Production efficiency and managerial inertia in *Oreochromis niloticus* (Linnaeus 1758) aquaculture: a Cobb-Douglas analysis

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Abstract. Study analysed the production efficiency and managerial inertia affecting Nile tilapia, *Oreochromis niloticus* (Linnaeus, 1758) aquaculture in Pandeglang Regency, Banten Province, Indonesia. A quantitative survey was conducted involving 94 small-scale tilapia farmers selected purposively from 35 sub-districts between May and July 2025. A Cobb-Douglas production function model was applied to evaluate the effects of pond area, fingerlings, feed quantity, labour, and farming experience on production output. The model was estimated using ordinary least squares (OLS) regression, while diagnostic tests were conducted to ensure model validity. The results showed that feed quantity was the only production factor with a statistically significant positive effect on tilapia output ($\beta = 0.833$; $p < 0.001$), indicating that feed management remains the principal determinant of productivity in extensive farming systems. In contrast, farming experience showed a negative and non-significant coefficient ($\beta = -0.010$), suggesting the presence of managerial inertia, where experienced farmers tend to rely on traditional production practices and exhibit low adoption of technological innovation. The total production elasticity was 0.972, indicating decreasing returns to scale and confirming that farming operations were indicating decreasing returns to scale and confirming that farming operations were operating within the rational production region (Stage II). Allocative efficiency analysis demonstrated that feed and labour inputs were under-utilised, whereas pond area and fingerlings were inefficiently allocated. Production projections for 2024-2030 indicated a stable upward trend in production output and economic value under current management assumptions. The findings highlight the importance of improving feed efficiency, strengthening extension services, and promoting technology adoption to enhance the sustainability and competitiveness of small-scale tilapia aquaculture.
Keywords: allocative efficiency,production function analysis, input elasticity, small-scale fish farming, freshwater aquaculture farming,production economics.

Introduction. Freshwater aquaculture has experienced progressive and accelerating growth globally. Recent studies have shown that sustainable aquaculture development increasingly depends on technological innovation, digital monitoring systems, and adaptive farm management practices to improve productivity and environmental efficiency (Huang 2025). The Food and Agriculture Organization of the United Nations (FAO 2024) reported that, for the first time in history, total aquaculture production (130.9 million tons) surpassed wild capture fisheries output. In Indonesia, the average annual growth rate of freshwater aquaculture production from 2020 to 2024 reached 5.95%, outpacing marine capture fisheries which grew at 3.60% annually (Republic of Indonesia 2020). This trajectory presents substantial developmental opportunities for freshwater fish species, particularly Nile tilapia *Oreochromis niloticus* (Linnaeus, 1758), whose production has been continuously promoted through intensification programs by the Directorate General of Aquaculture in Indonesia (MMAF 2023).

O. niloticus represents one of the most economically significant aquaculture commodities in Indonesia, with considerable potential for both domestic consumption and export markets, as an extensively cultivated species, *O. niloticus* is characterized by rapid growth, ease of reproduction, broad environmental adaptability, and high market demand (FAO 2024). However, the empirical reality of aquaculture in rural Indonesia remains dominated by small-scale, extensive farming systems, characterised by conventional technology, limited access to capital, technology, information, and markets, and comparatively low productive capacity (Sinha et al 2025).

Pandeglang Regency contributes 75.42% of total *O. niloticus* production in Banten Province, with a positive annual growth trend of 4.48% (Fisheries Agency of Pandegalng Regency 2025) Despite this significant production share, the performance of aquaculture in the study area is constrained by the predominance of extensive farming systems and suboptimal farm management practices. Although production volumes have shown an upward trend, farmer welfare remains pressured by the volatility of input and output prices, as reflected in the fluctuating Aquaculture Exchange Rate Index (NTPi). Furthermore, production continues to exhibit notable inter-farmer and inter-district variability, indicating systemic allocative inefficiency in production factor utilisation.

Among the most pressing constraints is the high and increasing cost of commercial feed (pellets), which constitutes between 75.5 and 91.2% of total aquaculture production costs (Nunes et al 2022). The dependence on externally sourced feed, combined with insufficient capital access and limited managerial capacity, perpetuates a cycle of suboptimal production and income instability. To address these structural inefficiencies, it is imperative to analytically determine the optimal combination of production factors through a rigorous economic modelling framework.

The Cobb-Douglas production function is widely employed in agricultural and aquaculture economics to model the relationship between factor inputs and output, estimate production elasticities, evaluate allocative efficiency, and generate medium- to long-term production projections (Kembauw et al 2022). Its log-linear specification facilitates straightforward statistical estimation and economic interpretation, rendering it particularly suitable for applied studies in developing-country farming contexts.

Although numerous studies have examined the determinants of aquaculture productivity using Cobb-Douglas production models, relatively limited attention has been given to the behavioural dimension of production inefficiency, particularly managerial inertia among small-scale fish farmers in developing countries. Most previous studies have primarily focused on technical variables such as feed, seed quality, stocking density, and labour utilisation, while overlooking farmers' resistance to innovation and adaptive management practices. In Indonesia, empirical evidence linking farming experience with technological inertia in aquaculture production remains scarce. Therefore, this study contributes to the literature by integrating the concept of managerial inertia into aquaculture production economics and by providing empirical evidence from small-scale *O. niloticus* farming systems in Indonesia. Previous studies on aquaculture production efficiency have primarily focused on technical input optimisation, while behavioural constraints such as managerial conservatism and resistance to innovation remain underexplored, particularly among small-scale fish farmers in developing countries (Sumon et al 2025).

The objectives of this study were: (1) to describe the sociodemographic characteristics of respondent fish farmers; (2) to analyse the partial and simultaneous effects of production input factors on Nile tilapia production; (3) to estimate the production elasticity of each input factor; (4) to assess the economic efficiency of input factor utilisation; and (5) to project *O. niloticus* production in Pandeglang Regency for the period 2024 to 2030. The findings are expected to contribute both theoretically to the literature on production economics in aquaculture and practically to regional policy formulation and strategic planning for the sustainable development of *O. niloticus* farming.

Material and Method

Research area. His study was conducted in Pandeglang Regency, Banten Province, Indonesia (Figure 1).

Figure 1. Location of the study area in Pandeglang Regency, Banten Province, Indonesia. The map shows the distribution of surveyed *Oreochromis niloticus* farms included in the study.

The regency was purposively selected due to its strategic role as the primary producer of *O. niloticus* in Banten Province, accounting for approximately 75.42% of provincial production. Geographically, Pandeglang covers 29.63% of the total land area of Banten Province and is economically dominated by the agricultural and fisheries sectors. The aquaculture sub-sector is predominantly composed of small-scale extensive farming operations with limited management sophistication. Primary data were collected over a three-month period from May to July 2025, spanning 35 sub-districts across the regency.

Sampling and data collection. A quantitative research approach employing a structured survey method was used. Data were collected through questionnaire instruments, field observations, and in-depth interviews with farmer respondents. The sampling method applied was non- probability purposive sampling, in which respondents were selected based on predetermined inclusion criteria relevant to the study objectives.

The population comprised all *O. niloticus* farmers registered across 35 sub-districts in Pandeglang Regency, totalling 1,480 individuals. The inclusion criteria for respondent selection were: (1) minimum of two years of *O. niloticus* farming experience; (2) micro-scale operation using an extensive system with small earthen ponds; (3) relatively low income from aquaculture; (4) aquaculture practised as a secondary livelihood activity; and (5) family members constituting the primary labour force. The sample size was determined using the Slovin formula:

$$n=N / (N*d^2 + 1)$$

where:
n = sample size;
N = total population (1,480);
d = acceptable margin of error (10%).

This yielded a sample of 94 respondents.

Proportional allocation of respondents across sub-districts was performed using a stratified sampling formula (Riduwan 2014).

Analytical model. Data analysis employed the Cobb-Douglas production function, expressed in its general multiplicative form as. Recent aquaculture studies have continued to apply Cobb-Douglas and stochastic frontier approaches to evaluate production efficiency and input allocation in tilapia farming systems (Cohen 2014).

$$Y = 0.9287\ X1^{0.075}\ X2^{0.006}\ X3^{0.833}\ X4^{0.068}\ X5^{-0.010}\ \mu$$

Where:
Y = *O. niloticus* production (kg per farming cycle);
X1 = pond area (m^2);
X2 = number of fingerlings (individuals per farming cycle);
X3 = feed quantity (kg per farming cycle);
X4 = labour (man-days equivalent, HKP);
X5 = farming experience (years);
a = model constant;
$\beta 1$-$\beta 5$ = regression coefficients (production elasticities of respective inputs);
μ = disturbance term.

The model was log-linearised and estimated using multiple linear regression via ordinary least squares (OLS). Statistical tests conducted included: the partial t-test (significance level $\alpha = 0.05$, df = 88, t-table = 1.987) to assess the individual contribution of each input; the simultaneous F-test (F-table = 2.31, df1 = 5, df2 = 88) to evaluate the joint significance of all production inputs; and the coefficient of determination (R^2) as a goodness-of-fit measure.

Allocative efficiency was evaluated using the ratio of the Value of Marginal Product (VMP / NPM) to the unit price of each input factor. Efficiency is achieved when NPMxi / Pxi = 1. A ratio greater than 1 indicates under-utilisation of the input (not yet efficient), while a ratio less than 1 indicates over-utilisation (inefficient). Production projections for 2024-2030 were generated by applying the estimated Cobb-Douglas model with proportional annual increments in input usage, under the assumptions of stable input prices and no significant inflationary adjustments.

Diagnostic tests of the regression model. To ensure the robustness and validity of the Cobb-Douglas regression model, several classical assumption tests were conducted prior to interpretation of the regression results. Multicollinearity among independent variables was assessed using the variance inflation factor (VIF), with VIF values below 10 indicating the absence of serious multicollinearity. Heteroscedasticity was examined using the Breusch-Pagan test, while normality of residuals was evaluated using the Kolmogorov-Smirnov test. These diagnostic procedures were applied to ensure that the estimated model satisfied the assumptions of OLS regression.

Research limitations. This study has several limitations. First, the analysis relied on cross-sectional survey data collected during a single production period, which may not fully capture seasonal production variability. Second, the production projections were based on constant input-price assumptions and did not incorporate inflation, climate variability, or market shocks. Third, the concept of managerial inertia was inferred indirectly from the regression coefficient of farming experience rather than measured using behavioural indicators or psychometric instruments. Future studies are therefore recommended to incorporate longitudinal data and behavioural innovation-adoption variables.

Results

Respondent characteristics. The sociodemographic profile of the 94 surveyed *O. niloticus* farmers in Pandeglang Regency is presented in Table 1.

The majority of respondent farmers were of productive age and relied predominantly on family labour in their aquaculture activities. Most farmers had low to moderate levels of formal education, indicating that practical farming knowledge was generally acquired through experience rather than formal technical training. Educational background and farming experience may influence farmers' ability to adopt improved aquaculture technologies, access production-related information, and implement efficient farm management practices. Farmers with limited educational exposure may face difficulties in adopting innovation-based production systems, particularly those involving modern feed management, water quality monitoring, and technology-assisted farming practices.

Most respondents had moderate farming experience, suggesting that they possessed substantial practical knowledge of tilapia farming. However, farming experience alone may not necessarily improve productivity when it is not accompanied by technological adaptation and continuous capacity development. This condition may partially explain the persistence of managerial inertia observed in the study area. The dominance of family labour reflects the small-scale and household-based nature of *O. niloticus* farming in Pandeglang Regency. While family labour may reduce operational costs, limited labour specialization may constrain production efficiency, particularly in feed management and pond maintenance activities.

Table 1

Socio-demographic characteristics of respondent farmers

Characteristic	*Category*	*Frequency (n)*	*Percentage (%)*
Age (years)	< 15	0	0
	15-64	89	94.68
	> 65	5	5.32
Total		94	100
Sex	Male	94	100
	Female	0	0
Total		94	100
Formal education	Primary school (SD)	11	11.70
	Junior high school (SMP)	42	44.68
	Senior high school (SMA)	27	28.72
	Diploma (D3)	2	2.13
	Bachelor's degree (S1)	12	12.77
Total		94	100
Extension services received (times)	Low (≤ 1)	65	69.15
	Moderate (2-3)	21	22.34
	High (> 3)	8	8.51
Total		94	100
Training received (times)	Low (≤ 1)	76	80.85
	Moderate (2-3)	15	15.96
	High (> 3)	3	3.19
Total		94	100
Farming experience (years)	Low (1-4)	29	30.85
	Moderate (5-10)	63	67.02
	High (> 10)	2	2.13
Total		94	100
Number of family dependants	Small (1-3)	65	69.15
	Moderate (4-6)	24	25.53
	Large (> 6)	5	5.32
Total		94	100
Primary occupation	Primary (aquaculture)	7	7.45
	Secondary (side income)	87	92.55
Total		94	100
Labour utilised	Low (1-2)	75	79.79
	Moderate (3-4)	17	18.08
	High (> 5)	2	2.13
Total		94	100

Partial effects of production input factors (t-test). The partial effects of each production input on *O. niloticus* output were assessed using t-tests at the 5% significance level (*t-table* = 1.987, df = 88). Results are presented in Table 2.

Table 2

Production elasticity and significance of production input variables

Variable	*Regression coefficient (βi)*	*t-calculated*	*t-table*	*Significance*
Pond area (X1)	0.075	1.232	< 1.987	0.221
Number of fingerlings (X2)	0.006	0.097	< 1.987	0.923
Feed quantity (X3)	0.833	12.878	> 1.987	0.000
Labour (X4)	0.068	1.343	< 1.987	0.183
Farming experience (X5)	-0.010	-0.231	< 1.987	0.818

Feed quantity (X3) was the only production input with a statistically significant positive effect on Nile tilapia production. This finding indicates that feed management remains the primary determinant of productivity in small-scale extensive aquaculture systems. Economically, the elasticity coefficient of 0.833 implies that a 1% increase in feed input was associated with an estimated 0.833% increase in production output, assuming other inputs remained constant. This result confirms the central role of feed in fish growth, biomass accumulation, and feed conversion efficiency.

Biologically, *O. niloticus* growth is highly dependent on the availability of adequate nutrients, particularly protein and energy intake. In extensive farming systems, natural food availability is often insufficient to support optimal growth, making commercial feed a critical production input. In addition, feed represents the largest operational cost component in aquaculture production; therefore, feed allocation strongly influences both productivity and economic performance. In contrast, pond area (X1), fingerlings (X2), and labour (X4) showed positive but statistically non-significant effects on production. Several factors may explain these findings. First, the utilization of these inputs may remain below their optimal levels, resulting in under-utilisation of production capacity. Second, substantial variability in stocking density, seed quality, and labour skills among farmers may reduce the consistency of their effects on production output. Third, the predominance of household-based labour without task specialization may limit management efficiency, particularly in feed management, water quality control, and pond maintenance.

Simultaneous effects of production inputs (F-test). The simultaneous influence of all five production inputs was assessed using analysis of variance (ANOVA). Results are presented in Table 3.

Table 3

Simultaneous effects of production input variables on *Oreochromis niloticus* production

Model	Df	*F-calculated*	*F-table*	Significance
Regression	5	103.783	> 2.31	0.000
Residual	88			
Total	93			

The F-test results indicated that all production inputs jointly exerted a statistically significant effect on *O. niloticus* production (F = 103.783; $p < 0.001$). The coefficient of determination ($R^2 = 0.855$) showed that approximately 85.5% of the variation in production output could be explained by the production variables included in the model, namely pond area, fingerlings, feed quantity, labour, and farming experience.

This relatively high R^2 value indicates that the model has strong explanatory power and is capable of representing the production conditions of small-scale *O. niloticus* farming in the study area. Practically, the findings suggest that production performance is highly dependent on the management and allocation of key production inputs. Therefore, improving input management strategies, particularly feed allocation and labour utilization, may substantially enhance farm productivity and operational efficiency. The remaining 14.5% of unexplained variation may be associated with external factors not included in the model, such as water quality, disease incidence, climatic variability, and farmer-specific management practices.

Production elasticity. Based on the estimated log-linearised Cobb-Douglas regression model, the production function for *O. niloticus* farming in Pandeglang Regency.

Table 4

Production elasticities derived from the regression coefficients are presented

Variable (input factor)	*Elasticity (βi)*	*t-calc.*	*t-table*	*Sig.*	*Interpretation*
Pond area (X1)	0.075	1.232	1.987	0.221	Positive, non- significant
Fingerlings (X2)	0.006	0.097	1.987	0.923	Positive (very small), non-significant
Feed quantity (X3)	0.833	12.878	1.987	0.000	Dominant and significant
Labour (X4)	0.068	1.343	1.987	0.183	Positive, non-significant
Farming experience (X5)	-0.010	-0.231	1.987	0.818	Negative and non-significant
Total production elasticity (εp)	0.972				Stage II – Rational Region
		$R^2 = 0.855$			

Table 4 indicates that the most dominant production factor in enhancing *O. niloticus* output is feed quantity (X3), with an elasticity of 0.833, implying that a proportional increase in feed input leads to a substantial increase in production. Although pond area (X1), fingerlings (X2), and labour (X4) showed positive elasticity coefficients, their effects on production were statistically non-significant and relatively small. From a practical perspective, these findings suggest that simply increasing the quantity of these inputs may not automatically improve production performance unless accompanied by improvements in management quality and production efficiency.

The small elasticity coefficient of pond area indicates that expanding pond size alone may have limited impact on productivity under extensive farming conditions. This may occur because production efficiency is more strongly influenced by feed management and operational practices than by physical pond expansion. Similarly, the very small elasticity value for fingerlings suggests that increasing stocking numbers without improving seed quality, stocking density management, and survival rates may not significantly enhance production output. In small-scale aquaculture systems, variability in seed quality and non-standardized stocking practices may reduce production efficiency.

The non-significant elasticity of labour indicates that additional labour input does not necessarily improve farm productivity. This condition may reflect the dominance of family- based labour systems with limited task specialization and technical skills. Therefore, improving labour quality and management capacity may be more important than simply increasing the number of workers. These findings imply that small-scale tilapia farmers should prioritize improving input quality, management efficiency, and technology adoption rather than focusing solely on increasing input quantities. The negative elasticity observed for farming experience (X5) reflects the presence of managerial inertia.

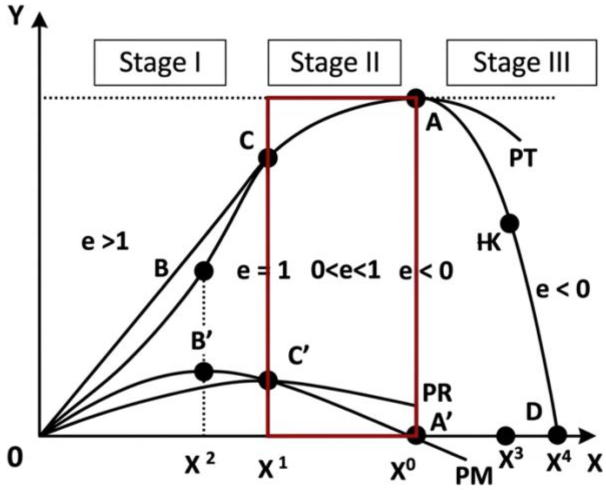

Figure 2. The law of diminishing returns: the relationship between a single input and a single output (Production function curve with three stages of the production process at the research site).

The total production elasticity (εp = 0.972) satisfies the condition 0 < εp < 1. In this stage, each additional unit of input continues to generate a positive marginal product, meaning that output increases with additional inputs, though at a diminishing rate. This characterises decreasing returns to scale, confirming that the existing combination of production factors is economically rational and that *O. niloticus* farming in Pandeglang Regency is viable for sustained continuation. Farmers operating in Stage II have no rational incentive to reduce their inputs, as the marginal product of every input remains positive.

Allocative efficiency of production inputs. The allocative efficiency analysis showed that feed (X3) and labour (X4) were under-utilised, as indicated by efficiency ratios greater than one. From a practical perspective, this finding suggests that farmers may still increase production and profitability by improving feed allocation and labour management. Additional feed input, when applied efficiently, may enhance fish growth and biomass production, while better labour allocation may improve pond maintenance, feeding schedules, and water quality management. However, the practical implication is not merely increasing input quantity, but also improving input quality and management efficiency. For example, improving feeding strategies, feed conversion efficiency, and labour specialization may provide greater productivity gains than indiscriminate increases in input use.

In contrast, pond area (X1), fingerlings (X2), and farming experience (X5) were categorized as inefficient or over-utilised inputs. This finding indicates that increasing these inputs without improving management practices may not significantly increase production output. Expanding pond area without adequate feed management, water quality control, and stocking regulation may reduce operational efficiency. Similarly, increasing the number of fingerlings may not improve production if seed quality remains inconsistent or stocking density exceeds optimal carrying capacity. The negative efficiency value associated with farming experience suggests that long-term farming practices may become less adaptive when farmers rely heavily on traditional management approaches and show limited responsiveness to technological innovation. These findings imply that small-scale *O. niloticus* farmers should focus not only on increasing production inputs, but also on improving technical efficiency, management quality, and innovation adoption to achieve sustainable productivity improvements. Results are presented in Tables 5 and 6.

Table 5

Allocative efficiency analysis of production inputs in small-scale *Oreochromis niloticus* aquaculture

Input	*Coeff. (βi)*	*Mean input used*	*Marginal product (MP)*	*Input unit price (USD)*	*Value of marginal product / NPM*
Pond area (X1)	0.075	481.56 m²	0.097 kg m^{-2}	0.67	0.2026
Fingerlings (X2)	0.006	3,349.52 ind.	0.001 kg $ind.^{-1}$	0.022	0.0699
Feed (X3)	0.833	854.91 kg	0.608 kg kg^{-1}	0.67	1.2676
Labour (X4)	0.068	2.31 HKP	18.383 kg HKP^{-1}	7.02	3.6767
Farming experience (X5)	-0.010	5.93 years	-1.053 kg $year^{-1}$	5,127.74	-0.0003

Table 6

Allocative of production inputs in small-scale *Oreochromis niloticus* aquaculture

Input	*Efficiency ratio (NPMxi / Pxi)*	*Efficiency status*
Pond area (X1)	0.2026	< 1 → Over-utilised (Inefficient)
Fingerlings (X2)	0.0699	< 1 → Over-utilised (Inefficient)
Feed (X3)	1.2676	> 1 → Under-utilised (Not yet efficient)
Labour (X4)	3.6767	> 1 → Under-utilised (Not yet efficient)
Farming experience (X5)	-0.0003	< 1 → Inefficient (negative marginal product)

Feed (X3) and labour (X4) recorded efficiency ratios greater than 1 (NPM/P = 1.2676 and 3.6767, respectively), indicating that these inputs are under-utilised relative to their optimal allocation. In microeconomic theory, an efficiency ratio exceeding unity implies that the value generated by an additional unit of the input exceeds its cost, meaning that farmers could increase their profit by adding more of these inputs until the ratio reaches 1. Pond area (X1), number of fingerlings (X2), and farming experience (X5) showed efficiency ratios below 1, indicating over-utilisation or inefficient application. The negative efficiency value for farming experience reflects its negative marginal product under current conditions—a phenomenon elaborated further in the Discussion section.

Production projection (2024-2030). Based on the estimated Cobb-Douglas production function, projections of production input requirements and output volume per farmer in Pandeglang Regency were generated for 2024-2030. The production projections presented in this study should be interpreted as scenario-based estimates rather than precise forecasts. The projections assume relatively stable production conditions and constant relationships between production inputs and outputs over time. External factors such as climate variability, disease outbreaks, feed price fluctuations, and policy changes may significantly influence future production trajectories. Assumptions applied include: stable input prices consistent with 2025 levels; annual proportional increments in input quantities equivalent to one-fold of the baseline year (2024); and no inflationary adjustments. Results are presented in Tables 7, 8, and 9.

The negative coefficient associated with farming experience should not be interpreted as evidence that experience is inherently detrimental to productivity. Instead, the result may indicate a behavioural rigidity phenomenon in which experienced farmers become increasingly dependent on traditional production routines and less willing to adopt improved management practices. Similar patterns have been observed in small-scale aquaculture systems in developing countries where older production experience is often associated with lower responsiveness to technological change and extension programmer.

Table 7

Projected production input requirements for *Oreochromis niloticus* farming (2024-2030)

Input	*2024 (existing condition)*	*2025*	*2026*	*2027*	*2028*	*2029*	*2030*
Pond area (m^2)	97,578	195,156	292,734	390,313	487,891	585,469	683,047
Fingerlings (individuals)	234.188	468.375	702.562	936.750	1,170.936	1,405.125	1,639.313
Feed (kg)	1,083.768	2,167.535	3,251.303	4,334.071	5,418.838	6,502.606	7,586.374
Labour (HKP)	8,493	16,986	25,479	33,973	42,470	50,959	59,452
Experience (years)	-0.0017	-0.0034	-0.005	-0.007	-0.009	-0.010	-0.012

Table 8

Projected production volume farmer (2024-2030)

Year	*Production volume (kg)*
2024	966.27
2025	1,932.54
2026	2,898.80
2027	3,865.07
2028	4,831.34
2029	5,797.61
2030	6,763.88

Table 9

Projected production value farmer (2024-2030)

Year	*Production value per farmer (USD)*
2024	1,248.55
2025	2,621.95
2026	4,129.57
2027	5,781.40
2028	7,588.09
2029	9,561.00
2030	11,712.22

The projection results indicate a relatively stable and linear upward trend in both production volume and production value from 2024 to 2030. This trend suggests that *O. niloticus* aquaculture in Pandeglang Regency has considerable potential for future expansion under current production conditions and management assumptions. From a practical perspective, these projections may assist farmers and policymakers in planning future input requirements, particularly feed, labour, and seed allocation. The increasing production trend also indicates potential opportunities for long-term investment, farm expansion, and income growth within the small-scale aquaculture sector.

Economically, the projected increase in production value suggests that improving production efficiency and management practices may contribute to higher farm profitability and stronger economic sustainability. However, achieving these projected outcomes will require continuous improvements in feed management, technology adoption, and farmer capacity development.

Discussion. Among the five production factors examined, feed quantity (X3) was the only input with a statistically significant and positive effect on *O. niloticus* output, recording an elasticity of 0.833. This implies that a 1% increase in feed input raises production by approximately 0.833%, confirming that feed is the principal determinant of productivity in the extensive farming systems studied. This finding accords with the principles of feed efficiency and the attainment of an optimal feed conversion ratio (FCR) in aquaculture (Mohammady et al 2023), which reinforces past literature demonstrating that feeding strategies are primary determinants of growth performance and feed utilization in *O.*

niloticus (Asri et al., 2013; Konnert et al 2022).

The pronounced influence of feed reflects both its biological and economic importance. Because the availability of natural food in pond systems is limited, growth depends heavily on supplementary feeding; at the same time, feed represents the single largest operational cost in fish farming, accounting for between 75.5 and 91.2% of total production costs (Nunes et al 2022) Effective feed management is therefore essential not only for improving fish growth and the FCR but also for sustaining farm profitability.

In contrast, pond area (X1), fingerlings (X2), and labour (X4) exhibited positive but statistically non-significant elasticities, indicating that these factors are not yet being utilised efficiently. Such inefficiencies are likely attributable to suboptimal seed quality, inappropriate stocking density, and the limited technical skills of available labour (Halver et al 2021). The non-significant contribution of pond area diverges from studies reporting a significant effect of pond size on productivity (Dewi et al 2018), which suggests that the empirical conditions at the study site differ from those settings. The weak effect of labour likewise reflects the predominance of household labour that lacks specialised competence in feed management, water quality control, and pond maintenance (Kembauw et al 2022). Taken together, these results imply that enhancing management quality and technical capacity is more consequential than simply increasing the quantity of inputs.

The negative elasticity of farming experience (X5) is the most theoretically salient result, as it signals the presence of managerial inertia, namely a tendency among experienced farmers to rely on conventional practices and to resist technological innovation, which can lead to stagnation or even a decline in production performance (Moradi et al 2021). Within extensive systems characterised by limited technological inputs, experience does not necessarily translate into higher productivity. This interpretation is consistent with the stochastic frontier perspective, in which socio-economic attributes such as experience may shape the level of technical inefficiency (Amri et al 2024); indeed, experience may even contribute negatively to efficiency when it is not accompanied by capacity building and innovation adoption (Chandravanshi et al 2025).The concept of managerial inertia has been examined extensively in the organisational and innovation literature (Godkin & Allcorn 2008).

In the study area, many farmers continued to apply conventional methods, including non-standardised feeding regimes, the stocking of mixed-sex fingerlings, and informal water quality management. Consequently, accumulated experience alone did not improve productivity unless it was accompanied by innovation adoption, extension support, and adaptive management. Comparable findings have been reported elsewhere, with education, access to information, and managerial capacity proving more decisive than experience per se in raising aquaculture efficiency (Amri et al 2024).

This pattern is particularly pertinent in extensive aquaculture systems, which are typified by low external-input use, informal management, and limited exposure to digital or technology-based approaches. Under such conditions, managerial inertia may erode adaptive capacity and constrain productivity gains despite increasing experience, mirroring the behavioural resistance observed in other small-scale farming systems where producers maintain conventional practices even when more efficient technologies are available. The propensity to adopt new technologies is itself shaped by farmers' educational background, digital literacy, institutional support, and perceived economic risk (Radosavljevic et al 2025). Recent advances in smart aquaculture reinforce this point, demonstrating that digital technologies, including IoT-based monitoring systems and AI-assisted management, can enhance feed efficiency and production performance in tilapia farming systems (Huang 2025).

The total production elasticity ($\varepsilon p = 0.972$) satisfies the condition $0 < \varepsilon p < 1$, placing the farming operation in Stage II of the production function, the rational region of production, and indicating decreasing returns to scale (Debertin, 2012). In practical terms, output continues to rise with additional inputs but at a progressively diminishing rate, which underscores the need for farmers to optimise the allocation of production factors in order to improve efficiency and profitability.

The allocative efficiency analysis further revealed that feed (X3) and labour (X4) were under-utilised, whereas pond area (X1), fingerlings (X2), and farming experience

(X5) were inefficiently allocated. This indicates that improvements in feed management and labour quality offer scope for raising both production and profitability.

The production projections derived from the model showed a stable upward trend in both production volume and economic value through 2030, signalling considerable development potential for *O. niloticus* farming in the study area. Realising these projected gains will nonetheless depend on sustained improvements in feed efficiency, farmer skills, and technology adoption.

The policy implications of these findings are clear and actionable. The Pandeglang Regency Department of Fisheries should prioritise four measures: (1) establishing community-level feed production units that use locally sourced raw materials to reduce input costs; (2) intensifying extension and capacity-building programmes that specifically target the managerial-inertia barrier, with particular attention to younger, more innovation-receptive farmers; (3) strengthening the role of the Freshwater Fish Seed Centre (BBIAT) in supplying certified, high-quality monosex tilapia fingerlings; and (4) facilitating a quadruple-helix partnership among farmers, government, academia, and the private sector to improve access to capital, market linkages, and technology transfer. Strengthening farmer capacity through innovation-oriented extension is essential to accelerate technology adoption and to narrow productivity gaps in small-scale aquaculture systems (Ohashi et al 2024).

Conclusions. This study demonstrated that the Cobb-Douglas production function provides a robust framework for evaluating production efficiency and projecting future output in *Oreochromis niloticus* farming in Pandeglang Regency, Banten Province, Indonesia. Feed management emerged as the primary determinant of productivity, underscoring the critical importance of optimising input use in small-scale aquaculture operations. Overall, farming operations were found to function within the rational production region, though there remains substantial room for improved allocation of labour and feed resources.

Production projections indicate a stable upward trend, with output and economic value expected to grow steadily through 2030. These findings suggest that *Oreochromis niloticus* aquaculture in Pandeglang Regency holds significant potential for sustainable development and regional food security. To enhance efficiency, productivity, and economic returns, this study proposes four targeted strategic interventions: (1) strengthening farmer training and technology adoption programmes; (2) supporting local feed production to reduce operational costs; (3) improving access to certified fingerlings, capital, and market networks; and (4) encouraging product diversification and digital marketing to broaden farmer income streams and increase market competitiveness. These findings collectively underscore that improvements in resource management and operational practices are essential to sustaining the growth and competitiveness of tilapia aquaculture in the region.

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