Journal of Agricultural Studies
ISSN 2166-0379
2019, Vol. 7, No. 1

Measuring Technical Efficiency of Wheat Farms in Punjab, Pakistan: A Stochastic Frontier Analysis Approach

Muhammad Aamir Shahzad

Department of Economics, Pakistan Institute of Development Economics (PIDE), Quaid-i-Azam University Campus, Islamabad (44000), Pakistan

Amar Razzaq (Corresponding Author)

College of Economics and Management, Huazhong Agricultural University, No. 1 Shizishan Street, Hongshan District, Wuhan (430070), China.
Email:amar.razzaq@webmail.hzau.edu.cn

Muhammad Aslam, Muhammad Faisal Gulzar

School of Commerce & Accountancy, Minhaj University, Lahore (54000), Pakistan

Muhammad Asad ur Rehman Naseer

Institute of Agricultural and Resource Economics, University of Agriculture, Faisalabad (38000), Pakistan

Nimra Nisar

Department of Education, National University of Modern Languages, H-9 Islamabad (44000), Pakistan

Received: Jan. 20, 2019 Accepted: Feb. 26, 2019 Published: Mar. 10, 2019

doi:10.5296/jas.v7i1.14239 URL: https://doi.org/10.5296/jas.v7i1.14239

Abstract-

The wheat productivity in Punjab is less than the potential maximum due to imbalanced input use and farm management issues. Many studies have attemped to estimate technical efficiency of wheat crops using different techniques. However, most of them used limited datasets that focus on only a few districts. This study study uses a comprehensive dataset which is representive of Punjab province. We used farm-level panel survey data collected from 1581 farms in 17 districts of Punjab from 2005-06 to 2007-08. The technical efficiency of the wheat farms was analyzed using Stochastic Frontier Analysis (SFA) approach. Further, we identified the determinants of (in)efficiency using the same method. The results show that the mean technical efficiency of wheat farmers in Punjab is 84 percent indicating a considerable room for efficiency improvement. Further, the results indicate that technical efficiency could be improved by educating the younger farmers, building road infrastructure, and improving farmers' access to essential inputs. The study supports the argument that wheat farmers are less technically efficient in Punjab, Pakistan.

Keywords: technical efficiency, wheat, stochastic frontier analysis, Punjab Pakistan

1. Introduction

Wheat is the most important crop and essential diet of people in Pakistan. Wheat contributes 10.1% to value added in agriculture and 2.2% to overall GDP. It is an important source of total calorie intake and fulfills 60% of carbohydrates and protein needs for an average person. The government announces support price from time to time for wheat that induces farmers to move from conventional production practices to advanced methods of production. However, Pakistan faced a severe wheat crisis in 2007-08. Currently, there is a shortfall of 2.7 million tons due to less production in Punjab province.

Although the average Pakistani farmer uses more inputs, the productivity of the wheat crop remains lower than that of the developed countries (Ahmad *et al.*, 2002; Byerlee, 1992). Factors such as conventional ways of farming, increases in input prices, bad quality of fundamental inputs and less use of modern technology are responsible for low production of wheat (Sher and Ahmad (2008). The constraint on land and limited water resources also cause wheat production to fall short of maximum potential production (Hassan and Ahmad (2005). Low yield also arises due to technical inefficiency which occurs when timing and application of production inputs are mismanaged (Ahmad *et al.* (2002); Bakhsh (2007); Hassan and Ahmad (2005).

Techincal efficiency can be measured by parametric and non-parametric methods. Non-parametric methods mainly include the Data Envelopment Analysis (DEA) approach which is a deterministic approach. Some studies have used DEA in measuring efficiency in agricultural production in Pakistan (Razzaq *et al.*, 2019; Watto & Mugera, 2015). The other approaches applied to measure efficiency are parametric techniques, which can be classified into two categories: 1) Non-Frontier approach; and 2) Frontier approach. Studies which employed a non-frontier approach to measuring the efficiency are Jamison and Moock (1984), Azhar (1991), Ahmad (2001) and Iqbal *et al.* (2001). The non-frontier approach is an average production function estimation technique in which the non-conventional inputs such as age, education, information, etc. are directly incorporated into the production function. This approach does not differentiate between allocative and economic efficiency and does not account for the aspect of technical efficiency.

To overcome this shortcoming, Battese and Coelli (1988), Battese (1992), Battese and Coelli (1992) and Battese and Tessema (1993) adopted a frontier approach. The frontier approach can further be classified into the deterministic and stochastic analysis. The deterministic approach was developed by Aigner and Chu (1968) that assumes an efficient frontier from a given data set and any deviation from the efficient frontier is due to technical inefficiency, but frontier may vary due to extreme observations while the stochastic frontier approach allows statistical noise (Bravo-Ureta and Pinheiro (1993); Afriat (1972). In stochastic frontier, the technical inefficiency is predicted in the first step and calculated in the second step by regressing socio-economic variables and time in an equation, but it violates the basic assumption of "independently and identically distributed technical inefficiency effects" (Battese and Tessema (1993); Ahmad and Ahmad (1998). The studies such as Battese and Coelli (1995), Battese *et al.* (1996) and Battese and Coelli (1993) estimated technical efficiency and its determining factors in a single step in which technical inefficiency is a function of various observable variables such as age, education, etc. Using the SFA method to identify determinants of inefficiency is advantageous it accommodates both stochastic frontier and technical (in)efficiency effects in a single equation, allowing hypotheses testing. The SFA also incorporates random shocks beyond the farmer's control that can affect output.

Different studies have been conducted for various countries to calculate technical efficiency for the wheat crop, such as Battese and Coelli (1993), Battese and Broca (1997), Ahmad *et al.* (2002), Hassan and Ahmad (2005) and Hussain *et al.* (2012). These studies applied stochastic frontier model using farm level cross-sectional data on farm specific and socioeconomic variables but dropped important physical variables of production such as land preparation cost and transportation cost. Battese and Coelli (1993) and Battese and Broca (1997) estimated technical efficiency of wheat farmers for selected districts of Pakistan. Ahmad *et al.* (2002), Hassan and Ahmad (2005), M Ishaq Javed *et al.* (2009), Mohammad Ishaq Javed *et al.* (2011) and Sohail *et al.* (2012) analyzed technical efficiency for wheat farms, but the scope of these studies was limited since they ignored the aspect of cropping zones, since technical efficiency differs from one cropping zone to another. Hussain *et al.* (2012) is the only research that studied technical efficiency for the wheat crop by cropping zone, but this study is also limited in scope since it relied on cross-sectional data. Within this background, this study has been designed to estimate technical efficiency of wheat farmers in Punjab using a comprehensive dataset which represents the whole Punjab province.

2. Materials and Methods

2.1 Estimating Technical Efficiency Using Stochastic Frontier Analysis

The stochastic frontier model using panel data proposed by Battese and Coelli (1995) can be written as:

$$Y_{it}=\exp(\beta \ln X_{it}+V_{it}-U_{it})$$

$$U_{it}=\delta Z_{it}+w_{it}$$

Where,

Y_{it} is the production of the i-th farm at t-time period;

β are the parameters to be estimated;

X_{it} are the explanatory variables of the i-th farm at t-time;

V_{it} is a random error term independently and identically distributed iid N $(0, \sigma_v^2)$

U_{it} represents the technical (in)efficiency—non-negative random variables truncated at zero of normal distribution at the mean δZ_{it} and variance σ^2 i.e. N (δZ_{it}, σ^2)

Z_{it} are the explanatory variables associated with technical (in) efficiency; δ are parameters to be estimated;

w_{it} is the random error term and is truncation of normal distribution at mean zero and variance σ^2 and the point of truncation is $w_{it} \geq -\delta Z_{it}$

The stochastic frontier and technical (in) efficiency models are estimated by maximum likelihood. The likelihood function is expressed in terms of variance parameters as $\sigma^2=\sigma_v^2+\sigma_u^2$ and $\gamma=\sigma_u^2/\sigma_u^2+\sigma_v^2$

The technical efficiency score of i-th farm at t^{th} time is obtained as follow:

$T.E_{it}= \exp(-U_{it}) = \exp(-\delta Z_{it}-w_{it})$

One step stochastic frontier model is estimated using computer software program FRONTIER 4.1.

2.2 Empirical Specification of the Stochastic Frontier Model

The most popular functional forms used in efficiency analyses are Cobb-Douglas (CD) and Translog. Ahmad and Bravo-Ureta (1996) have shown that the major sources of variation in (in) efficiency levels across models can arise from the assumption made regarding the distribution of the one-sided term in the stochastic frontier. However, the efficiency analyses provide fairly consistent results across alternative model specifications. Following this argument and the conclusions of this study, we preferred to use CD function due to its simplicity and to avoid possible collinearity among the independent variables. The stochastic frontier model with Cobb-Douglas specification is given below:

$lnyield=\alpha+\beta_1 lnfym+\beta_2 Dfym+\beta_3 lncpw+\beta_4 Dcpw+\beta_5 lnirrigation+\beta_6 Dirrigation+\beta_7 lnwheatarea+\beta_8 lnlabor+\beta_9 lnclp+\beta_{10} lnseed+\beta_{11} lnNPK+\beta_{12} Dbarrani/irrigated+\beta_{13} Year_{it}+V_{it}-U_{it}$

Where,

lnyield= Natural log of Wheat yield per acre in Mounds (40kg)

lnfym=Natural log of farmyard manure (FYM) for positive values of FYM-cartloads/acre otherwise zero

Dfym[1]= Dummy variable representing zero for positive values of FYM and value=1 for zero values of fym

lncpw= Natural log of the cost of pesticides and herbicides/acre for positive values and zero otherwise

[1]The dummy variables besides their respective continuous variables are used in the model to accommodate zero observations. There are farmers who do not use manure, do not apply pesticides/herbicides, and do not have access to irrigation water etc [see (Ahmad, 2003) and (Ahmad *et al.*, 2002)].

Dcpw=Dummy variable representing zero for positive values of cpw and value=1 for zero values of cpw

lnirrigation= Natural log of the number of irrigations per acre for positive values and zero otherwise

Dirrigation= Dummy variable representing zero for positive values of irrigation per acre and value=1 for zero values of irrigation.

lnwheatarea=Natural log of the total area under wheat crop in acres

lnlabor=Natural log of labor applied per acre in mandays

lnclp= Natural log of the cost of land preparation per acre (Rs.)

lnseed=Natural log of seed per acre in kgs

lnNPK=Natural log of fertilizer nutrients NPK per acre in kgs.

The following equation gives the technical (in) efficiency model:

$U_{it}=\delta_0+\delta_1 age_{it}+\delta_2 edu_{it}+\delta_3 tc_{it}+\delta_4 farmsize_{it}+ \delta_5 Year_{it}$[2]

Where,

Age=Age of the farmer in years

Edu=Education of the farmer in no. of years of schooling

TC=Total cost of transportation from farm to market (Rs.)

Farmsize=Total area of farm in acres.

Year= year of observation.

2.3 Study Area and Data Sources

The study was conducted in Punjab, Pakistan. Punjab is the largest producer of agricultural commodities in Pakistan. There are about 5.5 million farms in Punjab which cover an area of 28.77 million acres (Naseer *et al.*, 2016). Further, most farmers practice mixed cropping while producing crops and rearing dairy animals to meet their daily needs (Ashfaq *et al.*, 2015a); Ashfaq *et al.* (2015b). Considering the importance of Punjab in Pakistan's agricultural economy, we purposively selected this province for estimating technical efficiency of wheat farmers. The data used in this study was obtained from the Punjab Economic Research Institute (PERI), Lahore. To give appropriate coverage to all types of heterogeneous farms, PERI divided Punjab province into three regions based on the irrigation source: barrani (rainfed); partial barrani; and irrigated zones. In total, 17 districts were selected to give due coverage to all regions. These districts include Attock, Rawalpindi, and Chakwal representing the barrani areas; Bhakar and Khushab representing the partial barrani areas; and Jhang, Faisalabad, Sargodha, Okara, Hafizabad, Sheikhupura, Sialkot, D.G. Khan,

[2]Battese and Coelli (1995)

R.Y. Khan, Vehari, Multan, and Khanewal representing the irrigated areas. Two villages were randomly selected from each district, and thus, 34 villages in 17 districts were selected. The data was collected by the interviewers of Punjab Economic Research Institute (PERI) Lahore.

The variables used to estimate the efficiency are presented in Table 1.

Table 1. Summary statistics of variables used in the analysis

Variables	Units	Mean	Standard Deviation	Min	Max
Wheat yield per acre	Mounds	32.60	8.31	7.5	53
Wheat area sown	Acres	5.63	7.16	1	67
Farmyard manure per acre	No. of cartloads	3.20	8.27	0	60
Seed rate per acre	Kgs	50.00	6.46	30	60
Cost of pesticides and herbicides per acre	Rupees	310.00	219.78	0	960
Number of irrigations per acre	Numbers	4.30	2.01	0	6
Labour applied per acre	Man days	4.50	1.38	2.65	9.50
Cost of land preparation per acre	Rupees	885.00	321.70	500	2250
NPK nutrients per acre	Kgs	333.00	317.68	30	1596
Variables in the inefficiency model					
Transportation cost	Rupees	36.00	260.53	0	3000
Total farm area	Acres	14.10	15.06	1	98
Age of the farmer	No. of years	43.50	13.90	17	74
Education of the farmer	No. of years	6.00	4.62	0	16

3. Results and Discussion

3.1 The Results of Stochastic Frontier Model

The maximum likelihood parameters are obtained by estimating the model using computer program FRONTIER 4.1. The results of the MLE are reported in table 2. The hypothesis of no technical efficiency is rejected because the likelihood ratio value of 389.05 is higher than the critical value of 5.14-19.04 indicating the existence of technical inefficiency on the sampled farms. Hence, the stochastic frontier production approach is preferred over the average function estimated using the OLS technique. Furthermore, the parameters of σ^2 and γ are significant at the 1% critical level implying that average production function is not an adequate representation of the data. The results show that ten parameter estimates out of 12 are statistically significant at least at the 10% level of probability. All coefficients of the included variables carry the expected signs, except that of total labor which is negative and significant—that could be due to measurement error of allocating labor time to a specific crop, i.e. wheat in this case. Battese and Coelli (1993) found a similar result. Both coefficients of farmyard manure, FYM, are positive and statistically significant at the 1% level. Ahmad *et al.* (2002), Ahmad (2003) and Hassan and Ahmad (2005) found the same results. The parameters of the cost of pesticides and herbicides are statistically non-significant. However, the cost of pesticides and herbicides have a positive association with wheat yield. The coefficient of irrigation variables is positive and statically significant at the 5% level showing the importance of irrigation water to increase wheat productivity. This result is consistent with the outcomes of Hassan and Ahmad (2005), Ahmad (2003) and Ahmad *et al.* (2002). Also, (Razzaq *et al.*, 2018) found that wheat farmers in Punjab using high-efficiency irrigation systems obtained higher yields and gross margins. This implies that irrigation is an important factor influencing the productivity of wheat farms in Punjab.

The parameter of dummy variable of irrigation representing production regime of wheat with no irrigation is negative and statistically significant at the 1% level indicating significantly lower wheat productivity on the farm fields where no application of irrigation water was observed. The coefficient of wheat area is negative which implies that wheat farmers face diminishing returns to scale and the result is consistent with the results found by Ahmad *et al.* (2002), Bakhsh (2007) and Kumbhakar *et al.* (1991). The parameters of seed and cost of land preparation both have positive signs and significant at the 1% and 10% level respectively. The variable of year is negative and significant indicating that over time technical inefficiency decreases. The farmers located in irrigated regions are technically more efficient than those of Barrani regions. Finally, the parameter estimate of NPK nutrients used per acre of wheat area carries a negative sign and is insignificant. The results further show that the mean technical efficiency is estimated to be 84%, implying that the wheat production efficiency can be increased by 16% if the farmers use the existing technology more efficiently.

Table 2. The maximum likelihood estimates for Cobb-Douglas production function

Variables	Parameters	Coefficients	Standard-Errors	T-Ratio
Stochastic Frontier Analysis				
Constant	A	2.82***	0.200	14.1
lnFYM	β1	0.0406***	0.0123	3.30
DFYM	β2	0.0958***	0.0322	2.97
lnCPW	β3	0.0144	0.0118	1.22
Ddcpw	β4	0.0743	0.0712	1.04
lnIrrigations	β5	0.04182**	0.0204	2.05
DTI	β6	-0.390***	0.0355	-11.0
lnWheat area	β7	-0.001.73	0.00719	-0.241
lnLabor	β8	-0.0180	0.0206	-0.875
lnCLP	β9	0.0273*	0.0150	1.82
lnSeed	β10	0.130***	0.0395	3.30
lnNPK	β11	-0.00588	0.0740	-0.07.94
Year	β12	-0.01.46*	0.00786	-1.85
Inefficiency model				
Constant	δ0	1.00***	0.102	9.86
Age	δ1	0.000556	0.00143	0.390
Education	δ2	-0.02.35***	0.00642	-3.66
Transportation	δ3	-0.000676***	0.000180	-3.75
Farmsize	δ4	-0.00261*	0.00166	-1.58
Year	δ5	-0.911***	0.176	-5.16
Dbarrani/irrigated	δ6	-1.19***	0.236	-5.03
Variance Parameters				
sigma-squared	σ2	0.4189***	0.0914	4.58
Gamma	Γ	0.977***	0.00516	189.00
log likelihood function = 389.05 LR test of the one-sided error = 340.75				

Note: *, ** and *** represent the significance of variables at 10%, 5% and 1% level respectively.

3.2 SFA Estimates of Technical Efficiency

Technical efficiency measures for wheat farms are estimated using stochastic frontier analysis. The results are given in Table 3 and Table 4.

Table 3. Average Estimates of Technical Efficiency from SFA Model

Efficiency Score	SFA
Mean	84
Minimum	26.44
Maximum	97.90
Standard Deviation	13.00

Table 4. Frequency distribution of technical efficiency estimates from SFA model

Stochastic Frontier Analysis		
Range of TE	Farms under TE classes	
	No. of farms	% of farms
<50	65	4.11
50-60	41	2.59
60-70	103	6.51
70-80	256	16.19
80-90	495	31.30
90-100	621	39.30
Total	1581	100

3.3 Analysis of the Determinants of Farm Level Inefficiency

The SFA measures the technical (in)efficiency estimates and their determinants simultaneously in a single step. The technical (in) efficiency results of the SFA approach are provided in Table 5.

The estimated coefficient of age is positive, though insignificant in the SFA model. This result implies that younger farmers are technically more efficient than the older farmers because older farmers are rigid in the adaption of new technologies and younger have more adaptability to modern production practices.

The impact of education on technical inefficiency is negative. This indicates that educated farmers are more technically efficient than illiterate farmers.

The parameter of farm size is negative and statistically significant at 10% in the SFA model. This implies that large farmers are technically more efficient than small farmers—small farmers are less resourceful and having poor access to advanced technology and quality inputs.

The transportation cost parameter is negative and significant in the SFA model. This indicates that technical efficiency increases when the transportation cost increases. Ahmad *et al.* (2000) argued that the farmers who try to purchase superior quality inputs even from distant markets and rely less on village dealers have to bear the high cost of transportation. The use of better-quality inputs would naturally result in higher productivity than those farmers who relied on village dealers for their inputs. Moreover, even marketing their produce in grain markets rather than selling to the village dealers can fetch them a better price. Therefore, it is more likely that such farmers would be more technically efficient. The inefficiency is decreasing with the passage of time.

The technical efficiency estimates of wheat production in Punjab are very low. Van Tran (2001) argued that the low technical efficiency at the farm level is associated with resource management and cultural factors. These factors are categorized into socio-economic and biological factors. The socio-economic factors include farmer's age, education, farm area, and the transportation cost. However, biological factor includes, the seed rate, area cultivated, irrigation applied, labor used, and pesticides and fertilizers applied. Lastly, the technical efficiency estimates are also affected by the government policy which affect input/output prices, irrigation availability, fertilizer and pesticides resource management and the availability of technical information. These factors are important determinants of wheat productivity.

Table 4. Factors affecting technical (in)efficiency of wheat farms

Variables	Coefficients
Constant	1.00***
Age	0.000556
Education	-0.02.35***
Transportation	-0.000676***
Farm size	-0.00261*
Year	-0.911***
Dbarrani/irrigated	-1.19***
Log-likelihood	380.4134

Note: *, ** and *** represent the significance of variables at 10%, 5% and 1% level respectively.

4. Conclusions and Policy Recommendations

The major objective of the study was to estimate the technical efficiency of wheat farms using SFA analysis techniques. The data was obtained from Punjab Economic Research Institute (PERI), Lahore. The data consists of 1581 wheat farms during the period 2006-2008, and it contains information regarding input use and production costs for the wheat crop. The average technical efficiency estimated through SFA was 84 percent. The analysis implies that technical efficiency can be increased by 16 percent while using the same level on inputs. The results of SFA show that the education, transportation cost, farm size, year and regional factors have a positive impact on technical efficiency. The study supports the argument that the wheat farmers are in Punjab are not fully technically efficient, and wheat production can be increased by increasing efficiency.

Based on the results of this study, we recommend the following policy options to improve the productivity and efficiency of wheat farmers in Punjab. First, the parameters of SFA model show that the productivity is influenced by the inputs like farmyard manure, labor, and the seed. Therefore, the policymakers should pay attention to educate the farmers on the balanced use of these inputs. Second, irrigation water availability increases the crop productivity so canal water should be available during the required time. Water deficiency can be fulfilled by making the arrangements of popularizing the rain harvesting technology and by reducing the canal water loses either via canal lining or water-course lining. Third, the agricultural extension service plan should be designed to be held at the beginning of the season. Agricultural extension agents should arrange training programs to inform farmers about crop production techniques. Further, the wheat extension programs should be developed to equip the farmers with modern technology and knowledge of methods of production.

References

Afriat, S. N. (1972). Efficiency estimation of production functions. *International Economic Review,* 568-598.

Ahmad, M. (2001). Agricultural productivity growth differential in Punjab, Pakistan: a district-level analysis. *The Pakistan Development Review*, 1-25.

Ahmad, M. (2003). Agricultural productivity, efficiency, and rural poverty in irrigated Pakistan: A stochastic production frontier analysis. *The Pakistan Development Review,* 219-248.

Ahmad, M., & Ahmad, A. (1998). An Analysis of the Sources of Wheat Output Growth in the" Barani" Area of the Punjab. *The Pakistan Development Review,* 231-249.

Ahmad, M., & Bravo-Ureta, B. E. (1996). Technical efficiency measures for dairy farms using panel data: a comparison of alternative model specifications. *Journal of Productivity Analysis, 7*(4), 399-415.

Ahmad, M., Chaudhry, G. M., Iqbal, M., & Khan, D. A. (2002). Wheat Productivity, Efficiency, and Sustainability: A Stochastic Production Frontier Analysis [with Comments]. *The Pakistan Development Review,* 643-663.

Ahmad, M., Chaudhry, M. G., & Chaudhry, G. M. (2000). Some non-price explanatory variables in fertiliser demand: the case of irrigated Pakistan. *The Pakistan Development Review*, 477-486.

Aigner, D. J., & Chu, S. F. (1968). On estimating the industry production function. *The American economic review, 58*(4), 826-839.

Ashfaq, M., Razzaq, A., Haq, S. U., & Muhammad, G. (2015a). Economic analysis of dairy animal diseases in Punjab: a case study of Faisalabad district. *Journal of Animal and Plant Sciences, 25*(5), 1482-1495.

Ashfaq, M., Razzaq, A., Hassan, S., & Haq, S. U. (2015b). Factors affecting the economic losses due to livestock diseases: a case study of district Faisalabad. *Pakistan Journal of Agricultural Sciences, 52*(2), 515-520.

Azhar, R. A. (1991). Education and technical efficiency during the green revolution in Pakistan. *Economic Development and Cultural Change, 39*(3), 651-665.

Bakhsh, K. (2007). An analysis of technical efficiency and profitability of growing potato, carrot, radish and bitter gourd: a case study of Pakistani Punjab. University of Agriculture Faisalabad,

Battese, G. E. (1992). Frontier production functions and technical efficiency: a survey of empirical applications in agricultural economics. *Agricultural Economics, 7*(3), 185-208.

Battese, G. E., & Broca, S. S. (1997). Functional forms of stochastic frontier production functions and models for technical inefficiency effects: a comparative study for wheat farmers in Pakistan. *Journal of Productivity Analysis, 8*(4), 395-414.

Battese, G. E., & Coelli, T. J. (1988). Prediction of firm-level technical efficiencies with a generalized frontier production function and panel data. *Journal of Econometrics, 38*(3), 387-399.

Battese, G. E., & Coelli, T. J. (1992). Frontier production functions, technical efficiency and panel data: with application to paddy farmers in India. In International Applications of Productivity and Efficiency Analysis (pp. 149-165): Springer.

Battese, G. E., & Coelli, T. J. (1993). A stochastic frontier production function incorporating a model for technical inefficiency effects (Vol. 69): Department of Econometrics, University of New England Armidale.

Battese, G. E., & Coelli, T. J. (1995). A model for technical inefficiency effects in a stochastic frontier production function for panel data. *Empirical Economics, 20*(2), 325-332.

Battese, G. E., Malik, S. J., & Gill, M. A. (1996). An investigation of technical inefficiencies of production of wheat farmers in four districts of Pakistan. *Journal of Agricultural Economics, 47*(1-4), 37-49.

Battese, G. E., & Tessema, G. A. (1993). Estimation of stochastic frontier production functions with time-varying parameters and technical efficiencies using panel data from Indian villages. *Agricultural Economics, 9*(4), 313-333.

Bravo-Ureta, B. E., & Pinheiro, A. E. (1993). Efficiency analysis of developing country agriculture: a review of the frontier function literature. *Agricultural and Resource Economics Review, 22*(1), 88-101.

Byerlee, D. (1992). Technical change, productivity, and sustainability in irrigated cropping systems of South Asia: Emerging issues in the post‐green revolution Era. *Journal of International Development, 4*(5), 477-496.

Hassan, S., & Ahmad, B. (2005). Technical efficiency of wheat farmers in mixed farming system of the Punjab, Pakistan. *International Journal of Agriculture and Biology, 3*, 431-435.

Hussain, A., Saboor, A., Khan, M. A., Mohsin, A. Q., Hassan, F., & Anwar, M. Z. (2012). Technical efficiency of wheat production in Punjab (Pakistan): A cropping zone wise analysis. *Pakistan Journal of Life and Social Sciences, 10*(2), 130-138.

Iqbal, M., Khan, M. A., Ahmad, M., & Ahmad, B. (2001). Determinants of Higher Wheat Productivity in Irrigated Pakistan [with Comments]. *The Pakistan Development Review,* 753-766.

Jamison, D. T., & Moock, P. R. (1984). Farmer education and farm efficiency in Nepal: The role of schooling, extension services, and cognitive skills. *World Development, 12*(1), 67-86.

Javed, M. I., Adil, S. A., Hassan, S., & Al, A. (2009). An efficiency analysis of Punjab's cotton-wheat system.

Javed, M. I., Khurshid, W., Adil, S. A., Hassan, I., Nadeem, N., Ali, A., & Raza, M. A. (2011). Analysis of technical and scale efficiency of smallholder farms of rice-wheat system in Punjab, *Pakistan. J. Agric. Res*, *49*(1), 125-137.

Kumbhakar, S. C., Ghosh, S., & McGuckin, J. T. (1991). A generalized production frontier approach for estimating determinants of inefficiency in US dairy farms. *Journal of Business & Economic Statistics*, *9*(3), 279-286.

Naseer, M. A. U. R., Ashfaq, M., Abid, M., Razzaq, A., & Hassan, S. (2016). Current Status and Key Trends in Agricultural Land Holding and Distribution in Punjab, Pakistan: Implications for Food Security. *Journal of Agricultural Studies*, *4*(4), 14. doi:10.5296/jas.v4i4.9670

Razzaq, A., Qing, P., Naseer, M. A. u. R., Abid, M., Anwar, M., & Javed, I. (2019). Can the informal groundwater markets improve water use efficiency and equity? Evidence from a semi-arid region of Pakistan. *Science of the Total Environment*, *666*, 849-857. doi:doi.org/10.1016/j.scitotenv.2019.02.266

Razzaq, A., Rehman, A., Qureshi, A. H., Javed, I., Saqib, R., & Iqbal, M. N. (2018). An Economic Analysis of High Efficiency Irrigation Systems in Punjab, *Pakistan. Sarhad Journal of Agriculture*, *34*(4), 818-826.

Sher, F., & Ahmad, E. (2008). Forecasting wheat production in Pakistan.

Sohail, N., Latif, K., Abbas, N., & Shahid, M. (2012). Estimation of technical efficiency and investigation of efficiency variables in wheat production: A case of district Sargodha (Pakistan). *Growth*, *3*(10).

Van Tran, D. (2001). Closing the rice yield gap for food security. The New Development in Rice Agronomy and Its Effects on Yield and Quality in Mediterranean Areas, 2-12.

Watto, M. A., & Mugera, A. W. (2015). Efficiency of irrigation water application in sugarcane cultivation in Pakistan. *Journal of the Science of Food and Agriculture*, *95*(9), 1860-1867. doi:10.1002/jsfa.6887