DOI: 10.52131/pjhss.2024.v12i4.2571

Pakistan Journal of Humanities and Social Sciences

Volume 12, Number 04, 2024, Pages 3064-3084
Journal Homepage:
https://journals.internationalrasd.org/index.php/pjhss

Efficiency Analysis of Vegetable Production; An Appraisal of Tunnel Farming System in Punjab, Pakistan

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ARTICLE INFO

Article History:
Received: August 24, 2024
Revised: November 13, 2024
Accepted: November 14, 2024
Available Online: November 15, 2024

Keywords:
Stochastic Frontier Analysis
Efficiency Analysis
Off-season Vegetable Production
Tunnel Farming
Sustainability
Pakistan
Punjab

Funding:
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

ABSTRACT

In Pakistan, where traditional farming methods prevail, the potential benefits of tunnel farming remain unclear. To investigate, the study surveyed 353 farmers across five districts in Punjab, with 226 using tunnel technology and 127 employing conventional methods. Stochastic frontier analysis revealed that tunnel farmers demonstrated higher technical, economic, and overall efficiency compared to conventional farmers. Results indicated that tunnel farmers exhibit higher economic efficiency compared to conventional farmers, suggesting a potential 13% improvement in economic efficiency if conventional farmers transition to tunnel technology. Factors such as farm area, age, education, family size, irrigation, fertilizer use, and labour hours significantly influence technical inefficiency, highlighting the importance of these variables in enhancing farming efficiency. This efficiency stems from factors such as the use of hybrid seeds, advanced fertilizers, drip irrigation, and skilled labour, leading to increased output and extended market seasons. Despite these advantages, financial constraints hinder many farmers from adopting tunnel farming. By supporting the transition to tunnel farming, Pakistan can improve agricultural productivity, enhance food security, and uplift the livelihoods of its farming communities.

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1. Introduction

Current world population is 8 billion, expected to reach 8.5 billion by 2030 (Norrman, 2023). Under this rapid human population growth food security is a major challenge. As, global population approaching 9 billion people in the next few decades, it is often stressed by United Nations and Food and Agriculture Organization (FAO), that there is a need for 70-100% more food to feed the current population (Aly & Borik, 2023). Asia, with over 60 percent of the global population, possesses only 34 percent of arable land and 36 percent of drinkable water resources (Yang et al., 2022). Consequently, the continent grapples with severe food security challenges. Despite notable progress in poverty and hunger reduction, Asia still contends with significant levels of food insecurity and malnutrition. Recent estimates from the FAO (2023) reveal that nearly 600 million persons will be chronically malnourished in 2030. South Asia, facing limitations in land, energy, and escalating water stress, confronts the task of supplying sufficient resources to meet the food demands of its expanding populace (Salem, Pudza, & Yihdego, 2022). This situation mirrors that of Pakistan, where undernourishment persists across all segments of the population.With population of 192 million, Pakistan is the 5th most populated country in the world. If we talk about Punjab, despite agriculture rich province 27% of rural households are suffering from food insecurity. Landless households, family size and low profit margins are major contributors in the rising of food insecurity (Getaneh et al., 2022; Naz et al.; Panezai et al., 2022; Wolde et al., 2020).

The efficiency of vegetable production holds significant importance in meeting the food demands of a growing population, particularly in regions like Punjab, Pakistan, where agriculture is a vital sector of the economy. With the rising demand for food all around the world, there have been various interventions and technological advancements from ploughing to harvesting of crops in agriculture. Borojo et al. (2023); Caglar and Askin (2023) discussed the impacts of green revolution in developing countries. By the use of new high yield crop seeds especially for rice and wheat there is 50% increase in yield growth and almost 40% increase in production growth in almost all developing countries, leads to decline in food prices globally. With the ever-increasing pressure to enhance productivity while addressing resource constraints and environmental sustainability, there is a pressing need to critically appraise the efficiency of existing farming systems. Efficiency analysis provides valuable insights into the performance of agricultural practices, guiding policymakers and stakeholders towards informed decision-making. Moreover, understanding the determinants of efficiency can aid in the formulation of targeted interventions to improve productivity and profitability in vegetable cultivation.

New irrigation technologies prove very useful in increasing allocative efficiency of farmers by saving water. Irrigation interventions like improved farm layout, water course improvement, laser land levelling and drip irrigation are blessing for farmers living in areas where there is no proper irrigation system and rain is scarce (Ahmad, 2023; Mivumbi & Yuan, 2023). Tunnel farming offers a robust alternative to conventional agriculture, integrating various practices for enhanced efficiency (Jamarkattel et al., 2023).Studies in Pakistan and other countries underscore the need for improvement in agricultural practices. Marwat (2022) identified knowledge gaps and high input costs as barriers to adopting tunnel farming. Plastic tunnels, introduced in Pakistan in the 1980s, have gained popularity, with significant acreage under cultivation. Tunnel farming enables manipulation of environmental conditions, addressing food demand challenges. The method enhances off-season vegetable production and yield per acre through advanced technologies. With Pakistan's agricultural sector facing challenges, adopting modern interventions like tunnel farming becomes crucial for food security (Fatima, Almas, & Haroon, 2020). In this context, this research paper aims to assess the efficiency of vegetable production in Punjab, Pakistan, with a specific focus on the emerging farming method of tunnel farming. By examining the efficiency of tunnel farming alongside conventional methods, this study seeks to provide a comprehensive evaluation of the potential benefits and challenges associated with adopting this innovative approach in Punjab's agricultural landscape.

1.1. Problem Statement

Agricultural practices are inefficient in developing countries and with the use of such inefficient farming methods it is very hard to keep up with the growing demand of food (Giller et al., 2021; Nugroho, 2021; Takahashi, Muraoka, & Otsuka, 2020). Agricultural interventions like plastic tunnel farming are very important to fulfil rising food demands, but before adopting any new technology it is very important to answer "Whether new farming techniques are better than the old one?"

1.2. Research Gap

Agriculture in developed countries like the US demonstrates higher efficiencies, for technical, allocative, and economic efficiency than the developing countries (Guo et al., 2021). The disparity is attributed to modern techniques and interventions. Tunnel farming is relatively new in Pakistan, with previous studies focusing on conventional methods. Hence, a comparative efficiency analysis between conventional and tunnel farming is essential (Aziz et al., 2021; Bibi, Khan, & Haq, 2021; Imran et al., 2022; Parizad & Bera, 2021).

1.3. Objective

- To quantify tunnel vs. conventional farming systems in the study area.
- To compare technical, allocative and economic efficiencies of conventional and tunnel farming to determine which farming system is more efficient in the province of Punjab.

1.4. Significance of Study

This study will be an addition in the limited literature of tunnel farming in Pakistan. Comparative analysis of tunnel and conventional farming on the basis of their efficiency analysis will help to figure out which farming system is more efficient and beneficial for farmers. Thus, encourage farmers to adopt efficient agriculture technology, may result in increase in the production of fruits and vegetables and also increase farmers' profit margins which will improve overall efficiency of agriculture in Pakistan.

2. Review of Literature

Several studies have explored the impact of agricultural interventions, particularly tunnel farming, on food security and sustainable agriculture. This review focuses on assessing how such interventions, including tunnel farming, can enhance food production and whether they are more efficient than conventional farming methods. Agricultural interventions, such as hybrid seeds, modern irrigation techniques, and tunnel farming, have been instrumental in increasing food production, crucial for sustaining the growing population. Despite agriculture's significant contribution to Pakistan's GDP (24%), its productivity remains lower than other countries, largely due to limited mechanization. Pakistan's adoption of modern agricultural interventions, including mechanization, is essential to boost productivity and meet food demand.

2.1. Agriculture Intervention

The Green Revolution has had significant implications for agriculture in developing countries. The concept of growing vegetables in controlled environments dates back to Roman times (Nemali, 2022), although early glass greenhouses faced challenges in providing adequate heat to crops. Organic method of farming can also be helpful in reducing global warming (Gamage et al., 2023; Parizad & Bera, 2021). Latest irrigation interventions are very handy in improving allocative efficiency of farmers by saving water. Irrigation interventions like improved farm layout, water course improvement, laser land levelling and drip irrigation are blessing for farmers living in areas where there is no proper irrigation system and rain is scarce (Fishman, Giné, & Jacoby, 2023; Kale et al., 2024). Resource conservation interventions like laser land levelling, bed furrow and zero tillage can save 31, 40 and 49 percent of irrigation water per hectare and fertilizer use efficiency increases by 17.7, 18.19 and 19.1 percent per hectare respectively, therefor resource conservation interventions are very useful tools for making development towards sustaining and improving agriculture products. Levelling of lands and covers on fields can improve water efficiency by 10%-20% (Liu et al., 2023; Roy et al., 2022; Yaekob et al., 2022; Ye et al., 2022). Crops consumed much less water in drip irrigation compare to furrow irrigation. Orthodox irrigation methods like furrow irrigation, consumes large amount of water but area between the crop rows remains dry and get water only from incidental rainfall, whereas drip irrigation technology slowly applies water to the root area of plant. Drip irrigation technology also reduces irrigation and labour cost and also very useful in steeper areas where irrigation is very difficult by using conventional methods(Asif et al., 2024).

2.2. Review of the Efficiency Studies in Agriculture

Khan et al. (2022) investigated rice farmers' technical efficiency in Pakistan's Swat district. Findings suggested positive effects of chemicals, urea, DAP, labour, and farmyard manure on rice yield. Farmers' age correlated positively with inefficiency, while education and experience reduce inefficiency. Mean technical efficiency is 87%, indicating room for improvement. The study recommended training programs to enhance agronomic skills and boost rice yield in the area. Mahmood et al. (2022) investigated the impact of digital credit facilities on small-scale farmers' efficiency. Results show positive effects on technical, allocative, and economic efficiency. Factors like farmer education and internet access also influenced efficiency. Recommendations included providing digital credit and enhancing educational opportunities for farmers.

Khajjak, Mangan and Nangraj (2024) investigated groundwater depletion's impact on cotton growers' efficiency in Sindh, Pakistan. Data from 390 cotton producers revealed commendable technical but deficient allocative and economic efficiency, especially in groundwater utilization. Factors like experience and tube well depth influence allocative efficiency. Disparities among canal users highlight the need for stakeholder collaboration, with a focus on resource management education for sustainable agriculture. Most of the farmers in Pakistan use conventional methods in agriculture which are quite inefficient (Arshad et al., 2022; Aziz et al., 2021; Bibi, Khan, & Haq, 2021; Imran et al., 2022; Perveen et al., 2021) and as a result despite being the largest sector of Pakistan's economy agriculture have faced a negative growth of 0.19 percent last year (Pakistan Economic Survey, 2022-23). To ensure food security to its overwhelmingly growing population, introduction of modern agricultural interventions in agriculture sector is very important. Tunnel farming is one of latest and important intervention which gives control over temperature to farmers thus they can extend their growing season and also protect crops from plant diseases and insects (Jamarkattel et al., 2023). In this study comparative analysis of conventional and tunnel farming is done on the basis of their respective efficiencies. For the purpose of efficiency analysis of tunnel and conventional farmers, total of 353 farmers are interviewed from 5 districts of Punjab i.e. (Toba Tek Singh, Sheikhupura, Pakpattan, Rawalpindi and Sahiwal) from 4 agro ecological zones of Punjab province(Ahmed, Azhar, & Mohammad; Dler M Ahmed, Z Azhar, & Aram J Mohammad, 2024; Dler Mousa Ahmed, Zubir Azhar, & Aram Jawhar Mohammad, 2024; Mohammad, 2015a, 2015b; Mohammad & Ahmed, 2017).

3. Methodology

3.1. Study Site

With the population of 110 million people Punjab is a most populous province of Pakistan (Pakistan Bureau of Statistics. 2017). It is furthered divided into 36 districts and has 4 agro ecological zones. For the purpose of efficiency analysis of tunnel and conventional farmers, total of 353 farmers are interviewed from 5 districts of Punjab i.e. (Toba Tek Singh, Sheikhupura, Pakpattan, Rawalpindi and Sahiwal) from 4 agro ecological zones of Punjab province. Out of 353 farmers 226 farmers are using tunnel farming and 127 farmers are using conventional cultivation methods. Purposive sampling is used to select targeted farmers for the purpose of data collection.

3.2. Difference between Productivity and Efficiency

Productivity measures the output achieved with a given input, categorised into partial productivity focusing on specific factors such as labour or land, and total factor productivity, which encompasses all input factors (Hassan, 2004). Efficiency evaluates the economic performance of an entity, aiming to maximize output from known inputs (Farrell, 1957). Koopmans (1951) defines technical efficiency as achieving increased output with reduced input or vice versa, while allocative efficiency ensures optimal input-output combinations relative to market prices (Lovell, 1993). Technical inefficiency arises from the suboptimal use of production inputs, while allocative inefficiency occurs when input marginal products do not align with market prices. Economic efficiency integrates both technical and allocative efficiency (Farrell, 1957).

3.3. Measurement of Technical & Allocative efficiency

Various approaches are utilized to gauge technical inefficiency, primarily divided into two categories: frontier and non-frontier approaches. Within the frontier approach, statistical and non-statistical methods are employed to estimate efficiencies. Non-statistical methods include non-parametric and parametric approaches, with the former, known as Data Envelopment Analysis (DEA), lacking a fixed functional form for the frontier.

3.4. Parametric Frontier Production Function

Considering the disadvantages of non-parametric approach (DEA), parametric frontier approach is used in this study. Parametric approach is further divided into deterministic and stochastic frontier production functions. The methodology developed by Coelli (1998) stochastic frontier analysis also known as SFA, has been followed in the present study. This framework models production by considering output deviations as a result of both inefficiency and random noise. The former reflects a firm's inability to fully utilize its resources, while the latter captures external factors beyond its control. Frontier 4.1 is a tool designed to estimate stochastic frontier models and has been used for its robust capabilities. It offers a user-friendly interface, supports various functional forms like Cobb-Douglas and Translog, and ensures reliable results through maximum likelihood estimation. Additionally, it provides detailed outputs, such as inefficiency scores and likelihood-ratio tests, making it highly suitable for productivity and efficiency studies across sectors. This tool's alignment with Coelli's framework ensures methodological consistency and analytical rigor in efficiency analysis.

3.5. Empirical Models

Stochastic frontier production function method to estimate technical, allocative efficiency and economic efficiency of vegetable growers is adopted in this study, since agriculture production in commonly and vegetable production particularly exhibits random shocks and there is a need to separate out the effects of stochastic variables i.e., random shocks and measurement errors from resulting estimates of inefficiencies. Several studies have used stochastic production function methodology to determine technical, allocative and economic efficiencies (Koengkan et al., 2022; Raut, Shende, & Dangore, 2023). Trans-log functional form is a flexible functional form and does not involve restrictions of fixed rate of technical substitution (RTS) value and an elasticity of substitution equalling to one as in Cobb Douglas form. Therefore, in this study trans-log functional form is preferred over Cobb Douglas functional form. The empirical models are as under:

$$\ln Y_{ij} = \beta_o + \sum\beta_1 logX_{ij} + \sum\beta_{ij}(lnX_{ij})(lnX_{ji}) + v_{ij} - u_{ij}$$

i= 1, 2, n j= conventional, tunnel

Where Y_{ij} is the dependent variable in the production function showing yield in (mounds per acre) for the i-th farmer and j is either farmer using tunnel technology or conventional methods of farming. Variable yield and inputs are expressed in natural logarithms. X_{ij} is a vector of k inputs used in the production of vegetables and X_{ji} are the inputs used by farmers defined as under:

$\beta_o, \beta_1, \beta_{ij}$ are unknown parameters to be estimated and v_{ij} and u_{ij} are defined earlier
$u_t^{\prime s}$ are non-negative random variables, associated with inefficiency of production of the farmers assumed to be independently distributed such as the inefficiency effect if the i-th farmer using j-th farming technique is obtained by truncation (at zero) of the normal distribution with mean μ and variance σ^2, such that. Primary focus of this study is to find out the efficiencies of tunnel and conventional farmers and how the different inputs and demographic variables influence the efficiencies. For this purpose, inefficiency effects models are used in stochastic frontier analysis, by which we can analyse the effects of variables whether demographic or inputs used by farmers on inefficiencies caused in production. Frontier 4.1 software developed by T.M Coelli is used for analysis.

3.6. Technical Inefficiency Effects Model

$$\mu_{ij} = \delta_o + \delta_1 Z_{1ij} + \delta_2 Z_{2ij} + \delta_3 Z_{3IJ} + \delta_4 Z_{4ij} + \delta_5 Z_{5ij} + \delta_6 Z_{6ij} + \delta_7 Z_{7ij} + \delta_8 Z_{8ij} + \delta_9 Z_{9ij} + \omega_{ij} \quad (1)$$

Where,
Z_{1ij} represents Farm Area in Acre.
Z_{2ij} represents Age of farmer in years.
Z_{3ij} represents Education of farmer in number of years of education.
Z_{4ij} represents number of Family Members.
Z_{5ij} represents number of Irrigation per acre.

Z_{6ij} represents number of Fertilizer Bags per acre.
Z_{7ij} represents quantity of Manure in mounds per acre.
Z_{8ij} represents Number of sprays per acre.
Z_{9ij} represents Labour hours per acre.
δ_s are unknown parameters to be estimated.

Model to calculate technical inefficiency of farmers incorporates farmers and farm specific characteristics. Above mentioned variables in the technical inefficiency effects model are discussed below with their likely effects on technical efficiency. To analyse the impact of the area on which farmers is cultivating vegetables variable farm area is included in the model. Many studies extract a positive relationship between farm area and efficiency (Castro et al., 2023; Cillero & Reaños, 2023; Khatri-Chhetri et al., 2023) yet some other studies found no such association (Ali, Baker, & Al-Douri, 2022; Helfenstein et al., 2022; Malabayabas & Mishra, 2022; Munir, Junejo, & Rahpoto, 2020). So, no prior expectation for this model is made. Age of farmer is included in the model in order to estimate the effect of the age of primary decision maker on the level of technical inefficiency. Age of primary decision maker also represents the experience of a farmer and it serves as a proxy of farming experience. Nevertheless, it is anticipated that age may have positive effect on technical inefficiency as it is observed that older farmers are more reluctant towards adopting new farming technology and practices (Novisma & Iskandar, 2023; Tolinggi et al., 2023). A variable year of education is used as a proxy variable for managerial inputs. Higher level of education with increased farming experience could results in better farming management practices. Thus, this variable is expected to negatively effects technical inefficiency of vegetable grower.

Table 1: Expected Signs of Variables Influencing Technical Inefficiency

Variables	Parameters	Expected Signs
Farm Area	δ_1	+/-
Age	δ_2	+/-
Years of Schooling	δ_3	-
Family Size	δ_4	+/-
Number of Irrigation	δ_5	+
Number of Fertilizer Bags	δ_6	+
Quantity of Manure	δ_7	-
Number of Spray	δ_8	+
Labour Hours	δ_9	+

The technical inefficiency in vegetable production is assessed through several variables, including family size, number of irrigations, quantity of fertilizer bags used, manure application, number of sprays, and labour hours. Family size's impact on inefficiency remains uncertain, with potential advantages in labour utilization countered by increased financial strain on health and education. Increased irrigation may raise costs, potentially affecting inefficiency positively. Similarly, higher usage of fertilizer bags, while boosting output, may also escalate costs, thus potentially increasing inefficiency. Conversely, the use of manure, being a cost-effective organic fertilizer, may reduce inefficiency. More frequent pesticide sprays, though beneficial for output, could escalate production costs and thus raise inefficiency. Labour hours, reflecting unskilled labour and prolonged cultivation, are expected to exacerbate inefficiency due to increased labour costs and time demands. These factors highlight the complex interplay between agricultural inputs, costs, and productivity in vegetable farming.

3.7. Allocative Inefficiency Effects Model

$$\mu_{ij} = \delta_o + \delta_1 Z_{1ij} + \delta_2 Z_{2ij} + \delta_3 Z_{3IJ} + \delta_4 Z_{4ij} + \delta_5 Z_{5ij} + \delta_6 Z_{6ij} + \delta_7 Z_{7ij} + \delta_8 Z_{8ij} + \delta_9 Z_{9ij} + \delta_{10} Z_{10ij} + \omega_{ij} (2)$$

Where,
Z_{1ij} represents Farm Area in Acre.
Z_{2ij} represents Age of farmer in years.
Z_{3ij} represents Education of farmer in number of years of education.
Z_{4ij} represents number of Family Members.
Z_{5ij} represents price of seeds.
Z_{6ij} represents cost of single Irrigation per acre.

Z_{7ij} represents price of Fertilizer Bags per acre.
Z_{8ij} represents price of Manure per acre.
Z_{9ij} represents cost of single per acre.
Z_{10ij} represents Labour wage per acre.
δ_s are unknown parameters to be estimated.

As mentioned earlier firm or farmer is allocative efficient when it combines inputs and output in optimal combination in the light of established prices (Lovell, 1993). Above mentioned variables in the allocative efficiency model are discussed below with their likely effects on technical efficiency. The analysis incorporates several variables to assess their impact on vegetable farming efficiency. Farm area is included to evaluate its relationship with efficiency, with conflicting findings from previous studies leaving expectations uncertain. The age of the primary decision-maker serves as a proxy for experience, with older farmers potentially exhibiting higher levels of allocative inefficiency due to reluctance towards adopting new technologies. Conversely, higher levels of education, represented by years of education, are expected to enhance managerial skills and thereby decrease allocative inefficiency. Family size's impact on allocative inefficiency remains ambiguous, with potential benefits from labour utilization offset by increased financial strain on health and education expenses. These variables underscore the nuanced interplay between demographic factors, education, and farming practices in determining efficiency in vegetable production.

Table 2: Expected Signs of Variables Influencing Allocative Inefficiency

Variables	Parameters	Expected Signs
Farm Area	δ_1	+/-
Age	δ_2	+
Years of Schooling	δ_3	-
Family Size	δ_4	+/-
Price of Seeds	δ_5	+
Cost of Irrigation	δ_6	+
Cost of Fertilizer	δ_7	+
Price of Manure	δ_8	-
Cost of Spray	δ_9	+
Labour Wage	δ_{10}	+

To analyse the influence of cost of inputs on allocative efficiency researchers like Barokah et al. ; Kale et al. (2024); Mdoda et al. (2022); Munir, Shakeel and Waheed (2023); Singh, Singh and Kumar (2023) used variables like cost of seeds, irrigation, fertilizer, manure, spray and labour wages in their studies. High quality of seeds especially organic seeds which are used in tunnel farming are expensive compares to conventional seeds but they have very significant contribution in high yield of crop. But it is expected that price of seed would positively contribute in the allocative inefficiency as increase in the price of seed increases the cost of production of vegetables significantly.

As discussed in literature mostly drip irrigation is used in the tunnel farming. Cost of irrigation from drip irrigation is much less compare to conventional furrow system hence it is expected that cost of irrigation would positively affect the allocative inefficiency. Good quality fertilizers are used in tunnel farming results in better output of vegetables and increased plant protection but these fertilizers are expensive so impact of cost of fertilizer is may be positive or negative effect on allocative inefficiency. Manure used as organic fertilizer is a very useful natural source of nitrogen, potassium and other organic resources for vegetables. Manure is cheaper than the chemical fertilizers thus it may have negative impact on allocative inefficiency of farmer. Increase in cost of spray rises the cost of production thus it is anticipated that variable cost of spray would have a positive impact on allocative inefficiency of farmer. Increase in labour wage per hours results the increase in the cost of labour and it is a major factor in increasing the cost of production. So, it is expected that labour hours would positively affects the allocative inefficiency of farmer. The above-mentioned stochastic frontier production function and inefficiency effects model is estimated with the help of software called, FRONTIER 4.1, developed by Coelli (1998). The parameters of the frontier model are estimated, such that the variance parameters are defined as:

$$\sigma_s^2 = \sigma_v^2 + \sigma^2 \; and \; \gamma = \sigma^2/\sigma_s^2$$

Where γ has a value between 0 and 1

3.8. Log Likelihood Estimation

Log likelihood estimation test is used for hypothesis testing. The test employs the following calculation.

$$LR\ (\lambda) = \ -2\{ln[\frac{L(H_0)}{L(H_1)}\}$$
$$= -2\{ln[L(H_0)] - \ln[L(H_1)]\}$$

Where L (H_o) and L (H_1) is the value of log likelihood estimate under the null and alternate hypothesis i.e., H_o and H_1 respectively. In most cases this statistic has asymptotic chi square distribution.

3.9. Hypothesis testing for Technical Inefficiency Effects

In first null hypotheses we have tested that whether technical effects are present in the technical efficiency model or not. Hypotheses state that technical effects are absent.

$$H_o: \gamma = \ \delta_o = \ \delta_1 = \ \delta_2 = \ \delta_3 = \cdots = \ \delta_9 = 0$$

By imposition of the above restriction on the technical in efficiency effects model i.e., equation 1. The value of log-likelihood function estimation is 43.6 for tunnel farmers and -26.09 for conventional farmers. These estimated values of log-likelihood are less than the values of the original model. On the basis of generalized log-likelihood ratio test we find test statistics for the tunnel and conventional farmers as 55.12 and 52.81 respectively, which are significantly higher than the critical value of 5.14-19.04 which suggests that we can reject null hypothesis which means technical effects are present in the data.

Table 3: Hypothesis Testing in Technical Inefficiency Effects Model for Tunnel and Conventional Farming

Null Hypothesis	Log Likelihood Statistic	Test Statistic	Critical Value	Decision
$\boldsymbol{H_o: \gamma = \ \delta_o = \ \delta_1 = \ \delta_2 = \ \delta_3 = \cdots = \ \delta_9 = 0}$				
Tunnel Farmers	43.6	55.12	5.14-19.04	Reject H_0
Conventional Farmers	-26.09	52.81	5.14-19.04	Reject H_0
$H_o: \delta_o = \ \delta_1 = \ \delta_2 = \ \delta_3 = \cdots = \ \delta_9 = 0$				
Tunnel Farmers	43.51	55.14	18.31	Reject H_0
Conventional Farmers	-14.18	20.72	18.31	Reject H_0

Another very important null hypothesis is concerned with farmer and farm specific influence on technical inefficiency. Null hypothesis is following.

$$H_o: \delta_o = \ \delta_1 = \ \delta_2 = \ \delta_3 = \cdots = \ \delta_9 = 0$$

Null hypothesis states that farmer and farm specific variables do not influence technical inefficiency. By imposition of the above restriction on the technical in efficiency effects model i.e., equation 1. Log-likelihood for the tunnel and conventional farmers are 43.51 and -14.18 respectively. The generalized likelihood ratio statistic for concerned farmers of tunnel and conventional is 55.14 and 20.72 respectively. As these test statistics are statistically higher than the critical value of 18.31 hence, we can reject the null hypothesis i.e., farm and farmer and farm specific variables do not affect technical inefficiency. It must be noted that it may be possible that the individual effects of some variables may not significantly different from zero.

3.9.1. Hypothesis testing for Allocative Inefficiency Effects

The hypothesis state that:

$$H_o: \gamma = \ \delta_o = \ \delta_1 = \ \delta_2 = \ \delta_3 = \cdots = \ \delta_{10} = 0$$

By imposition of the above restriction on the technical in efficiency effects model i.e., equation 2 the value of log-likelihood function estimation is 7.90 for tunnel farmers and -2.80 for conventional farmers. These estimated values of log-likelihood are less than the values of the original model. On the basis of generalized log-likelihood ratio test we find test statistics for the tunnel and conventional farmers as 107.60 and 47.61 respectively, which are significantly higher than the critical value of 5.14-19.04 which suggests that we can reject null hypothesis which means technical effects are present in the data.

Table 4: Hypothesis Testing in Allocative Inefficiency Effects Model for Tunnel & Conventional Farming

Null Hypothesis	Log Likelihood Statistic	Test Statistic	Critical Value	Decision
$H_o: \gamma = \delta_o = \delta_1 = \delta_2 = \delta_3 = \cdots = \delta_{10} = 0$				
Tunnel Farmers	7.9	107.6	18.31	Reject H_0
Conventional Farmers	-2.8	47.61	18.31	Reject H_0
$H_o: \delta_o = \delta_1 = \delta_2 = \delta_3 = \cdots = \delta_{10} = 0$				
Tunnel Farmers	9.16	105.24	18.31	Reject H_0
Conventional Farmers	-13.31	70.12	18.31	Reject H_0

Now in second null hypothesis is concerned with farmer and farm specific influence on allocative inefficiency. Null hypothesis is following.

$$H_o: \delta_o = \delta_1 = \delta_2 = \delta_3 = \cdots = \delta_{10} = 0$$

Null hypothesis states that farmer and farm specific variables do not influence Allocative inefficiency. By imposition of the above restriction on the technical in efficiency effects model i.e., equation 2. Log-likelihood for the tunnel and conventional farmers are 9.16 and -13.31 respectively. The generalized likelihood ratio statistic for concerned farmers of tunnel and conventional is 105.24 and 70.12 respectively. As these test statistics are statistically higher than the critical value of 18.31 hence, we can reject the null hypothesis i.e., farm and farmer and farm specific variables do not affect technical inefficiency.

4. Results and Discussion

4.1. Descriptive Analysis

Primary data were collected from five districts of Punjab (i.e., Toba Tek Singh, Sheikhupura, Pakpattan, Rawalpindi and Sahiwal). This study was conducted by gathering primary data through interviews from 353 farmers across five districts of Punjab, Pakistan. A well-structured questionnaire was used for data collection. Purposive sampling is used to select targeted farmers for the purpose of data collection.

Table 5: Frequency Distribution of Farmers Interviewed in Each District

Districts	Number of Farmers	Tunnel Farmers	Conventional Farmers
Toba Tek Singh	85	58	27
Sheikhupura	73	53	20
Pakpattan	76	60	16
Rawalpindi	66	26	40
Sahiwal	53	29	24
Total	353	226	127

Demographic variables such as age, education and family size are very important as ultimately, they influence the farmer’s efficiency. In table 6 descriptive analysis of demographic variables for tunnel and conventional farmers are done.

Table 6: Descriptive Analysis of Demographic Variables

Variables	Unit	Conventional Farmers			Tunnel Farmers		
		Mean	Min	Max	Mean	Min	Max
Age of household Head	Years	36.0	27.0	45.0	38.1	24.0	53.0
Education of Household Head	Years	9.2	0.0	14.0	10.0	5.0	16.0
No. of Family Members	No.	5.5	5.0	6.0	8.0	3.0	14.0
Farm Area (Acre)	Acre	8.5	5.0	12.0	28.8	2.0	150.0
Land Owned (Acre)	Acre	8.5	5.0	12.0	21.0	0.0	150.0

The above table shows the descriptive statistics of the entire variable with respect to the farmer use Tunnel farming method and non-Tunnel farming method. The table shows that the average age of the household head was 36 who are using conventional farming and it was less than the average ages that using tunnel farming that was 38. It means, farmers who are using tunnel farming were more senior in terms of age than the farmers who were using conventional farming and possesses more farming experience. The minimum age of conventional farmers was 27 and maximum as 45, while the tunnel farmers have 24, and 53 respectively. Tunnel farmers tend to be more educated (mean of 10 years) than the conventional ones (mean of 9.2 years). This may be because the technical know-how and skills involved in tunnel farming are greater. The system is based on sophisticated practices like controlled environment agriculture, irrigation technologies, and input management, which usually require a better understanding. Educated farmers are more likely to adopt innovative techniques, understand the benefits of tunnel farming, and handle problems such as high initial investment costs and operational complexities. On the other hand, conventional farming relies on traditional methods that may not demand the same level of technical expertise, making it more accessible to individuals with lower educational backgrounds.

The average family size of the tunnel farmers is much larger than that of regular farmers, with a mean size of 8 members in contrast to the latter's 5.5 members. Larger households may have an influence on adoption because they have more dependents to be supported, thus requiring greater financial input. Tunnel farming, on the other hand, may provide a possible means for them to raise money to satisfy the household's financial needs. In addition, larger household sizes of conventional farmers often provide labour to farm activities, which helps offset some of the high labour costs often associated with tunnel farming. Small family sizes among conventional farmers may thus reflect limited resources or a tendency toward subsistence-level farming that does not require much labour input. Tunnel farmers cultivated more area than conventional farmers. The average cultivated area was 28.8 acres for tunnel farmers compare to an average of 8.5 acre for conventional farmers. The minimum cultivated area was 5 acres for conventional farmers and maximum was 12 acres while the tunnel farmers have 2 and 150 respectively. In the table 7 district wise descriptive analyses of farmer’s demographic variables are done and we can see that trend in of age, education, family members, farm area and land owned are almost same in each district.

Table 7: Descriptive Analysis of Demographic Variable District wise

Variables	Unit	TT Singh	Sheikhupura	Pakpattan	Rawalpindi	Sahiwal
Age of Household Head	Years	40.2	40.3	40.7	40.4	40.3
Education of Household Head	Years	9.1	9.1	9	9.1	9.1
No. of family members	No.	8.1	8.2	8.1	8.2	8.15
Farm Area	Acre	21	20.8	20.7	20.8	20.8
Land Owned	Acre	12.7	12.5	12.05	12.6	12.5

In table 8 per acre cost analysis of inputs for tunnel and conventional farmers are done. Average input cost, output and revenue per acre for tunnel and conventional farmers are shown.

Table 8: Descriptive Analysis of Input Output Variables

Variables	Unit	Conventional Farmers			Tunnel Farmers		
		Mean	Min	Max	Mean	Min	Max
Cost of seeds	PKR	5500	4000	7000	17103	2000	55000
Cost of Irrigation	PKR	4067	4050	4085	18203	2200	74000
Cost of Fertilizer	PKR	18500	16400	20600	26705	15466	70480
Cost of sprays	PKR	4500	1000	8000	21793	4666	75000
Cost of labour	PKR	38275	35875	40675	62043	17938	185410
Total input cost	PKR	93183			168139		
Output	Munds	187			572		
Revenue	PKR	86137			372095		

The above table described the per acre average input cots in the production of vegetables. Tunnel farmers spend more money on seeds (PKR. 17100), irrigation (PKR. 15020), fertilizer (PKR. 26706), spray (PKR. 21793) and labour (PKR. 62043). Total input cost spends by tunnel farmers was (PKR. 168139) per acre as an average. The conventional farmers spend more financial resources on seeds (PKR. 500), irrigation (PKR. 4067), fertilizer (PKR. 18500), spray (PKR. 4500) and labour (PKR. 38275). Total input cost spends by conventional farmers was (PKR. 93183) per acre. Ali, Baker and Al-Douri (2022) also reported similar type of results, but there are some different results as well, because their work has been just on the tomato production while our work is on different vegetables. There is a huge difference in the output of both farming systems. The tunnel farmers obtained more production per acre vegetable cultivation. Per acre vegetable production was 572 mounds and 187.5 mounds for tunnel and conventional farmers respectively. Total revenue was PKR 372095for tunnel farmers and PKR 86137 for conventional farmers.

4.2. Efficiency Analysis in Tunnel and Conventional Farming

Table 9 shows the frequency distribution of technical, allocative and economic efficiencies of farmers using tunnel technology.

Table 9: Tunnel Farming Efficiency Analysis

Efficiency Levels	Technical	Allocative	Economic
<10	0	0	0
10 to 19	0	0	1
20 to 29	0	0	8
30 to 39	0	10	18
40 to 49	0	12	41
50 to 59	4	31	73
60 to 69	4	69	71
70 to 79	62	76	13
80 to 89	154	26	1
>= 90	2	2	0
Mean	0.81	0.66	0.53
Minimum	0.51	0.31	0.15
Maximum	0.90	0.94	0.80

The estimated technical efficiency result for tunnel farmers lies between 0.51 to 0.90 with the mean 0.81. It shows that there is a possibility of 19% reduction in inputs for working at technical efficient level while output and technology remains unchanged. Out of 226 farmers using tunnel technology 70 farmers are operating below 80 percent of technical efficiency level and remaining 156 farmers possesses 80 or more than 80 percent of technical efficiency. If we talk about allocative efficiency its value varies from 0.31 to 0.94 for tunnel farmers with mean of 0.66. It represents the possibility of 44 % reduction in total cost for an allocatively efficient farmer keeping the level of output and technology constant. Out of 226 farmers 198 farmers holds allocative efficiency less than 80 percent and remaining 28 farmers have allocative efficiency of 80 or more than 80 percent. Value of economic efficiency for tunnel farmers lie within 0.15 to 0.80 with the mean of 0.53. 225 farmers out of 226 have economic efficiency less than 80 percent and only 1 farmer holds more than 80 percent of economic efficiency. Following table shows the frequency distribution of technical, allocative and economic efficiencies of farmers using conventional technology.

Table 10: Conventional Farmers Efficiency Analysis

Efficiency Levels	Technical	Allocative	Economic
<10	0	0	1
10 to 19	1	2	7
20 to 29	0	3	15
30 to 39	1	10	30
40 to 49	4	18	48
50 to 59	10	38	19
60 to 69	26	39	6
70 to 79	68	14	1
80 to 89	17	3	0
>= 90	0	0	0
Mean	0.70	0.56	0.40
Minimum	0.16	0.15	0.03
Maximum	0.87	0.86	0.73

The estimated technical efficiency result for conventional farmers lies within the range of 0.16 to 0.87 with the mean 0.70. It shows the possibility of 30% reduction in inputs for working at technical efficient level while output and technology remains unchanged. Out of 127 farmers using conventional methods of farming 110 farmers are operating below 80 percent of technical efficiency level and remaining 17 farmers possesses 80 or more than 80 percent of technical efficiency. If we talk about allocative efficiency its value varies from 0.15 to 0.86 for conventional farmers with mean of 0.56. It illustrates that there is a possibility of 44% reduction in total cost for an allocatively efficient farmer keeping the level of output and technology constant. Out of 127 farmers 124 farmers holds allocative efficiency less than 80 percent and just 3 farmers have allocative efficiency of 80 or more than 80 percent. Value of economic efficiency for conventional farmers is between 0.03 to 0.73 with the mean of 0.40. All the farmers have economic efficiency less than 80 percent. The results discussed above reveal that farmers were not successful in applying best-practice production methods and achieving the maximum possible output from new and existing technologies. Mean technical efficiency of conventional farmers to be just 70 percent indicates the possibility of 30% reduction in inputs for working at technical efficient level while output and technology remains unchanged. farmers can increase their yield upto30 percent with the current technology. Mean allocative efficiency of conventional farmers is 56 percent illustrates that there is a possibility of 44% reduction in total cost for an allocatively efficient farmer keeping the level of output and technology constant. Mean economic efficiency for conventional farmers is 40 percent. As mentioned above economic efficiency is a product of technical and allocative efficiency.

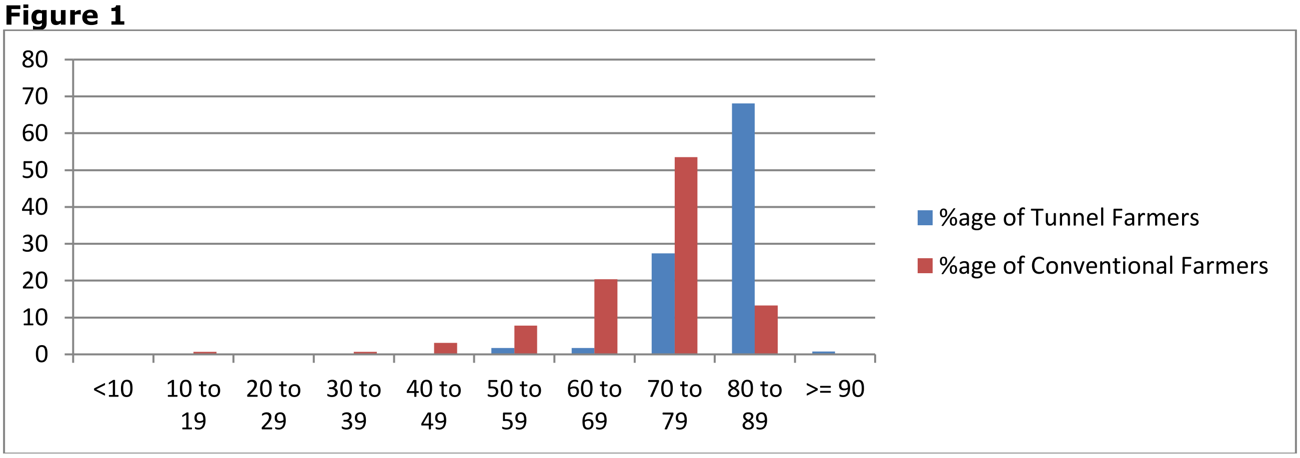
4.3. Comparative Analysis of Efficiencies in Tunnel and Conventional Farming

Frequency distribution of technical efficiency for famers who are using tunnel technology and conventional methods of farming are compared in the following table.

Table 11: Comparative Analysis of Technical Efficiency in Tunnel and Conventional Farming

Efficiency Levels	Technical Efficiency of Tunnel	%	Technical Efficiency of Conventional	%
<10	0	0	0	0
10 to 19	0	0	1	0.7
20 to 29	0	0	0	0
30 to 39	0	0	1	0.7
40 to 49	0	0	4	3.1
50 to 59	4	1.7	10	7.8
60 to 69	4	1.7	26	20.4
70 to 79	62	27.4	68	53.5
80 to 89	154	68.1	17	13.3
>= 90	2	0.8	0	0
Total	226		127	
Mean	0.81		0.70	
Minimum	0.51		0.16	
Maximum	0.90		0.87	

Figure 1



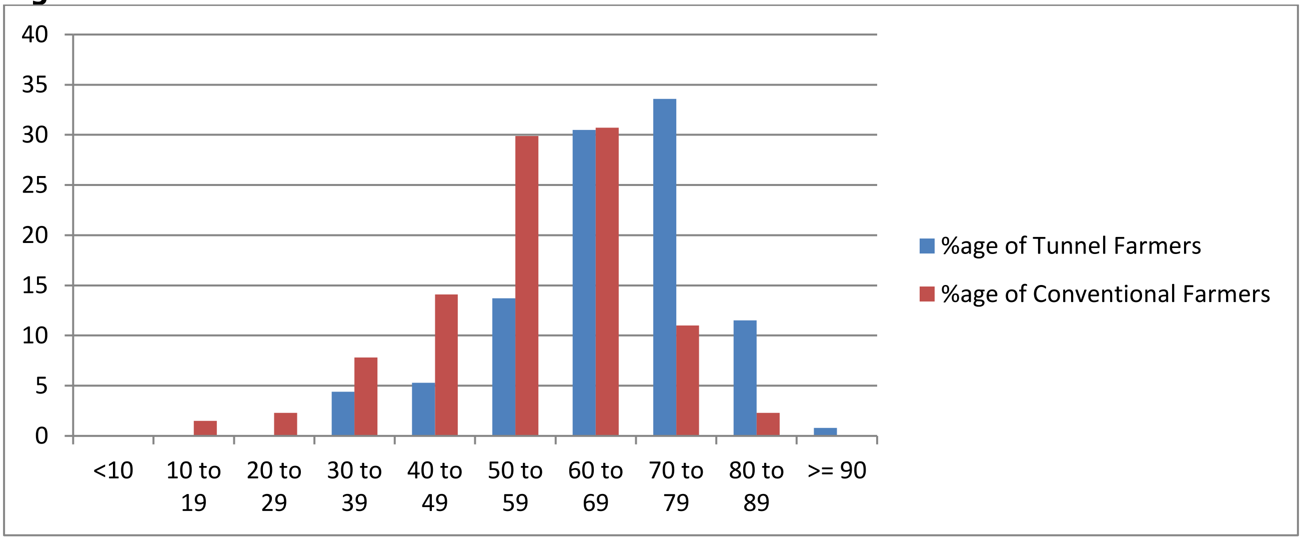
As we can see from the comparison of technical efficiencies of conventional and tunnel farmers that mean of technical efficiency in farmers using tunnel technology is 81 percent while farmers who are using conventional methods for farming have technical efficiency of 70 percent. More importantly almost 70 percent of tunnel farmers have technical efficiency greater than 80 percent and almost 1 % of farmers using tunnel technology have technical efficiency more than 90 while only 13 percent of farmers using conventional farmers have technical efficiency more than 80 percent and none of the conventional farmer possesses technical efficiency more than 90 %. Maximum value of technical efficiency in tunnel farmers is 90 percent while maximum value of technical efficiency in conventional farming is 87 percent while minimum value of technical efficiency in tunnel farming is 51 percent while in conventional farming this value is 16 percent. From above table it is evident that farmers who use tunnel technology in vegetable production produce more with the available level of inputs or we can say they utilize inputs more efficiently compare to farmers who rely on conventional methods of cultivating vegetables. With the adoption of tunnel technology conventional farmers can improve their technical efficiency up to 11 percent.

Table 12: Comparative Analysis of Allocative Efficiency in Tunnel and Conventional Farming

Efficiency Levels	Allocative Efficiency of Tunnel Farmers	%	Allocative Efficiency of Conventional Farmers	%
<10	0	0	0	0
10 to 19	0	0	2	1.5
20 to 29	0	0	3	2.3
30 to 39	10	4.4	10	7.8
40 to 49	12	5.3	18	14.1
50 to 59	31	13.7	38	29.9
60 to 69	69	30.5	39	30.7
70 to 79	76	33.6	14	11
80 to 89	26	11.5	3	2.3
>= 90	2	0.8	0	0
Total	226		127	
Mean	0.66		0.56	
Minimum	0.31		0.15	
Maximum	0.94		0.86	

Frequency distribution of allocative efficiency for famers who are using tunnel technology and conventional methods of farming are compared in the following table.

Figure 2

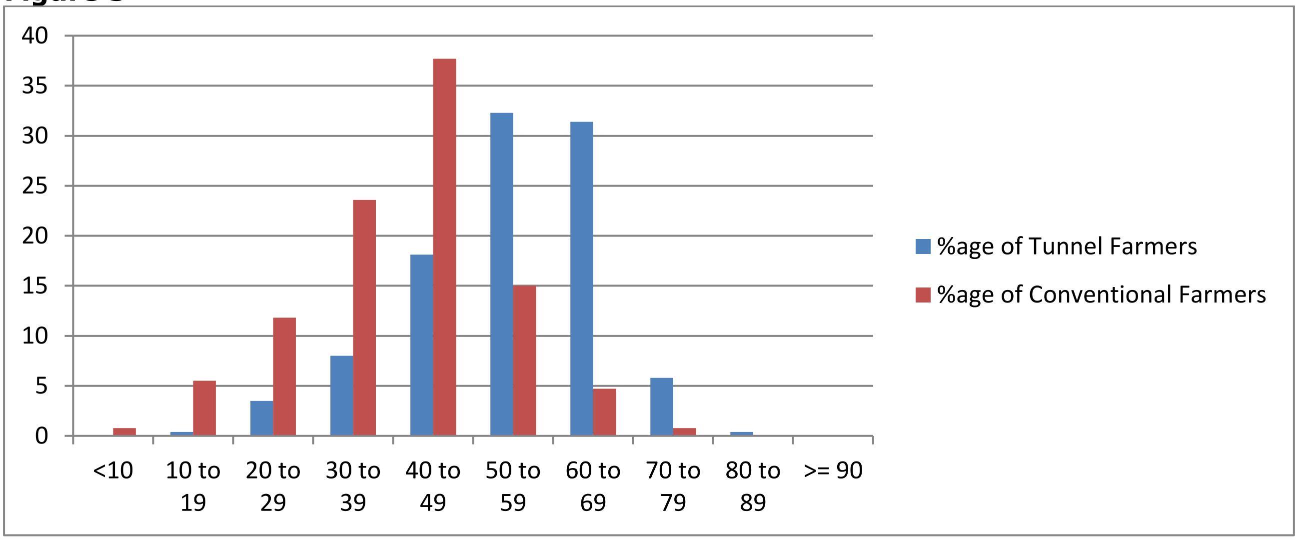


Now if we compare the allocative efficiency of tunnel and conventional farmers, we can see from above table that farmers using tunnel farming technology also have better allocative efficiency compare to their conventional counterparts. Mean allocative efficiency score for tunnel farmers varies from 0.31 to 0.94 with an average score of 0.66. Out of 226 tunnel farmers 122 have allocative efficiency less than 70 percent and 104 have allocative efficiency more than 70 percent. Mean allocative efficiency of conventional farmers lies between 0.15 to maximum 0.86 with an average of 0.56. More importantly 12.3 percent of tunnel farmers have allocative efficiency more than 80 and only 2.3 percent of conventional farmers achieved allocative efficiency more than 80. After the comparison of allocative efficiencies, it is evident that farmers who use tunnel technology in the production of vegetables are more efficient in the allocation of available resources and inputs. With the adoption of tunnel technology conventional farmers can increase allocative efficiency up to 10 percent. Frequency distribution of Economic efficiency for famers who are using tunnel technology and conventional methods of farming are compared in the table 13.

Table 13: Comparative Analysis of Economic Efficiency in Tunnel and Conventional Farming

Efficiency Levels	Economic Efficiency of Tunnel Farmers	%	Economic Efficiency of Conventional Farmers	%
<10	0	0	1	0.78
10 to 19	1	0.4	7	5.5
20 to 29	8	3.5	15	11.8
30 to 39	18	8	30	23.6
40 to 49	41	18.1	48	37.7
50 to 59	73	32.3	19	15
60 to 69	71	31.4	6	4.7
70 to 79	13	5.8	1	0.78
80 to 89	1	0.4	0	0
>= 90	0	0	0	0
Total	226		127	
Mean	0.53		0.40	
Minimum	0.15		0.03	
Maximum	0.8		0.73	

Figure 3



Since tunnel farmers are more technical and allocative efficient, they are also more economically efficient compare to conventional farmers as economic efficiency is a product of technical and economic efficiency. For farmers using tunnel technology score of economic efficiency varies from 0.15 to maximum 0.80 with the mean of 0.53. Farmers using conventional methods of farming minimum value of economic efficiency are 0.03 and maximum 0.73 with the mean of 0.73. As, expected tunnel farmers are more economically efficient with the average economic efficiency of 53 percent while conventional farmers are 40 percent economically efficient. From this comparison it is evident that if farmers who are using conventional methods in the cultivation of vegetables switch to tunnel technology, they can improve economic efficiency 13 percent which will increase their output and profitability. A 13% improvement in economic efficiency as a result of transitioning to tunnel farming provides significant gains for farmers and the larger economy. Increased efficiency enhances farmers' profitability, allowing them to reinvest in high-order inputs and practices that in turn improve productivity and income stability. Tunnel farming increases the availability of vegetables, stabilizes their prices, and enhances food security while reducing reliance on imports. It generates rural employment opportunities and enhances Pakistan's export potential through quality crops for the international market. Moreover, less wastage of resources promotes environmental sustainability. This change will enhance economic growth, improve living standards, and support a sustainable agriculture sector for the benefit of both farmers and consumers throughout the country.

4.4. Maximum Likelihood Estimates

Maximum likelihood estimates for the parameters of the technical and allocative inefficiency effects models are given in the following tables. Ratios of the estimated coefficients to their corresponding standard errors i.e., t-ratios are used to test the statistical significance of the parameters.

Table 14: Maximum Likelihood Estimates of Technical Inefficiency Effects Model for Tunnel & Conventional Farmers

Variables	Tunnel Farmers	Conventional Farmers
Constant	0.51** (0.27)	0.28 (0.43)
Farm Area	- 0.88* (0.10)	0.10 (0.14)
Age	- 0.16** (0.07)	0.80* (0.11)
Education	- 0.80* (0.14)	- 0.28** (0.14)
Family	- 0.49** (0.28)	0.67* (0.10)
No. of Irrigation	0.11** (0.06)	-0.16 (0.12)
No. of Fertilizer Bags	0.10 (0.45)	0.15** (0.21)
Quantity of Manure	- 0.88* (0.11)	-0.84* (0.15)
No. of Sprays	-0.29* (0.1)	0.99** (0.54)
Labour Hours	0.24** (0.14)	0.46* (0.18)
σ^2	0.40 ** (0.25)	0.12** (0.07)
γ	0.91* (0.11)	0.95* (0.23)
Log Likelihood Function	54.27	0.34

Figures in parameters are standard errors. *, ** and *** indicate that coefficients are statistically significant at one, five and 10 percent level of significance respectively. The technical inefficiency models for both tunnel and conventional farming methods incorporate nine variables, with eight in tunnel farming and seven in conventional farming showing statistical significance. Notably, variables such as farm area, age of farmer, years of education, family size, and agricultural practices like irrigation, fertilizer usage, and labour hours significantly influence technical inefficiency in both farming methods. For tunnel farmers, larger land holdings, higher education levels, and efficient resource allocation within the family contribute to reduced inefficiency, while conventional farmers face challenges with excessive fertilizer usage and labour-intensive practices. These findings highlight the importance of adopting modern agricultural practices and efficient resource management techniques to enhance productivity and reduce inefficiencies in vegetable production.

Table 15: Maximum Likelihood Estimates of Allocative Inefficiency Effects Model for Tunnel & Conventional Farmers

Variables	Tunnel Farmers	Conventional Farmers
Constant	0.13 (0.27)	0.92* (0.10)
Farm Area	0.65* (0.30)	0.34* (0.13)
Age of Farmer	0.11 (0.14)	0.16 (0.14)
Years of Education	0.87* (0.11)	-0.19** (0.11)
No. of Family Members	-0.39*	0.52***

	(0.16)	(0.31)
Price of Seeds	0.30*	0.33*
	(0.11)	(0.14)
Cost of Irrigation	0.56**	0.59*
	(0.28)	(0.14)
Price of Fertilizer Bag	0.23**	0.28**
	(0.13)	(0.16)
Price of Manure	0.28**	-0.39*
	(0.16)	(0.11)
Cost of Single Spray	0.16	0.76**
	(0.19)	(0.39)
Per Hour Wage of Labour	0.78*	0.31*
	(0.21)	(0.12)
σ^2	0.49*	0.55*
	(0.13)	(0.18)
γ	0.69**	0.66*
	(0.41)	(0.14)
Log Likelihood Function	0.216	0.54

Figures in parameters are standard errors. *, ** and *** indicate that coefficients are statistically significant at one, five and 10 percent level of significance respectively. Out of 10 variables which includes in the allocative inefficiency effects models of tunnel and conventional farmers 8 variables in tunnel farming and 9 variables in conventional farming are statistically different from zero and indicates the authenticity of our model. Following those variables are discussed which are statistically different from zero in case of tunnel and conventional farmers. Coefficient of farm area is significant at 1 percent level of significance for both tunnel and conventional farmers and it carries a positive sign, which means as farm size is increased thus increased the allocative inefficiency of tunnel farmer by 0.65 percent and 0.35 percent in conventional farmers, one possible reason is that it is difficult for farmers who have large farms to supervise and manage things properly therefore there would be mismanagement of resources causes a decrease in the allocative efficiency of farmer. Years of education have positive sign for tunnel farmers and negative for conventional farmers. In case of conventional farmers, it has expected negative sign as more educated farmers can manage and utilize resources in better way and increase its allocative efficiency compare to less educated farmer. Increase in one year of education will increase allocative inefficiency by 0.87 percent for tunnel farmers and decrease allocative inefficiency in conventional farmers by 0.19 percent.

The coefficient of family size is negative in case of farmers using tunnel technology but positive for conventional farmers and statistically significant at 1 percent and 10 percent in case of tunnel and conventional farmers respectively. In case of farmers using tunnel technology numbers of family members are negatively affecting technical inefficiency by 0.39 percent. Which means farmers with large families are more efficient as his family members can participate in farming and cost of hired labour reduces but in case of conventional farmers positive sign indicates that the larger the family size the greater is the allocative inefficiency. Hassan, Jonathan and Idris (2022); Ogunya and Tijani (2022) in their studies discussed that large family size can positively affects allocative inefficiency as the allocation of financial resources to family members for their education and health increased with the increase in family size and it was also observed that vegetable growers with small piece of land have limited financial resources and if they have children under age 10 who cannot participant in the process of vegetation thus increase their inefficiency. As, discussed earlier according to Lovell (1993) a firm is allocatively efficient when it combines inputs and outputs in optimal combination in the light of established prices. So as expected cost effecting variables like price of seeds, cost of single irrigation, price of fertilizer bag, price of manure, cost of single spray and per hour wage of labour all are statistically different from zero except in case of tunnel farming cost of single spray is not statistically different from zero. And all above mentioned cost related variables are positively affecting allocative inefficiency except price of manure negatively effecting allocative inefficiency in case of conventional farmers. Increase in the prices of inputs ultimately increases the cost of production thus producers will not be able to put inputs in the right combinations necessary to achieve cost minimization.

5. Conclusion and Recommendations

Vegetables are rich in vital nutrients, offer lucrative returns, and generate employment opportunities, yet Pakistani growers predominantly rely on traditional farming methods, hesitant to embrace new technologies due to a lack of evidence on their benefits. Despite advancements like hybrid seeds and drip irrigation, adopting isolated technologies falls short; a comprehensive farming system integrating all innovations is needed. Over the past decade, tunnel farming emerged as an alternative, integrating various technical interventions and enabling off-season vegetable production, providing farmers with greater control over crop conditions and profitability. This study aims to demonstrate that tunnel farming users exhibit higher efficiency compared to conventional farmers. Tunnel farmers achieve 81% technical efficiency, 66% allocative efficiency, and 53% economic efficiency, surpassing conventional farmers in all aspects. Educating farmers on modern farming technologies and plant protection measures, such as tunnel farming, and adjusting resource use in line with input prices can reduce inefficiencies. Shifting to tunnel farming could increase technical, allocative, and economic efficiencies by 11%, 10%, and 13% respectively, attributed to increased output and off-season vegetable production fetching higher prices.

5.1. Recommendations

Most agricultural studies focus on quantitative production analysis, overlooking efficiency, a critical factor influencing production levels. The agriculture sector in Pakistan presents significant opportunities for growth, warranting attention. This study aims to assess technical, allocative, and economic efficiencies of tunnel and conventional farming systems, revealing tunnel farming as notably more efficient. Thus, a shift towards tunnel farming is strongly recommended for vegetable growers. The findings of this research suggest that shifting from conventional to tunnel farming can have an 11% technical efficiency increase, with significant implications for Pakistan's agriculture sector. The improvement reflects higher yields using the same or fewer inputs, thereby increasing agricultural productivity and significantly adding to food security. Increased efficiency will reduce input wastage, thus saving farmers cost and improving their profitability, which in turn will raise rural living standards. In addition, the extra output from tunnel farming can stabilize or even reduce vegetable prices in local markets, making nutritious food more accessible and thus helping to address malnutrition concerns. Some of the suggestions for Punjab farmers to enhance vegetable production include utilizing high-quality hybrid seeds for increased yield per acre. Adopting drip or spray irrigation technology for optimal water supply, which is cost-effective compared to conventional methods. Use of fertilizers and pesticides judiciously to protect crops and improve output, with emphasis on biofertilizers like manure. They should employ trained labour to reduce inefficiencies associated with increased labour hours and wages while expanding farm area to decrease technical inefficiency, particularly through the use of walk-in or high tunnels for those with larger land and resources. At the same time policy recommendations for the government to contribute to initial tunnel building costs to facilitate farmers' adoption of tunnel technology, ensuring access to quality seeds and fertilizers by improving seed production and distribution systems and launching awareness campaigns and providing hands-on training to farmers to promote adoption of new farming technologies. These measures will help to enhance agricultural efficiency and productivity in Pakistan, benefiting both farmers and the broader economy.

5.2. Ethical Considerations

The rights and well-being of the participants were protected at all stages of the research process. The farmers were informed about the purpose of the study, and their consent was taken before participating in the study. Participation was strictly voluntary, and the farmers were guaranteed that their responses would be confidential and used only for academic purposes. Moreover, steps were taken to ensure that no form of harm—be it financial, social, or otherwise—would result from their participation in the study. These steps are in line with the ethical standards of research and protect the dignity and autonomy of all participants.

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