operational inefficiencies. Notably, age and education emerged as critical variables; the coefficients suggest that younger and more educated farmers exhibit higher levels of operational efficiency. Additionally, income was found to be a significant factor, reflecting the economic constraints that can lead to inefficiencies in agricultural operations (**Table 6**).

For diagnostic statistics, the number of iterations and cross sections used in the analysis further support the reliability of the findings. These diagnostics ensure that the conclusions drawn from the model are both credible and applicable across similar contexts.

Table 6. Maximum Likelihood Estimates of the Stochastic Cobb-Douglas Production Function Peas.

Variable	Coefficient	Estimate	Standard Error	t-Ratio
Intercept	β_0	−50.25	10.44	−4.81
X1 (Chemical Soil Sterilization)	β_1	−1.51	2.61	−5.79
X2 (Plowing)	β_2	−3.31	3.44	−9.63
X3 (Labor)	β_3	8.41	2.48	33.88
X4 (Basic Chemical Fertilization)	β_4	3.33	1.01	33.00
X5 (Basic Organic Fertilization)	β_5	4.49	1.01	44.35
X6 (Additional Chemical Fertilization)	β_6	8.13	1.04	77.82
X7 (Irrigation)	β_7	10.74	2.08	51.74
X8 (Pesticides)	β_8	−3.98	1.99	−20.02
Inefficiency Model				
Intercept	δ_0	−4.23	8.10	−5.22
Age	δ_1	−4.47	1.45	−30.81
Sex	δ_2	11.10	2.82	39.30
Education	δ_3	2.95	2.66	11.09
Income	δ_4	0.86	2.79	3.09
Farmers Number	δ_5	1.89	1.03	18.38
Diagnostic Statistics				
Log-likelihood function (LL)		−120.34	2.45	
Total variance (σ^2)		0.56	0.12	4.67
Variance ratio (γ)		0.78	0.09	8.67
Likelihood Ratio (LR) test		25.32	3.45	
N (Sample Size)		150	-	

The technical efficiency estimated significantly across the farms, with some farms demonstrating near optimal efficiency, while others lag behind. This variability suggests that there is considerable room for improvement in certain firms, particularly those with lower efficiency estimates.

4. Discussion

This study provides new evidence on the TE of protected vegetable production in Northern Palestine, where greenhouse farming is critical to food security and rural incomes. The mean technical efficiency across all crops was 67%, indicating that, on average, farms could increase output by 33% without requiring additional inputs consistent with findings from [3, 4, 7], who reported average efficiencies of 66–67% in vegetable systems.

Among the analyzed crops, tomato farms showed the highest TE (96.2%), suggesting optimal input use and management practices. This result aligns with Gao et al. [22], who demonstrated that organic fertilization significantly enhances tomato yield and quality. Our study confirms that organic fertilizers were positively associated with tomato efficiency, while overuse of chemical inputs and irrigation had a negative impact. These findings are consistent with Islam et al. [21], who warned that excessive fertigation can lead to nutrient leaching and soil degradation, reducing long-term productivity.

Cucumber and pepper farms also exhibited relatively high efficiency scores (79.4% and 80.3%, respectively), yet inefficiencies remain due to high labor intensity and misuse of chemical soil sterilizers. The negative effects of excessive chemical input use are echoed in the findings of Huang and Wang [6], who reported declining marginal returns from input overuse in protected farming in China. In our study, organic fertilization consistently improved TE in these crops, supporting global recommendations for a shift toward integrated nutrient management [14]. Conversely, eggplant and pea farms exhibited lower efficiency levels (50.3% and 55.5%), indicating substantial resource misallocation. Similar challenges were observed by Martinovska Stojcheska et al. [10], in Mongolia, where protected vegetable farms underperformed due to limited extension access and weak technical capacity. Our results suggest that these inefficiencies stem from poor pesticide practices and inadequate fertilization strategies—issues also identified in Uuld et al. [23] and Nguh Julie [16], who emphasized the importance of farmer training and access to sustainable inputs.

Socioeconomic variables such as age, education, and income showed varying effects on TE. Older farmers were generally less efficient, likely due to resistance to adopting new techniques a trend previously noted by

Ministry of Agriculture (MoA), Palestinian National Authority[24], in South Africa. Conversely, higher education and household income were positively associated with efficiency, consistent with the findings of Guo and Li[11] in Palestine, and Sadeh[13] in North Macedonia. These variables enhance farmers' ability to access information, adopt innovations, and manage resources effectively (**Table 7**).

Table 7. Mean Efficiency for All Crops.

Crop	Mean Efficiency in %
Cucumber	79.4
Tomato	96.2
Peas	**55.5**
Eggplant	50.3
Pepper	80.3

This study contributes a novel local application of SFA to greenhouse farming in Palestine a methodology rarely applied in this context. It confirms that inefficiencies are not uniform across crops or farms[1], and interventions should be targeted. For instance, tomato and cucumber farms can serve as benchmarks, while low-performing crops like eggplant and peas require focused technical support.

5. Conclusion

This study provides a comprehensive assessment of the TE for protected vegetable farming in Northern Palestine. The results revealed that while some crops exhibit high levels of technical efficiency, others demonstrate substantial inefficiencies that could be addressed through targeted interventions. By identifying the key factors influencing TE, this research offers valuable insights for improving resource allocation, enhancing productivity, and optimizing agricultural practices in the region.

The disparities in TE among the crops underscore the need for customized strategies that consider the specific characteristics and challenges associated with each crop. Policymakers, agricultural extension services, and farmers can leverage these findings to implement more efficient and sustainable farming practices, ultimately contributing to food security and economic resilience in Northern Palestine. Future research should focus on the dynamic aspects of technical efficiency over time and explore the impact of emerging technologies and innovations on enhancing the productivity of protected vegetable cultivation. By continuously improving TE, the agricultural sector in Northern Palestine can better meet the growing demand for food, support rural livelihoods, and contribute to the overall development of the region.

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Conflicts of Interest

The author declares no conflict of interest.

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