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Efficiency of Soybean Production in Bangladesh: Application of Stochastic Frontier Approach

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Abstract

Although soybean is a crop of considerable nutritional and economic value in Bangladesh, most existing research is primarily focused on profitability and cultivation challenges with limited attention to production efficiency. Despite the growing importance of soybean cultivation, empirical studies focusing on the technical, allocative, and economic efficiency of soybean farming remain limited. Moreover, there is a noticeable gap in the literature concerning the identification and analysis of socio-economic and agronomic factors that contribute to inefficiency in soybean production. Addressing this gap, this study aims to estimate the efficiency of soybean production in Bangladesh. Cross-sectional data are collected randomly during the 2023-24 cropping season from 200 soybean farmers from the two southern districts of Bangladesh, namely Bhola and Noakhali. Using the Stochastic Production Frontier (SPF) model, the findings of this study reveal that the mean technical, allocative, and economic efficiency of soybean production in this region are 75%, 88%, and 67%, respectively. Specifically, increasing the use of labor, manure, irrigation, and machinery contributed to enhanced technical efficiency, while reallocating resources toward labor, irrigation, fertilizer, and manure improved allocative efficiency. The results of the regression show that factors such as the delayed seed sowing, the number of tillages, land area, education, and limited access to extension services contribute to inefficiencies in production. The findings suggest that there is significant potential for improving the efficiency of soybean farming in Bangladesh by addressing these inefficiency issues.

Keywords: Soybean production, Economic efficiency, Stochastic Production Frontier, Bangladesh.

1. Introduction

Agriculture is the backbone of the economy in Bangladesh, serving as the primary source of livelihood for the majority of the rural population and contributing significantly to national GDP and food security (Miah et al., 2020). Within this sector, oilseed crops such as soybean, sunflower, mustard, and rapeseed play a significant role in both household consumption and industrial processing. These crops are transformed into edible oils, biofuels, livestock feed, and a variety of industrial products; linking them closely to both food and energy systems (Lu et al., 2011). Among the oilseeds, soybean stands out as the most important and widely cultivated crop in Bangladesh due to its high nutritional and economic value. It is a low-cost, protein-dense crop, comprising approximately 36% protein, 19% oil, 35% carbohydrates, and 17% dietary fiber, along with essential vitamins and amino acids (Liu, 1997). As a plant-based protein source, it provides a viable

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alternative to animal protein, especially for low-income populations, and helps address malnutrition and food insecurity (Betebo et al., 2017; WHO, 1989). Soybeans also contain bioactive compounds with potential health benefits, including reduced risks of cardiovascular diseases and certain cancers. In Bangladesh, a significant portion of locally produced soybeans, accounting for only about 5% of national demand, is used by the feed industry (Bokhtiar et al., 2023). Globally, soybean meal (SBM), a byproduct of oil extraction, is a critical component of livestock and poultry feed. SBM comprises 47–49% crude protein and is rich in digestible amino acids, making it the most efficient and cost-effective plant-based protein feed (Pagano & Miransari, 2016; Kerley & Allee, 2003). It is estimated that SBM constitutes around 30% of poultry feed and about two-thirds of total global protein feed production. In addition to its nutritional and economic contributions, soybean plays a crucial agroecological role. Through biological nitrogen fixation (BNF), soybeans can supply up to 70% of their nitrogen requirement, thereby improving soil fertility and reducing the need for chemical fertilizers (Islam et al., 2022). Crop rotation involving soybeans also enhances soil organic carbon, microbial activity, and nutrient cycling, leading to better yields and reduced greenhouse gas emissions (Poeplau & Don, 2015). Moreover, soybean intercropping and inoculation with beneficial microbes can help restore degraded soils, increase resource-use efficiency, and support sustainable smallholder farming systems (Chianu et al., 2009).

However, domestic soybean production remains insufficient to meet the growing demand. For instance, in 2012, the value of imported edible oils and oilseeds increased dramatically from 2003 levels, reaching Tk 14,200 million and Tk 130,510 million, respectively (Miah et al., 2015). By 2024–2025, the country's edible oil requirement is projected to reach 28 million tons, with an estimated 10 million tons to be met through imports (Mathur et al., 2023). This persistent import dependency underscores the urgent need to boost local soybean production and efficiency. While the efficiency of crops such as maize, litchi, and rice has been studied in Bangladesh (Rahman et al., 2024; Uddin et al., 2020; and Hossain, 2012), research specifically focusing on soybean production efficiency is notably lacking. Given the country's growing population and limited land resources, it is imperative to investigate whether soybeans are being produced efficiently. With evidence from other countries indicating inefficient soybean production practices (Rinaldi et al., 2023; Wake et al., 2019 and Osman et al., 2018), it is vital to assess whether farmers of Bangladesh are utilizing their limited land and resources efficiently in soybean cultivation. Understanding production efficiency in soybean farming can provide critical insights for policymakers. It can guide strategies to increase output on existing farmland, reduce import dependency, enhance self-sufficiency, and improve the balance of payments. Efficient domestic soybean production also holds potential for strengthening food security and supporting sustainable agricultural growth. Therefore, it is essential to conduct in-depth studies on the efficiency of soybean production to guide policy, improve farmer outcomes, and support sustainable agricultural development. To address this gap, the study aims to assess the technical, allocative, and economic efficiency of soybean production and to identify the factors contributing to inefficiency among soybean farmers.

The outline of this study begins by establishing the significance of soybeans within the agricultural sector of Bangladesh, emphasizing its nutritional, economic, and industrial importance. It addresses the increasing domestic demand for soybeans, continued reliance on imports, and the notable absence of empirical research on production efficiency. Following a review of relevant literature and the identification of existing research gaps, the study underscores the necessity of estimating efficiency in soybean cultivation. The methodology section details the selection of study areas, sampling procedures, and the application of stochastic frontier models to estimate technical, allocative, and economic efficiency. The results section presents the efficiency levels of soybean producers and explores the socioeconomic and agronomic determinants of inefficiency, including education, land size, tillage frequency, and access to extension services. The study concludes by summarizing key findings and offering policy recommendations to improve soybean production efficiency and reduce import dependency, thereby promoting agricultural sustainability in Bangladesh.

2. Literature Review

In general, efficiency is the capacity to provide a favorable outcome with the least amount of work. It involves organizing and utilizing both people and material resources to accomplish a better project management objective (Bäckman et al., 2011). Although they are conceptually distinct and related; technical efficiency, allocative efficiency, and economic efficiency can all be quantified in terms of efficiency. Technical efficiency is the efficiency with which a particular set of inputs is used to produce an output for effective manufacturing (Nyagaka, 2010). Allocative efficiency refers to a state where resources are allocated in such a way that they are distributed among different uses to maximize overall social welfare or utilities (Kopp & Diewert, 1982). The ideal distribution of resources to promote social welfare while limiting the usage of existing resources is known as economic efficiency. This efficiency comprises both technical and allocative efficiencies (Kilic et al., 2009). The input-output performance in production that falls below the maximum output with given input is referred to as technical inefficiency (Dlamini et al., 2010). Due to external shocks, inefficiency occurs in the process of production (Coelli & Battese, 2006). In the Mandsaur district of Madhya Pradesh in India, approximately 5.56 million hectares of land are used for soybean cultivation. A study finds that as farm size increases, there is a corresponding rise in net income, family labor income, farm business income, and investment income. Additionally, key inputs such as manure, chemical fertilizers, and machine work are found to have a significant influence on soybean production (Srivastava et al., 2015). Using information from 500 farmers, a research was conducted in the Northern Region of Ghana to examine the economic efficiency of soybean cultivation. The results showed that one characteristic of soybean production in the region has been increasing returns to scale, with 82.7% technical efficiency. However, the study also found that access to extension services, improved seed varieties, and increased schooling can reduce technical and economic inefficiency. The majority of farmers lacked access to financing during the agricultural season, making insufficient capital the most urgent limitation. Policies to improve soybean production efficiency should be pursued (Osman et al., 2018). The technical, allocative, and economic efficiency of soybean production among smallholder farmers in the Benishangul-Gumuz area in Ethiopia is examined in another study. Data for the study were collected from 266 farmers in the districts of Assosa and Bambasi. Technical efficiency was 72.81%, according to the results, while allocative and economic efficiency were 55.13% and 40.08%, respectively. Distance to input centers and cooperatives, farming experience, frequency of extension contacts, and educational attainment all decreased economic inefficiencies (Wake et al., 2019). Researchers conducted a study assessing the technical, allocative, and economic efficiency of soybean production in the Pawe district, Ethiopia. Collected from 203 households, the data was analyzed using descriptive and economic models. The results showed that technical inefficiency accounted for 73.84% of the variation in soybean output. Efficiency was impacted by variables like age, education, credit availability, farming experience, income participation, and training (Argaw et al., 2020). A recent study evaluating soybean production across five districts in Bangladesh highlights significant potential for soybean production due to high profitability, suitable land, mechanized practices, and farmer interest. Although challenges such as insect infestations, climate change, and resistance from industrial stakeholders persist, the study concludes that opportunities outweigh these obstacles, pointing to potential prospects for increased soybean cultivation in the country (Islam & Khatun, 2022). A study examines the technical and economic efficiency of the factors influencing Indonesian soybean production and found that data from farmers in Tabanan Regency revealed that factors like land area, fertilizers, and seeds positively affect production. The study TE value was 0.77 on average (Rinaldi et al., 2023). In Charwapda village, Subornachar Upazila, Noakhali district of Bangladesh, a study assesses the economic feasibility of growing soybeans using a conservation agriculture (CA) seed planter created by BARI. Reduced tillage, cost savings, fuel usage, and carbon emissions were only a few of the machine's noteworthy advantages. The machine was financially feasible for soybean planting in the south coastal region of Bangladesh, with a payback duration of 2.71 years and a break-even use of 9.65 hectares of land annually (Mottalib et al., 2024). One study focused on the socio-economic dimensions of soybean cultivation in Noakhali and Laxmipur districts of Bangladesh, examining costs and returns, competitive and comparative advantages, production challenges, and farmers' attitudes. Soybean yielded the highest return (Tk. 25,599/ha) and benefit-cost ratio (1.43) among competing crops, with a DRC of 0.55 indicating a clear advantage over imports. Functional analysis showed that inputs like TSP, MP, gypsum, and pesticides positively impacted yield. Despite its profitability, expansion is hindered by fertilizer scarcity, high input costs, lack of HYV seeds, limited technical knowledge, and natural calamities (Salam & Kamruzzaman, 2015).

The effect of integrated nutrient management on soybean development and yield was examined in a field experiment carried out in Laxmipur during the 2015–16 Rabi season. Among the six treatment options, applying 50% of the recommended dose of NPK (Nitrogen, Phosphorus, and Potassium) combined with biofertilizer (Bradyrhizobium) resulted in the highest seed yield (2.93 t/ha), improved plant development, and the greatest economic returns. In contrast, the control treatment showed the poorest performance. The findings indicate that using a combination of reduced chemical fertilizers and biofertilizers is a productive and sustainable strategy for enhancing soybean cultivation in the coastal char areas of Bangladesh (Farhad et al., 2017). Another study conducted in Bangladesh found that 47% of soybean farmers were smallholders. Soybean cultivation was financially profitable, with a benefit-cost ratio of 1.43. Key factors influencing the decisions of farmers to grow soybeans included education, farm size, income, extension services, crop diversification, and distance to markets. Major challenges identified were high input costs (especially seeds and fertilizers), low output prices, and poor transportation, with high input costs being the most significant issue (Yousuf et al., 2023). An experiment conducted in the Barind Tract of northwestern Bangladesh evaluated the yield and profitability of maize, soybean, and their intercrop under different row orientations. While sole cropping of maize and soybean produced the highest individual yields, intercropping resulted in greater economic returns. Maize had the highest yield (5.66 t/ha) when grown alone in a north–south orientation, and soybean yielded the most (1.39 t/ha) as a sole crop. However, the maize and soybean intercrop proved to be the most profitable system, suggesting it as the optimal practice for improving agricultural productivity and livelihoods in water-scarce regions like the Barind Tract (Ali et al., 2017).

The majority of research on soybean production in Bangladesh indicates that it is profitable, but it is difficult to find a study that examined the efficiency of soybean farmers in Bangladesh, stating that there is a scope for research on farmer productivity efficiency. Therefore, knowledge about the current state of farmers' soybean production efficiency is urgent. Due to the daily rise in the price of edible oil, this study attempted to investigate the performance of soybean production in Bangladesh based on farmer efficiency findings.

3. Methodology

3.1 Study Area, Sampling Procedure, and Method of Data Collection

This study is conducted in two of the 64 administrative districts of Bangladesh, Bhola from Barisal division and Noakhali from Chattogram division. In this study, two-stage random sampling procedures were followed for the sample farmers. Firstly, two divisions of Bangladesh that grow soybeans (Barisal and Chattogram) were chosen randomly for the study. Using a straightforward random sampling method, Bhola and Noakhali districts were chosen for the second stage from the six districts in the Barisal division and the eleven districts in the Chattogram division. Farmers who grow soybeans were chosen at random and interviewed to gather the field-level data and socioeconomic data required to meet the study objectives. A questionnaire was prepared to collect data from the study region to meet the objectives of the study. In May and June of 2024, the researchers themselves conducted in-person interviews with the respondents to obtain the necessary data. Quantitative data were included in the questionnaire. In this investigation, primary data sources are used. Two hundred farmers were interviewed to gather primary data. Consequently, 200 is the overall sample size in this study. The internet, journals, articles, and BBS are the sources of secondary data.

3.2 Empirical Model of Technical Efficiency, Allocative Efficiency, and Economic Efficiency of Soybean Farm

Because of unpredictable shocks and measurement errors brought on by imprecise farm operating records, agricultural productivity is inherently variable (Beckman et al., 2011). A stochastic production function is employed because of the random shocks (white noise, 0 mean, and constant variance) and errors that cause output fluctuation. There are two components to the disturbance term of the stochastic production function: symmetric and one-sided. Inefficient deviation from the frontier is shown by the one-sided component, whereas random error is represented by the symmetric component.

The stochastic frontier approach, a different estimation technique proposed by Meeusen (1977) and Aigner et al. (1977), went against popular perception to solve the issue of random error in the deterministic approach (Nguyen, 2010). The stochastic error of the model includes two terms: external random factors and farm-specific factors. It was developed by adding the equation's symmetric error term as

$$ln\,(y_i) = F(x_i; \beta) + v - u_i \qquad \dots.(1)$$

$$Where, i = 1,2,3, \dots \dots n$$

It is possible to define the stochastic production frontier model as

$$ln\,y_i = \beta_0 + ln\textstyle\sum\beta_i X_{ij} + ln\sum a_k Z_{ik} + e_i \qquad \dots.(2)$$

Where, ln- represents the natural logarithm, n- Quantity of seeds utilize, m- Number of the model's explanatory variables, Y_i- yield of soybean, X_{ij}- The input variable used for soybean production, Z_{ik}- Inefficiency explanatory factors, β, α- Vector of the parameter that needs to be approximated.

$e_i = v_i - u_i; v_i$ =symmetric error term or disturbance term (both endogenous and exogenous with assumed $N(0, \sigma^2)$ and u is non-negative and reflects the inefficiencies are considered to be half normal about the stochastic frontier, $u \sim N\,|(0, \sigma^2)|$ The parameter of the stochastic frontier maximum likelihood approach is used to estimate the production function, and the findings are reliable and effective (Aigner et al., 1977). Economic efficiency is measured by the following formula.

$$EE = TE \times AE$$

The model of technical efficiency (TE), which calculates the factors influencing inefficiency and the stochastic frontier, is specified as follows.

$$lny_i = \alpha_0 + \alpha_1 ln(x_1) + \alpha_2\, ln(x_2) + \alpha_3\, ln(x_3) + \alpha_4\, ln(x_4) + \alpha_5\, ln(x_5) + \alpha_6\, ln(x_6) + \alpha_7\, ln(x_7) + v_i - \mu_i \qquad \dots\dots(3)$$

Where, y_i is the soybean output per bigha, α_1-α_7 are the parameters to be estimated, $ln(x_1)$ = the amount of labor applied per bigha of soybean (8 hours/day), $ln(x_2)$ = the amount of manure applied per bigha, $ln(x_3)$ = irrigation times for soybean production, $ln(x_4)$ = the amount of machinery applied per bigha, $ln(x_5)$ = the amount of fertilizer applied per bigha, $ln(x_6)$ = the amount of seed applied per bigha, $ln(x_7)$ = the amount of pesticides applied per bigha and μ_i - random error minus component error.

The model of allocative efficiency (AE), which determines the factors that contribute to inefficiency and incorporates the stochastic frontier, is specified as follows

$$ln(cost) = \beta_0 + \beta_1 ln(x_1) + \beta_2 ln(x_2) + \beta_3 ln(x_3) + \beta_4 ln(x_4) + \beta_5 ln(x_5) + \beta_6 ln(x_6) + \beta_7 ln(x_7) + \mu_i \quad ....(4)$$

Where, $ln(cost)$ = Cost of soybean production per bigha, $ln(x_1)$ = labor cost per bigha, $ln(x_2)$ = manure cost per bigha, $ln(x_3)$ = irrigation cost per bigha, $ln(x_4)$ = machinery cost per bigha, $ln(x_5)$ =inorganic fertilizer cost per bigha, $ln(x_6)$ = Seed cost per bigha, $ln(x_7)$ =Pesticides cost per bigha and μ_i - random error minus component error.

The production frontier of i-th farmer is as follows

Efficiency= exp ($-\mu_i$)

The model of the factors that contribute to the inefficiency of soybean cultivation is specified as follows.

$$y_i = \gamma_0 + \gamma_1(x_1) + \gamma_2(x_2) + \gamma_3 ln(x_3) + \gamma_4 ln(x_4) + \gamma_5(x_5) + \gamma_6 ln(x_6) + \mu_i \quad ... (5)$$

Where, $y_i = (1 - efficiency)$, (x_1) = dummy variable one for delayed seed sowing, (x_2) = number of tillages per bigha, $ln(x_3)$ = land area, $ln(x_4)$ = education of the farmer, (x_5) =Extension service, $ln(x_6)$ = Spouse education and μ_i - random error.

The half-normal distribution is utilized to estimate the stochastic production frontiers with the efficiency level using the flexible package software STATA 17. Manure, irrigation, machinery, fertilizer, seed, labor, pesticides, spouse education, the number of tillages, the sowing period of soybean seeds, land area, farmers' education, and extension services are among the variables included in the analysis for this study. The expected effect of the variables used in this study may have a positive or negative impact on the efficiency of soybean production. Efficiency indicators show the degree of efficiency of a particular farm or farmer in the research area. It is known to have been influenced by several socioeconomic independent variables; a positive estimated parameter sign indicates that the associated variable hurts inefficiency but has a beneficial effect on efficiency, and vice versa.

3.3 Model Specification Issues

An investigation is conducted into the validity of the model utilized for the analysis. Next, the factors influencing the efficiency of the farmers who produce soybeans, as well as the parameter estimations of the soybean production frontier, are analyzed. The trans-log functional form or Cobb-Douglas production function served as the foundation for much of the research on agricultural production analysis. Therefore, this study conducts the hypothesis test. The first hypothesis is whether the Cobb-Douglas production function more accurately reflects the soybean farmer's production technique. Cobb-Douglas functional forms are approximated to determine this outcome. Secondly, checking whether the half-normal distribution is a superior way to estimate the efficiency levels. The study tested the likelihood ratio statistics to determine this outcome of a half-normal distribution. The results of the likelihood ratio (LR) tests state that with 7 degrees of freedom, the calculated LR statistic is 61.16, which is lower than the critical value of 67.505 at the 5% level of significance. This result indicates that the Cobb-Douglas (C-D) production functional form provides a better fit for the data and is therefore used to measure efficiency. Additionally, the calculated LR statistics for the distributional assumption is 0.024, which is less than the critical value of 3.84 at the 5% significance level. This supports the use of the half-normal distribution for modeling inefficiency effects among soybean growers in the study area (Appendix: Table 1).

The researcher employs an econometric model to analyze the data. Following the verification of the regression model assumptions, encompassing outliers, multicollinearity, and the model specification test, the investigator employs econometric techniques to scrutinize the data. The model calculates the soybean farmers' inefficiencies as well as the degree of efficiency, coefficients, and significant levels of various variables.

4. Results and Discussions

4.1 Soybean Production in Bangladesh

The division-wise analysis of soybean cultivation area and production from 2020–21 to 2022–23 reveals notable regional variation (Table 1). In Barisal Division, the cultivated area remained relatively stable, increasing slightly from 13,759.55 acres in 2020–21 to 13,918 acres in 2021–22, before declining marginally to 13,651 acres in 2022–23. Production followed a similar trend, rising from 9,598.62 metric tons in 2020–21 to 11,410 metric tons in 2021–22, and then slightly decreasing to 11,295 metric tons in 2022–23. Chattogram Division consistently recorded the highest area and production across all three years. The cultivated area expanded from 128,693.05 acres in 2020–21 to 131,919.50 acres in 2022–23. Correspondingly, production rose steadily from 81,576.96 metric tons to 96,003.98 metric tons over the same period, indicating improvements in both land utilization and productivity.

Table 1: Area and production of soybeans in Bangladesh

Division	2020-21		2021-22		2022-23	
	Area (acre)	Production (M. Ton)	Area (acre)	Production (M. Ton)	Area (acre)	Production (M. Ton)
Barisal	13759.55	9598.62	13918	11410	13651	11295
Chattogram	128693.05	81576.96	131482.50	87227.34	131919.50	96003.98
Dhaka	0	0	8.25	7	7.50	6.80
Rangpur	1.40	1.01	4	1.72	4.25	1.81

Sources: BBS, 2024

In Dhaka Division, cultivation was absent in 2020–21 but was introduced on a small scale in the following years, with 8.25 acres cultivated in 2021–22 yielding 7 metric tons, and a slight decline in 2022–23 with 7.50 acres producing 6.80 metric tons. This suggests a minimal yet emerging engagement in crop production. Rangpur Division also showed a limited extent of cultivation, with the area increasing from 1.40 acres in 2020–21 to 4.25 acres in 2022–23. Production in Rangpur grew marginally from 1.01 metric tons to 1.81 metric tons during the same period.

4.2 Descriptive statistics

This section presents the descriptive analysis of the primary data collected from soybean farmers in the study area. Table 2 summarizes the key variables used in the efficiency analysis of soybean farming. All variables are expressed in natural logarithmic form to reduce heteroskedasticity and facilitate the interpretation of elasticities in subsequent regression analyses.

Table 2: Description of estimated variable

Variable	Minimum	Maximum	Mean	Std. deviation
Ln yield	0.00	11.28	8.64	0.764
Ln irrigation	0.00	6.40	1.89	2.558
Ln labor	0.00	10.38	8.31	0.793
Ln machinery	0.00	9.57	7.00	0.616
Ln seed	0.00	6.96	3.44	2.140
Ln manure	0.00	8.01	2.26	3.122
Ln pesticide	0.00	6.36	1.97	2.568
Ln fertilizer	3.58	8.58	8.02	0.108
Ln cost	8.38	11.09	9.32	0.370
Ln pesticide cost	0.00	6.36	1.98	2.578
Ln seed cost	0.63	6.96	3.44	2.140
Ln labor cost	2.31	11.36	7.87	1.307
Ln manure cost	0.00	8.01	2.26	3.122
Ln irrigation cost	0.00	6.40	1.89	2.558
Ln capital cost	1.22	9.57	7.00	0.616
Ln fertilizer cost	4.12	8.58	8.02	0.208

The soybean yield (Ln yield) ranges from 0.00 to 11.28, with a mean of 8.64 and a standard deviation of 0.764. This indicates a relatively consistent distribution of output among farmers, with limited variation. In contrast, substantial variability is observed in several input variables. For instance, the log of labor input (Ln labor) has a high mean value of 8.31 (SD = 0.793), indicating that labor is a major input in soybean production, with relatively low variation. Similarly, both Ln machinery and Ln capital have high mean values of 7.00, suggesting that capital-intensive inputs play a central role in soybean cultivation. Conversely, the variables Ln irrigation, Ln manure, and Ln pesticide exhibit greater variation, with standard deviations of 2.558, 3.122, and 2.568, respectively. These high standard deviations highlight inconsistencies in the use of these inputs.

Regarding input costs, Ln labor cost shows the highest variability, with a mean of 7.87 and a standard deviation of 1.307, indicating a wide range of labor expenditures among farmers. Similarly, Ln manure cost, Ln pesticide cost, and Ln irrigation cost all exhibit high standard deviations (above 2.5), reflecting significant disparities in cost allocation for these inputs. Ln fertilizer cost displays very low standard deviations (0.208), suggesting a more uniform application and pricing of fertilizer across farms.

4.3 Parameter Estimates of the Stochastic Production Frontier (SPF) Model

This section presents the estimated results of the stochastic frontier production function, highlighting the key input variables that significantly influence soybean production and cost efficiency based on field data collected in 2024. The estimated input elasticities and cost efficiencies influencing soybean are summarized in Table 3 and 4, respectively. The model identified fourteen parameters influencing soybean production and cost. Among these, manure and irrigation are statistically significant at the 10% level, while labor quantity, machinery, labor cost, manure cost, irrigation cost, and fertilizer cost are significant at the 1% level.

The coefficient for labor quantity in the computed stochastic production function is 0.029, suggesting that soybean output is responsive to variations in labor quantity. For instance, the output of soybeans should grow by 2.9% with every additional worker, which is consistent with findings by Hasnain et al. (2015) and Hossain, (2012). At the 10% level of significance, the predicted coefficient for manure utilized in soybean growing is 0.018, consistent with findings by Srivastava et al. (2015). Consequently, a 1.8% increase in soybean yield would follow a 1% increase in manure, all other things being equal. Once, an increase in irrigation would typically result in a 2.1% increase in soybean production, consistent with findings by Uddin et al. (2020).

Table 3: Input elasticity for the production of soybeans

Variables	Co-efficient	t-value	p-value
Ln labor	0.029***	2.16	(0.000)
Ln manure	0.018*	1.89	(0.063)
Ln irrigation	0.021*	1.65	(0.093)
Ln machinery	0.072***	2.19	(0.000)
Ln fertilizer	0.106	0.68	(0.490)
Ln seed	0.019	1.34	0.192
Ln pesticides	0.011	0.47	0.329
Constant	1.953	7.16	0.126
Log likelihood value	-110.238		
Prob.	0.000***		
No. Of observation	200		
Wald (7)	250.38		
Note: * denotes significance at the 10% level of significance, whereas *** denotes significance at the 1% level			

Source: Field survey, 2024.

The coefficient of machinery, 0.072, implies that an increase of 1% unit of machinery will increase 7.2% of the soybean output, consistent with findings by Srivastava et al. (2015). Other estimations for the stochastic production frontier are statistically insignificant. For fertilizer, seed, and pesticides used in soybean cultivation, the expected coefficients are 0.106, 0.019, and 0.011, respectively. Therefore, if all else is equal, a 1% increase in fertilizer, seed, and pesticides will result in a 10.6%, 1.9%, and 1.1% increase in soybean production, respectively. The model's log-likelihood value is -110.238, and the Wald chi-square test statistic is 250.38 with a p-value of 0.000, indicating that the overall model is statistically significant.

Table 4 shows the estimated stochastic cost function in which the coefficient for fertilizer of 0.029 suggests a statistically significant result ($p < 0.001$) indicating that soybean production cost is to some extent elastic to changes in the use of the fertilizer, consistent with findings by Rinaldi et al., (2023); Salam and Kamruzzaman, (2015); Srivastava et al., (2015). For example, an increase of 1% in fertilizer cost should introduce a 2.9% rise in allocative efficiencies. This finding is consistent with Dagar et al. (2018). Similarly, the labor cost coefficient of 0.017 suggests that a 1% increase in labor expenditure leads to a 1.7% improvement in allocative efficiency. This statistically significant result ($p < 0.001$) highlights labor as a vital input in enhancing cost efficiency in soybean production. The coefficient for manure cost, also 0.017, and statistically significant at the 1% level ($p < 0.001$), indicates that a 1% increase in manure cost is linked to a 1.7% rise in allocative efficiency. Irrigation cost shows a coefficient of 0.016, statistically significant at the 1% level ($p = 0.008$), suggesting that a 1% increase in irrigation expenditure results in a 1.6% increase in allocative efficiency. This reflects the importance of water management in optimizing soybean production costs. In contrast, the coefficient for pesticide cost is 0.001, and is statistically insignificant ($p = 0.800$), indicating that variations in pesticide expenditure do not meaningfully affect the cost efficiency of soybean production. This may imply either overuse or inefficiency in pesticide application practices among the sampled producers. Irrigation, labor, manure, machinery, and pesticide costs are all positively related to allocative efficiency, suggesting that raising these costs in soybean production would raise allocative efficiency for soybean producers, while machinery is statistically insignificant. For seeds used in soybean cultivation, the expected negative coefficient is 0.006. Therefore, if all else is equal, a 1% increase in seed cost would result in a 0.6% decrease in soybean production, consistent with findings by Kranniqi et al. (2023). The model's Wald chi-square statistic is 365.79 with a p-value of 0.0000, indicating that the overall model is highly significant. The constant term is 5.439 and is statistically significant, representing the baseline log of production cost. The model is based on 200 observations, and the log-likelihood value is 38.1518.

Table 4: Input elasticity for the cost of soybean production

Variables	Co-efficient	t-value	p-value
Ln labor cost	0.017***	3.45	(0.000)
Ln manure cost	0.017***	3.85	(0.000)
Ln irrigation cost	0.016***	2.75	(0.008)
Ln machinery cost	0.006	0.24	(0.813)
Ln fertilizer cost	0.029***	2.91	(0.000)
Ln seed cost	-0.006	-1.01	0.320
Ln pesticides cost	0.001	0.17	0.863
Constant	5.439***	8.96	0.000
Log likelihood value	38.1518		
Prob.	0.0000***		
No. Of observation	200		
Wald (7)	365.79		
Note: *** indicates significance at 1%			

Source: Field survey, 2024.

4.4 Efficiency of Soybean Farms in Bangladesh

The frequency distribution of technical efficiency estimates among soybean farmers, derived from the Stochastic Production Frontier model, is presented in Table 5, highlighting variations in input use and overall production efficiency. The results indicate that technical efficiency among the sampled farmers varies considerably, ranging from a minimum of 0.25 to a maximum of 0.99, with an overall mean efficiency of 0.75 and a standard deviation of 0.13. This suggests that, on average, soybean farmers in the study area operate relatively close to their production frontier, consistent with findings by Agraw et al. (2020) and Wake et al. (2019).

The distribution shows that 50.5% of farmers achieved a technical efficiency (TE) score above 0.85, with a mean of 0.956, indicating high adherence to optimal input-output relationships. In contrast, 49.5% of farmers operated below this threshold, reflecting variability in production performance. A small segment (5.5%) exhibited low-efficiency levels, scoring between 0.25 and 0.51 (mean: 0.421), suggesting considerable potential for improvement. Meanwhile, 10% of farmers fell within the 0.52–0.60 range (mean: 0.556), 14% between 0.61–0.73 (mean: 0.672), and 20% within the 0.74–0.85 category (mean: 0.790). These results indicate that although a significant portion of farmers operate efficiently, targeted interventions could help those in lower efficiency ranges to improve resource utilization and productivity.

Table 5: Value of technical efficiency for Soybean farmers

Efficiency category	Mean value	No. of frequency	Percent (%)	Minimum	Maximum
0.25-0.51	0.421	11	5.5	0.25	0.50
0.52-0.60	0.556	20	10	0.51	0.59
0.61-0.73	0.672	28	14	0.61	0.72
0.74-0.85	0.790	40	20	0.74	0.84
Above 0.85	0.956	101	50.5	0.85	0.99
Overall efficiency					
Maximum	0.99				
Minimum	0.25				
Mean	0.75				
Standard Deviation	0.13				

Source: Calculated from field survey, 2024

Table 6 displays the distribution of allocative efficiency scores for soybean farmers, highlighting considerable variation across the sample. Allocative efficiency ranges from a minimum of 0.37 to a maximum of 0.95, with an overall mean efficiency of 0.88. This high average suggests that the majority of soybean producers are allocating resources close to the cost-minimizing frontier, consistent with the findings of Osman et al. (2018). The results indicate that 86% of the farmers achieved allocative efficiency (AE) scores above 0.85, with a mean of 0.95, demonstrating a strong capacity to allocate inputs cost-effectively. In contrast, only 14% of farmers operated below this threshold, indicating some inefficiencies in input allocation.

Table 6: Value of allocative efficiency for Soybean farmers

Efficiency category	Mean value	No. of frequency	Percent (%)	Minimum	Maximum
0.35-0.51	0.46	5	2.5	0.35	0.45
0.52-0.60	0.55	3	1.5	0’55	0.59
0.61-0.73	0.66	3	1.5	0.61	0.67
0.74-0.85	0.83	3	8.5	0.76	0.84
Above 0.85	0.95	172	86	0.86	0.95
Overall efficiency					
Maximum	0.95				
Minimum	0.37				
Mean	0.88				
Standard Deviation	0.11				

Source: Field survey, 2024

Specifically, 2.5% of farmers fell into the lowest efficiency category (0.35–0.51) with a mean AE of 0.46, while 1.5% are in both the 0.52–0.60 and 0.61–0.73 ranges, each with mean values of 0.55 and 0.66, respectively. A slightly larger group (8.5%) fell within the 0.74–0.85 range, with a mean of 0.83. These findings imply that while the vast majority of soybean farmers demonstrate a high level of allocative efficiency, a small segment would benefit from improved input management and decision-making strategies to reduce production costs further.

Table 7 presents the distribution of economic efficiency scores among soybean farmers, calculated as the product of technical and allocative efficiency. The results show that economic efficiency ranges from 0.09 to 0.94, with a mean value of 0.67 and a standard deviation of 0.17. This indicates that, on average, soybean producers in the study area are operating at 67% of the optimal economic efficiency level, suggesting significant potential for improvement in both resource utilization and cost management, consistent with findings by Wake et al. (2019).

Table 7: The value of economic efficiency for Soybean farmers

Efficiency category	Mean value	No. of frequency	Percent (%)	Minimum	Maximum
0.09-0.51	0.30	30	15	0.09	0.49
0.52-0.60	0.55	32	16	0.53	0.60
0.61-0.73	0.66	45	22.5	0.62	0.73
0.74-0.85	0.83	80	40	0.74	0.85
Above 0.85	0.95	13	6.5	0.86	0.94
Overall efficiency					
Maximum		0.94			
Minimum		0.09			
Mean		0.67			
Standard Deviation		0.17			

Source: Field survey, 2024

The distribution reveals that a large majority, 93.5% of farmers, had economic efficiency (EE) scores below 0.85, while only 6.5% exceeded this threshold, with a mean EE of 0.95, reflecting optimal production performance in terms of both technical and allocative aspects. The largest share of farmers (40%) fell within the 0.74–0.85 efficiency range (mean: 0.83), followed by 22.5% in the 0.61–0.73 range (mean: 0.66), 16% in the 0.52–0.60 range (mean: 0.55), and 15% in the lowest category of 0.09–0.51 (mean: 0.30), indicating serious inefficiencies in a notable portion of the sample.

Overall, while a fraction of soybean farmers operate near the economic frontier, the majority demonstrate moderate to low economic efficiency, pointing to a need for identifying the sources of inefficiency to rectify the situation and enhance productivity and profitability.

4.5 Determinants for Inefficiencies of Soybean Production

Socioeconomic determinants are estimated based on inefficiency value and it is found that the primary causes of inefficiencies in soybean production include spouse education, the number of tillages, the sowing period of soybean seeds, land area, farmers' education, and extension services (Table 8).

At the 1% level of significance, the estimated coefficient for tillage is positive and statistically significant, indicating that increased tillage is associated with higher inefficiencies. In contrast, spouse education emerges as a major determinant with a negative coefficient at the 1% significance level, suggesting that higher levels of spouse education are associated with reduced inefficiencies in soybean production. Furthermore, the coefficient for extension contact is statistically significant and negative at the 5% level, implying that more frequent visits to extension service tents contribute to lower inefficiency levels. These findings corroborate those reported by Wake et al. (2019) and Osman et al. (2018).

Table 8: Inefficiency sources of soybean production

Variables	Co-efficient	t-value	p-value
Delayed seed Sowing	0.26***	5.20	0.000
Number of tillages	0.19***	6.33	0.000
Land area	-0.19***	-8.26	0.000
Education	-0.27***	5.87	0.000

Extension services	-0.04**	-2.35	0.018
Spouse Education	-0.017***	-2.83	0.000

Source: Field survey, 2024

According to the estimates, the coefficient for the seed sowing period is statistically significant and positive at the 1% level. This result indicates that early planting of soybean seeds is associated with a reduction in inefficiencies. Additionally, the estimated land area parameter is negative and statistically significant at the 1% level, suggesting that larger farms tend to operate more efficiently, a result that is consistent with the findings of Rinaldi et al. (2023). Finally, at the 1% level of significance, farmers' education is identified as a critical factor influencing production efficiency. More educated farmers appear to be more adept at reducing inefficiencies in soybean production, which aligns with the conclusions drawn by Rahman et al. (2024), Argaw et al. (2020), and Hasan et al. (2016).

5. Conclusion

This study estimates the technical, allocative, and economic efficiency of soybean production and examines the factors contributing to production inefficiency. The findings reveal that soybean output is moderately responsive to key inputs, including labor, manure, irrigation, and machinery. The cost function analysis further indicates that increased fertilizer use enhances allocative efficiency. Other input costs, including labor, manure, irrigation, and machinery, exhibit positive associations with allocative efficiency, underscoring the importance of optimal input allocation in enhancing production performance. Efficiency estimates suggest that economic inefficiency is the most critical constraint among the three efficiency dimensions. Socioeconomic and agronomic factors, particularly the education levels of farmers and their spouses, seed sowing timing, tillage frequency, landholding size, and access to agricultural extension services significantly influence efficiency outcomes. While frequent tillage operations are linked to increased inefficiency, higher levels of education, earlier seed sowing, larger landholdings, and more frequent contact with extension services contribute to enhanced efficiency. Notably, the education levels of both farmers and their spouses emerge as strong predictors of reduced inefficiency. Despite the valuable insights offered by this study, differences in agro-climatic conditions, infrastructure, and market accessibility across regions may lead to variations in efficiency outcomes. Moreover, this study did not account for factors such as soil quality, local weather conditions, technology adoption rates, and farmers' risk preferences due to data limitations. Based on these findings, several recommendations are proposed for future research. Conducting efficiency analyses across major soybean-producing regions in Bangladesh would help capture regional disparities and inform more targeted interventions. Employing longitudinal or panel data could account for seasonal and temporal effects, as well as exogenous shocks such as climate change and market fluctuations. Future studies should also include a broader range of economic variables, such as access to credit, off-farm income, market prices, and input cost dynamics, to gain a more comprehensive understanding of the financial determinants of inefficiency. Additionally, incorporating environmental and agronomic variables—such as soil fertility, rainfall variability, technology adoption, and behavioral factors like farmers' risk preferences—would offer a more holistic perspective on the drivers of efficiency in soybean production.

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Appendix

Table 1: Summary of the Cobb-Douglas and half-normal distribution hypothesis test

Hypothesis	Df	Calculated χ^2 (LR)	Critical χ^2	Decision
H0: The production function is Cobb-Douglas	7	61.16	67.505	Accepted
H0: production function followed the half-normal distribution	1	0.024	3.841	Accepted

Source: computed from field survey data, 2024