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Assessing technical and scale efficiencies in tilapia production: influential factors and insights

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Abstract – This study assessed the technical and scale efficiency of tilapia farmers in Bangladesh with a focus on identifying key factors influencing their efficiency levels. Data from 199 randomly selected tilapia farmers were analyzed using Data Envelopment Analysis (DEA), followed by a Tobit regression model to determine the key variables affecting efficiency. The results revealed a mean TE of 0.77 under CRS, 0.83 under VRS, and a mean SE of 0.92, indicating that most inefficiencies were technical rather than scale-related issues. The study also identified farming training, credit access, and years of experience had a positive effect on TE, while adverse climatic conditions negatively impacted efficiency. The findings emphasize the importance of mitigating climate impacts and improving resource management to enhance efficiency. Expanding credit access, improving training programs, and taking initiatives for mitigating climate impacts could significantly improve the efficiency and long-term viability of tilapia production in the region.

Keywords: Productivity / efficiency / tilapia / aquaculture / Bangladesh

1 Introduction

Global fish production, sourced from aquaculture and capture fisheries, has not been able to keep up with the rising demand brought on by the population's rapid expansion, rising income, and growing consumer preferences for healthier foods like fish. This growing need to align global food production with population expansion highlights the importance of exploring alternative production methods and strategies to improve the efficiency and sustainability of aquaculture (Hunter et al., 2017). Tilapia, *Oreochromis mossambicus*, is a rapidly expanding and resilient fish species that has become a critical dietary component in numerous regions worldwide, particularly in developing regions where the availability of affordable and reliable protein sources is a significant concern. The increasing global preference for tilapia among consumers is indicative of its nutritional value and adaptability. However, tilapia producers are frequently impeded by challenges such as a lack of suitable technical expertise and resources, substantial post-harvest losses, poor productivity, and inefficiencies at the farm level (Uddin et al., 2021). Addressing these issues could unlock significant benefits for global food security.

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Fish is deeply ingrained in Bengali culture and diet, as evidenced by the adage "fish and rice make a Bengali." In keeping with this cultural significance, Bangladesh's per capita fish consumption is currently 63 grammes day, exceeding the 60 grammes daily target (DoF, 2022a). As a major contributor to this consumption, the aquaculture industry produced 47.59 lakh metric tonnes of fish in 2022 (DoF, 2022b). In addition to meeting food demands, aquaculture is crucial for Bangladesh's socioeconomic growth, employment generation, aquatic biodiversity preservation, and animal protein supply (Khan et al., 2012; Belton et al., 2018; Mitra et al., 2019). This sector directly or indirectly employs over 12% of the total population and contributes 2.08% of the national GDP and 21.83% of agricultural GDP. Bangladesh is home to a wide variety of fish species as a result of its favorable geographical location and abundant aquatic resources (Rahman et al., 2020; Das et al., 2022). Tilapia is particularly popular among farmers in Bangladesh due to its attractive appearance, delicious flavor, and capacity to endure a variety of adverse climatic conditions (Rahman et al., 2021). Furthermore, tilapia is a preferred choice for fish cultivation due to its rapid growth and brief generation time, which are both superior to those of many other fish species. Bangladesh is the third-largest tilapia producer in Asia, as indicated by the 2022 Food and Agriculture Organization report.

The Department of Fisheries in Bangladesh has reported a remarkable increase of approximately 37% in the total production of tilapia between 2013-14 and 2021-22. Although this substantial expansion is apparent, the production of tilapia varies significantly among various farms and regions. This variability is frequently associated with factors such as inefficiencies and output risk (Alam et al., 2019). Technical inefficiencies are especially common among traditional farmers, who constitute the majority of producers and are a major contributor to this variability. To develop a more comprehensive understanding of these issues, this study aims to analyze the factors driving these inefficiencies and assess the scale efficiency of tilapia producers in Bangladesh by drawing insights from the country's tilapia production sector.

It is essential for both farmers and policymakers to be aware of the primary factors that influence the technical and scale efficiency of tilapia producers in Bangladesh. This knowledge is instrumental in the selection of the appropriate strategies to mitigate production variability, thereby increasing the productivity and profitability of this essential aquaculture sector. Farmers can accomplish economic stability, boost competitiveness, optimize resource utilization, increase productivity, and adopt sustainable practices by identifying these factors. Additionally, this understanding can assist policymakers and support organizations in the development of effective interventions to strengthen the aquaculture sector.

The technical efficiency of tilapia farming has been the subject of extensive research in a variety of countries. The results consistently indicate that producers rarely reach their optimum production capacity. Alam et al. (2012) found that cultivators in Bangladesh achieve an efficiency rate of 78%, which is significantly influenced by factors such as age, education, and income. Dey et al. (2000) Tan et al. (2011) and conducted comparable studies in the Philippines, which reported higher efficiency rates of 83% and 79%, respectively. These efficiencies were influenced by farm size, education, and age. Yuan et al. (2019) observed that the average efficiency in China was 79%, which implies a positive correlation between farm size and efficiency.

Subsequent investigations have disclosed substantial regional disparities in efficiency levels. Rahman et al. (2019) attributed these variations to the selection of species that are well-suited to local conditions, producers' ability to manage inputs, and differences in the production environment. They also observed that aquaculture farmers are positively impacted by the scale of the regional industry in terms of the production possibility frontier, but they are adversely affected in terms of technical efficiency. Rayos and Macaraeg (2024) conducted a recent study that investigated the factors that influence the technical efficiency of tilapia production in the Philippines. The study found that all fish producers in the examined areas were operating below their production potential.

The aquaculture industry's substantial expansion and the prominence of tilapia cultivation are underscored by the expanding body of literature, which is attributable to the species' adaptability, affordability, and consumer appeal. However, the industry continues to encounter obstacles in improving the technical efficiency of tilapia farmers. A number of studies (Young and Muir 2002; Chertkov 2020; Wati et al., 2020) suggest that a variety of critical factors, such as farm size, age, education, income, and regional production environments, are responsible for gaps in technical efficiency among tilapia producers. Collectively, these studies emphasize the complexity of enhancing technical efficiency in tilapia farming and the importance of addressing the diverse influences that affect production efficiency across various regions and farming conditions.

Despite the significant contributions of earlier research, the majority of studies on the effectiveness of tilapia aquaculture have focused on technical efficiency, frequently overlooking the significance of scale efficiency in the production process. Furthermore, a number of aspects have not been thoroughly investigated, including the size of the household, the impact of the climate, the experience of farmers, the availability of financial resources, and educational skills. By examining the sociodemographic variables that influence farm performance and evaluating the technical and scale efficiency of tilapia farmers in Bangladesh, this study seeks to close these gaps.

Therefore, the objectives of the study is assessed the technical and scale efficiency of tilapia farmers in Bangladesh and identified the factors that influence their efficiency. Through this analysis, the study anticipations to gather important information that will improve the sector's productivity and resource utilization, ultimately directing policy frameworks that promote sustainable development in aquaculture sector.

The remainder of the paper is organized as follows. Section 2 focuses on the data, and Section 3 discusses the methods used. Section 4 presents the empirical data, which are then discussed in Section 5. The conclusions are then stated in Section 6.

2 Data collection

Bangladesh's fish market relies on both wild-caught and produced fish, with tilapia being a key species in aquaculture (E-Jahan et al., 2010; Fitzsimmons et al., 2011). Bangladesh is regarded an excellent site for tilapia farming due to its favorable geographical location and plenty of resources, particularly in the Barishal division, such as ponds, canals, rice paddies, and cost-effective labor. Following the literature study, a data collection questionnaire was created, which underwent an initial trial with 25 farmers, followed by focus group discussions and pilot tests in all of Bangladesh's Barishal districts. Participants were asked about tilapia farming processes and other aspects of tilapia production. They were also asked to give their opinions on the elements that influence the technical efficiency of tilapia growers.

Before the field survey began, the enumerators received extensive training. They were thoroughly informed about the study's goals and objectives, as well as how to effectively connect with customers throughout data collecting. To recruit individuals, a random sample method was used, ensuring easy access and voluntary participation. Using this strategy, we were able to interview 199 respondents from six districts in Bangladesh's Barishal division.

In order to ensure the collection of representative and unbiased data from tilapia producers in the Barisal, Bhola, Barguna, Jhalokati, Patuakhali, Pirojpur, and Borguna districts, random sampling was implemented (Fig. 1). The study sought to ensure that the sample accurately represents the

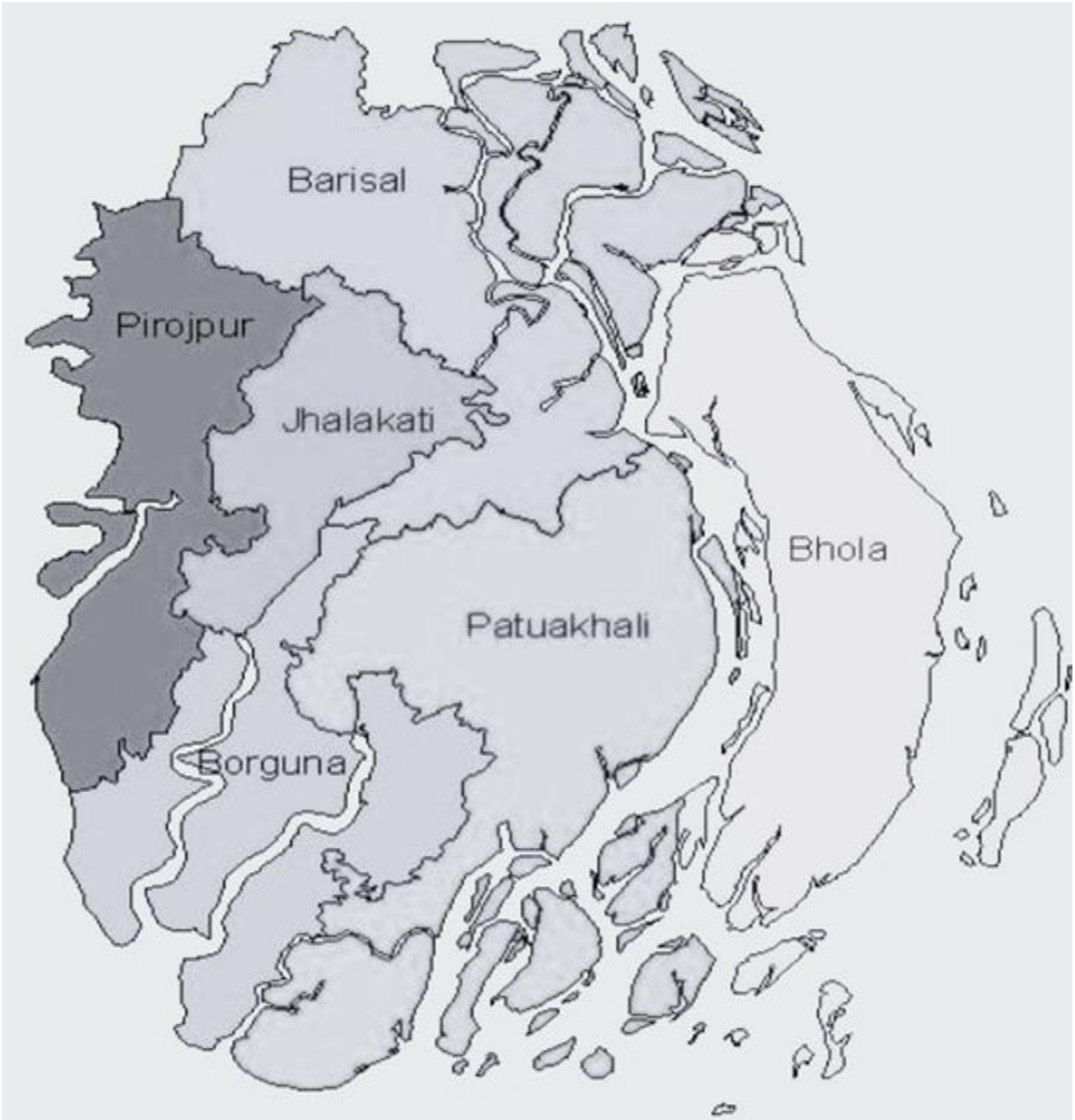

Fig. 1. The study area's map from where data are collected.

diversity and characteristics of the broader population by randomly selecting participants. This approach guarantees that the results are not influenced by the researchers' preferences and that the findings can be applied to a broader population of tilapia producers, thereby minimizing selection bias. Furthermore, the statistical validity of the study is improved by random sampling, which enables a more precise identification of the factors that influence technical efficiency through robust inferential analysis. It also assures that the sample will encompass all potential variations within the population, thereby facilitating a thorough comprehension of the variety of factors that influence the efficiency of tilapia aquaculture. Ultimately, this methodology aids in the creation of policy recommendations and interventions that are well-informed and designed to enhance the profitability and productivity of tilapia aquaculture in the region.

To overcome language barriers and guarantee high response rates, the study included in-person interviews. There were three sections on the questionnaire. In the first, the study's title, idea, and goal were presented. The second gathered sociodemographic information, such as family size, education level (years of schooling), and age (years). Farm size (hectare), fingerlings (per hectare), fertilizer, feed (kg), and labor (hired and family, measured in man-days per hectare, with one man-day equal to 8 h) were the main production variables covered in the third segment. Perceptions of climatic impacts, credit access, farming training (days), and experience (years) were all covered by open-ended questions. Both perceptions of the effects of climate change on production and credit access were evaluated using a yes/no question. A randomized translation-back-translation procedure was used to meticulously translate the questionnaire from its original English into Bangla.

3 Methodology

Within the data envelopment analysis (DEA) framework, this empirical study evaluated the performance of tilapia producers in Bangladesh by employing the concepts of technical efficiency (TE) and scale efficiency (SE). In addition, the research implemented Tobit regression in the subsequent phase to evaluate the influence of socio-demographic variables. The production frontier is estimated by evaluating the performance of decision-making units (DMU) with specified inputs and outputs using DEA, a non-parametric technique (Haynes and Dinc 2005). Scholars who employ the DEA methodology must determine an orientation that is most appropriate for the inputs and outputs that producers can effectively manage. Input-oriented technical efficiency is focused on the reduction of input levels without compromising output, while output-oriented measures are designed to optimize production without increasing input quantities (Ferdous et al., 2008). The DEA is composed of two primary models: constant returns to scale (CRS) and variable returns to scale (VRS). CRS is applicable when firms are operating at optimal scale, whereas VRS is applicable in situations where this is not the case (Huguenin 2012). However, the input-oriented CRS and VRS models were selected for this specific investigation.

If K is the observed unit for, $k=1,\ldots K$, x_j^k is the amount of input $i(i=1,\ldots, m)$ consumed by unit k to produce each of n output y_j^k ($j=1,\ldots, n$), and (x^0, y^0) represents the unit under analysis, and the VRS and CRS model can be expressed as:

VRS input oriented model	CRS input oriented model
$\boldsymbol{Eff}(\boldsymbol{x}^0,\boldsymbol{y}^0)=\theta^{0*}=\boldsymbol{Min}\,\theta$	$Eff(x^0,y^0)=\theta^{0*}=Min\,\theta$
$\sum_{k=1}^{K}\lambda^k \boldsymbol{x}_i^k \le \theta \boldsymbol{x}_i^0, \boldsymbol{i}=1,\ldots,\boldsymbol{m}$	$\sum_{k=1}^{K}\lambda^k x_i^k \le \theta x_i^0, i=1,\ldots,m$
$\sum_{k=1}^{K}\lambda^k \boldsymbol{y}_j^k \ge \boldsymbol{y}_j^0, \boldsymbol{j}=1,\ldots,\boldsymbol{n}$	$\sum_{k=1}^{K}\lambda^k y_j^k \ge y_j^0, j=1,\ldots,n$
$\sum_{k=1}^{K}\lambda^k=1$	$\lambda^k \ge 0, k=1,\ldots,K$
$\lambda^k \ge 0, \boldsymbol{k}=1,\ldots,\boldsymbol{K}$	

A farm is considered to have scale inefficiency when the TE scores from CRS and VRS diverge, as evidenced by the disparity between the TE scores from VRS and CRS. The efficiency of the scale is operationally determined by the ratio of the constant return scale and variable return scale models (Banker, 1984; Charnes et al., 1979):

$$SE=\frac{TE_{i,CRS}}{TE_{i,VRS}}.$$

The firm is operating at the optimal scale when the scale efficiency is one; otherwise, it is not operating at the optimal scale (Altaie 2022).

Decision-makers can enhance efficiency by managing controlled factors (fingerlings, labor, feed, and capital) that are associated with input and output variables in DEA. However, they are unable to control contextual variables (such as farming training, years of education, and climate impact) that affect production (Da Silva et al., 2019). In order to investigate the influence of the socioeconomic characteristics of the tilapia producers on the TEs, this investigation implemented a second-stage DEA analysis. This time, we apply the CRS and VRS TEs to socio-economic variables on an individual basis. Second-stage analysis is an intuitive method for policymakers and regulators to examine the impact of socio-demographic factors on DEA-estimated efficiency scores, according to numerous statistical studies (Hoff, 2007; Simar and Wilson, 2007).

Tobit regression and OLS are the most common and straightforward methods for evaluating the linear relationship between socio-demographic factors and DEA efficiencies (Holloway et al., 2004). Conversely, the present investigation is more suitable for Tobit regression due to the fact that the dependent variable (efficiency scores) is both discrete and continuous (Wooldridge, 2012; Tobin, 1958).

Efficiency scores obtained from the solution of the DEA models (VRS and CRS) at the first stage have been regressed on the socio-economic characteristics of producers and the farm at the second stage using a Tobit regression. The efficiency scores from the DEA models (VRS and CRS) were regressed on farm and farmer socioeconomic characteristics using Tobit regression in the second stage (Zongli et al., 2017). The equations used were as follows:

$$TE_{VRS}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3+\beta_4X_4+\beta_5X_5+\beta_6X_6+\beta_7X_7+\Phi \quad (1)$$

$$TE_{CRS}=\rho_0+\rho_1X_1+\rho_2X_2+\rho_3X_3+\rho_4X_4+\rho_5X_5+\rho_6X_6+\rho_7X_7+\Psi. \quad (2)$$

Here, TE_{VRS} and TE_{CRS}, respectively indicate the technical efficiency score obtained from the VRS and CRS DEA models. X_1-X_7 indicate socio-economic factors where, X_1 = farming training, X_2 = years of education, X_3 = years of experience, X_4 = age, X_5 = family size, X_6 = credit access, and X_7 = climate impact on production. Tobit equations (1) and (2) determine how the farmer's contextual variables affect TE_{VRS} and TE_{CRS}, respectively. Φ and Ψ are the models' error terms.

Table 1. Measurement of output and input variables of technical efficiency in the data envelopment analysis and tobit analysis.

Variables description		Unit
Variables used in measuring technical efficiency		
Y	Total production of Tilapia during the year of the sample farms per hectare(ha)	Kilogram (Kg)
X_a	Quantity of feeds (traditional and commercial) applied per hectare per year	Kg
X_b	Quantity of fingerling used for the production per hectare per year	Number
X_c	Quantity of labor used per hectare per year	Man-day[a]
X_d	Quantity of fertilizer per year per hectare	Kg
X_e	Amount of others input cost incurred per hectare per year	US$
Variables used in Tobit analysis		
X_1	Taking Tilapia farming-related training (1= taken, 0= otherwise)	1,0
X_2	Education of the farmers	Years
X_3	Farming Experience of the Farmers	Years
X_4	Age of the farmers	Years
X_5	Number of dependents of the farmers	Number
X_6	Famers who have institutional credit access (1=credit access, 0=otherwise)	1,0
X_7	Impact of climate change on Tilapia farming (1= have climate change impact, 0=otherwise)	1,0

[a] 1 man-day equals 8 hours of work.

Table 2. Summary statistics of the variables.

Name of the variables	Mean	Max	Min	SD
Farm Size (ha)	1.05	4.09	0.26	1.07
Feed (kg/ha)	21,174.38	64500.00	890.00	16,517.36
Fingerlings(no./ha)	59718.14	98,500	10,000	27906.88
Labor (man-days/ha)	361.54	1789.00	112.50	336.59
Fertilizer(kg/ha)	620.72	2650.00	95.82	555.08
Other costs (US$/ha)	135.75	295.92	34.57	78.78
Production (kg/ha)	9,360.68	22,078.55	7,355.46	4,510.44
Education (years)	3.34	6.00	1.00	1.23
Experience (years)	12.00	24.00	5.00	5.52
Age (years)	38.00	69.00	24.00	11.20
Family Size (no.)	3.24	8.00	3.00	2.11

*US$ 1 equaled approx. Bangladesh Taka 117 in the year 2024.

The input and output variables used to evaluate technical efficiency and perform Tobit analysis are outlined in Table 1. These variables include total Tilapia production, feed, fingerlings, labor, fertilizer, and other expenses. Furthermore, it evaluates the influence of climate change, education, and experience on farmer attributes. These variables are indispensable for the examination of technical efficiency through Data Envelopment Analysis (DEA) and for the comprehension of the factors that influence Tilapia farming outcomes through Tobit analysis.

4 Empirical result

4.1 Summary statistics

The characteristics of the Tilapia cultivation that were sampled are presented in Table 2. Ranged from 7,355.46 kg/ha to 22,078 kg/ha, the average production output was 9,360.68 kg/ha. Production utilized an average of 59,718.81 fingerlings. The average fodder quantity used per hectare was 21,174.38 kg. The average number of man-days was 361.54, with a range of 112.50 to 1,789 when labor was measured in man-days. The minimum farm size was 0.26 hectares, and the maximum farm size was 4.09 hectares. The average farm size was 1.05 hectares. The average fertilizer use was 620.72 kg/ha, and the average cost of other inputs was $135.75 per hectare. The education level of Tilapia cultivators was generally low, as indicated by socioeconomic variables. The average number of dependents per farmer was 3.24.

The technical and scale efficiency (SE) scores of tilapia producers are analyzed in detail, as shown in Table 3. The data have been thoroughly examined to provide an accurate representation of the producers' efficiency levels. The findings indicate that a majority of farmers in the sample demonstrate high efficiency in tilapia production. The mean technical efficiency (TE) score for the farmers is estimated at 0.77, based on the assumption of Constant Returns to Scale (CRS). This estimate highlights that over 50% of the farmers have TE scores ranging from 0.60 to just below 0.80, indicating a substantial level of efficiency within this group.

Table 3. Distribution of TE and SE in tilapia production.

TE Range	TE(CRS)		TE(VRS)		Scale efficiency	
	Frequency	%	Frequency	%	Frequency	%
1.00	29	14.60	55	27.60	29	14.58
0.90 >1.00	17	08.50	19	09.50	112	56.28
0.80> 0.90	27	13.60	41	20.60	37	18.64
0.70>0.8	50	25.10	39	19.60	14	07.00
0.60>0.70	50	25.10	34	17.10	5	02.50
<0.60	26	13.10	11	05.60	2	01.00
Mean	0.77		0.83		0.92	
Maximum	1.00		1.00		1.00	
Minimum	0.45		0.51		0.53	

Additionally, it is interesting to note that approximately 8.5% of the households in the sample have a TE score between 0.90 and just below 1.00. The average TE score is an impressive 0.83 when we concentrate on the Variable Returns to Scale (VRS) TE scores. This estimate is extremely encouraging, as it implies that more than 40% of the producers are capable of achieving TE scores that fall within the range of 0.70 to just below 0.90, which is a remarkable level of efficiency. Furthermore, it is important to note that 27.60% of the farm-households included in the sample can be classified as technically efficient, which is encouraging for the future and progress in the prestigious field of tilapia production. Overall, the findings of the analysis emphasize the vast potential and numerous opportunities that are present in the tilapia production sector, as a growing number of farm-households exhibit their technical proficiency and contribute to the industry's expansion and prosperity.

It is crucial to acknowledge that the farms operating under the Variable Returns to Scale (VRS) assumptions indicate a higher level of efficiency than those operating under the Constant Returns to Scale (CRS) assumption. This discovery has substantial implications, as it underscores the importance of taking VRS assumptions into account when evaluating the efficiency of tilapia production. Farmers are afforded the opportunity to pinpoint specific areas in their operations that can be improved in order to increase their efficiency levels by considering this. The estimation of Scale Efficiency (SE) also provides useful insights, indicating that over 70% of tilapia producers operate with moderate efficiency, with SE scores in the range of 0.90 to 1.00. This result suggests that a substantial number of tilapia farmers are able to reach high efficiency levels. These findings support the potential for further efficiency improvements within tilapia production and underscore the value of detailed efficiency analysis for advancing best practices in the industry.

The findings, in general, are quite optimistic for those involved in tilapia production, as shown in Table 3. The results indicate that there is potential for more efficiency improvement as most producers in the sample are operating at a moderate degree of efficiency. Farmers need to fine-tune their operations rather than changing the size of their farms to improve their productivity. Hence, farmers can concentrate on specific areas to increase productivity. In addition, the mean scale efficiency is 0.92, indicate that, on average, farms are operating at 92% of the optimal scale efficiency. A high mean SE (0.92) compared to mean TE CRS (0.77) and TE VRS (0.83) also suggests that most inefficiency is due to technical inefficiency rather than scale inefficiency.

The findings of a Tobit analysis that investigated the factors that affect the technical efficiency (TE) of producers under the Constant Returns to Scale (CRS) and Variable Returns to Scale (VRS) frameworks are summarized in Table 4. Several factors with substantial effects on TE are identified in the analysis. TE is substantially and positively influenced by Farming Training and Credit Access in both CRS and VRS models. The coefficient of Farming Training is 0.039 (significant at the 5% level) under CRS and 0.023 (significant at the 5% level) under VRS, suggesting that training improves efficiency. In the same vein, Credit Access exhibits positive coefficients (0.034 for CRS and 0.033 for VRS, both significant at the 5% level), indicating that financial resources empower producers to invest in superior inputs and technologies, thereby enhancing efficiency.

Years of Experience also emerge as a critical factor, with a positive and substantial effect on TE in both models. The coefficient is 0.006 under CRS (significant at the 5% level), whereas it is 0.016 under VRS (significant at the 5% level). This suggests that producers with more experience are more adept at optimizing production processes and managing resources. On the contrary, the coefficients of −0.058 for CRS and −0.048 for VRS (both significant at the 10% level) indicate that Climate Impact has a negative and substantial impact on TE in both models. This emphasizes the necessity of strategies to mitigate climate impacts in order to maintain and improve efficiency, as it highlights the detrimental impact of adverse climatic conditions on agricultural productivity.

Despite displaying positive coefficients, the analysis shows that Age, Years of Education, and Family Size have no discernible effects on technical efficiency (TE). This implies that although these elements may seem to be related to efficiency intuitively, they have a less noticeable direct effect on TE than essential elements like experience, training, loan availability, and climatic impact. The statistical significance of the models is confirmed by the log-likelihood values (70.81 for CRS and 59.80 for VRS) and Wald chi-squared statistics (CRS: Prob > $chi^2 = 0.002$; VRS: Prob > $chi^2 = 0.004$), further supported by Wald chi-squared values of 25.17 for CRS and 21.12 for VRS, underscoring the models' robustness in

Table 4. Factors affecting the farmer's technical efficiency (A Tobit analysis).

SL	Factors	CRS		VRS	
		Coefficient value	Standard error	Coefficient value	Standard error
1	Farming Training	0.039*	0.021	0.023**	0.017
2	Years of Education	0.049	0.023	0.043	0.021
3	*Years of Experience*	*0.006***	*0.003*	*0.016**	*0.011*
4	Age	0.089	0.058	0.083	0.055
5	Family Size	0.059	0.026	0.051	0.042
6	Credit Access	0.034*	0.028	0.033*	0.021
7	Climate Impact	–0.058*	0.046	–0.048*	0.041
Log likelihood = 70.81	Log likelihood = 59.80				
Prob>chi2 0.002	Prob>chi2 0.004				
Wald^{x2} = 25.17	Wald^{x2} = 21.12				
Pseudo R^2 = 0.563	Pseudo R^2 = 0.521				

capturing key determinants of TE among tilapia producers. Additionally, the Pseudo R-squared values of 0.563 for CRS and 0.521 for VRS demonstrate the models' moderate explanatory power, suggesting that although unobserved factors may also affect TE, the models successfully capture significant relationships between TE and important predictors like experience, training, credit availability, and climate impact. This indicates that the factors included in the model collectively account for a substantial portion of the variation in TE among farmers.

5 Discussion of results

Key insights into the efficiency of tilapia production are revealed through the examination of DEA-estimated technical and scale efficiency scores. A small number of farm households have attained optimal performance, showing their exceptional capacity to effectively manage resources. The majority of the sample is outperformed by these efficient farmers, which suggests that they are making greater use of the available technology. However, the relatively low mean technical efficiency scores under both variable and constant returns to scale indicate that the majority of farmers operate inefficiently. This is consistent with the results of Phiri and Yuan (2018), who observed that the mean technical efficiency score of tilapia farmers in Malawi was 47%, which is considerably lower than that of their counterparts in China. This implies that the majority of farmers in the sample are not optimizing resource use as effectively as the most efficient farmers.

The substantial opportunity for development in tilapia production in Bangladesh is suggested by the high level of technical inefficiency among the sampled farm households. The average technical efficiency scores of 77% under CRS and 83% under VRS indicate that farm households could substantially increase production using the same inputs. Technical efficiency could be enhanced by 23% under CRS and by 17% under VRS assumptions, on average. This suggests that there is a significant opportunity to improve productivity by rectifying the inefficiencies in current agricultural practices.

The higher mean SE score relative to the TE score under both VRS and CRS models suggests that technical inefficiency is a more significant issue than scale inefficiency when comparing technical and scale efficiency scores. This suggests that the inefficiency of tilapia productivity is more a result of insufficient farm management practices than of the size of the farm. The efficiency of tilapia production could be considerably improved by enhancing the farm management practices of inefficient farmers, which would allow for a higher output with the same inputs. Dissemination of optimal farm management practices through extension services could enhance the efficiency scores of farm households, resulting in improved overall productivity in tilapia farming, from an agricultural policy perspective.

The study shows that technical efficiency (TE) in tilapia production is largely determined by years of experience and farming training, although climate and loan availability also have a significant impact. Higher technical efficiency is positively correlated with experience, as demonstrated by both constant returns to scale (CRS) and variable returns to scale (VRS) models, which indicate that more efficient farming is accomplished by experienced farmers. This connection supports the findings of Anh et al., (2018), who stress that management expertise and practical knowledge acquired by aquaculture experience lead to increased efficiency.

The findings showed that technical efficiency is positively impacted by credit availability as well. This result is consistent with research by Manurung et al. (2021) and Sumon et al. (2022), which highlights the importance of credit in removing financial obstacles. With credit, farmers can expand, innovate, and invest in critical resources such as inputs, machinery, and infrastructure that ultimately boost both technical efficiency and productivity. These findings suggest that, to foster sustainable growth in aquaculture, governments should prioritize enhancing access to credit.

On the other hand, technical efficiency is negatively impacted by climate. This result is in line with Rahman et al. (2021) and Nguyen et al. (2018), who point out that climate-related issues, such as flooding and rising salinity, can drastically reduce efficiency. Extreme weather, temperature swings, and variations in water quality are examples of unfavorable conditions that hinder tilapia development and health, which lowers productivity. Tilapia farmers may need to use adaptation measures including making investments in robust infrastructure and enhancing water management in order to mitigate these climate risks. Together, these observations show that in order to improve technical efficiency and resilience in tilapia production, public policies supporting training, finance access, and climate adaption strategies are required.

The empirical results regarding the efficiency of tilapia aquaculture are consistent with economic theories of human capital theory and resource optimization. The need to optimize output with available inputs is underscored by inefficiencies among producers, while technical efficiency is enhanced by experience, training, and credit access, thereby bolstering human capital theory. The significance of sustainable practices is emphasized by the detrimental effects of climate change on efficiency. These findings indicate that the efficiency of tilapia farming can be considerably improved through policy interventions that enhance human capital, financial support, and climate change strategies. This can result in improved resource allocation, increased productivity, and economic resilience in the aquaculture sector.

Policies must combine ecological sustainability and social welfare in order to increase the efficiency of tilapia production and solve environmental and social-ecological issues. Reducing feed waste, improving water management, and utilizing environmentally friendly inputs are examples of sustainable techniques that can boost production while lowering negative environmental effects including nitrogen loading and eutrophication. Adaptive water management techniques and climate-resilient infrastructure are also necessary to handle climatic issues like flooding and increasing salinity.

Growing tilapia production is also a major source of revenue in rural areas. Farmers can earn more money by adopting new technologies, getting training, and improving technical efficiency. But for rural development to be equitable, governments need to prioritize affordable financing, smallholder support, and inclusive training in order to alleviate socioeconomic inequities. Social-ecological resilience can be improved through stakeholder participation and community-based tactics, guaranteeing more fair and sustainable production.

However, there are numerous constraints within the broader economic context that must be taken into account, despite the potential for efficiency enhancements. Consumer behavior and tilapia pricing can be substantially affected by market fluctuations, policy changes, and economic downturns. For example, price stability and profitability for producers may be impacted by abrupt fluctuations in market demand or disruptions in the supply chain. Operational costs and resource access may be affected by policy changes, such as new regulations or subsidy modifications. Farmers' capacity to invest in efficiency-enhancing practices may be restricted by economic downturns, which can exacerbate financial constraints. Consequently, in order to ensure the tilapia aquaculture industry's long-term growth and stability, stakeholders must remain adaptable and responsive to broader economic dynamics.

6 Conclusion

The prevalence of tilapia fish in Bangladesh is on the rise as a result of favorable environmental factors and consumer preferences. Therefore, it is imperative to identify the primary factors that affect the technical efficiency of tilapia farmers. Data Envelopment Analysis (DEA) is employed in this investigation to determine efficiency and identify the factors that contribute to inefficiencies among tilapia producers. The results indicate a substantial potential for increased output, as they disclose significant technical inefficiency in tilapia production. The significant issue of resource misallocation is indicated by the higher average scale efficiency scores in comparison to technical efficiency scores. According to Tobit regression models, technical efficiency is significantly influenced by years of experience, participation in training programs, and enhanced access to credit. This implies that productivity could be improved through targeted interventions in these areas.

The analysis of DEA-estimated technical and scale efficiency scores shows that a mere minority of tilapia farm households achieve optimal performance by effectively utilizing resources and technology. The results showed a mean TE of 0.77 under CRS, 0.83 under VRS, and a mean SE of 0.92, suggesting that most inefficiencies stemmed from technical rather than scale-related issues. The primary cause of this inefficiency is the inadequacy of farm management practices, rather than the size of the property. It is imperative to implement policies that prioritize the dissemination of optimal agricultural management practices through extension services, improve access to credit, and enhance training. These interventions have the potential to result in substantial productivity and profitability improvements for producers, a more stable supply chain for retailers, and increased economic resilience within the aquaculture sector.

The research is consistent with classical economic theories, underscoring the significance of investing in human resources and optimizing output with available resources. It emphasizes the detrimental effects of climate change on efficiency, which requires the implementation of sustainable practices. Credit access, climate-resilient infrastructure, and farmer training should be the primary focus of policymakers. In order to assess the long-term effects of interventions, future research should broaden its geographical scope and incorporate longitudinal studies. It is imperative to conduct a more comprehensive analysis of variables such as disease management, technology adoption, socio-economic conditions, market dynamics, and supply chain disruptions. Robust insights are recommended for policymakers, agricultural services, and financial institutions to support sustainable tilapia aquaculture, and advanced methodologies such as logit estimation and SEM are recommended.

Conflicts of interest

All authors confirm that they have read and approved the content of the submitted article. They also declare that there are no conflicts of interest among the authors or with the publication ethics of the journal.

Data availability statement

The datasets generated and analyzed during this study are accessible from the corresponding author upon reasonable request.

Author contribution statement

This work was carried out in collaboration among all authors.

Shah Mahmud Sumon: Contributed to the study's conception, design, data curation, analysis, and visualization, and wrote the original draft.

Mohammad Sabbir Hossain: Conducted analysis and contributed to the writing process through reviewing and editing.

Md. Nezum Uddin: Participated in writing the methodology, and contributed to review and editing.

Badiuzzaman: Conducted investigations, allocated resources, provided supervision, and participated in writing through review and editing.

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