

Article

Link Between Livelihoods and Technical Efficiency: Empirical Data from Pond-Based Grouper Aquaculture in Coastal Lamongan, Indonesia

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Abstract

This research studied the role of the fisheries sector, specifically pond-based grouper aquaculture, in coastal Lamongan, Indonesia, which is crucial for coastal food security and economy. Despite relatively high productivity, technical efficiency was not optimal because of its limited livelihood assets, which include human, natural, social, financial, and physical capital. The gap in ownership of these assets has resulted in technical efficiency variations across farmers and has affected both their livelihoods and environmental sustainability. Previous research has mostly focused on capture fisheries or non-grouper species, leaving a critical gap regarding the linkage between livelihood assets and technical efficiency in pond-based grouper aquaculture. This research measured livelihood asset levels, technical efficiency, and the effect of assets on efficiency, using quantitative data from 83 respondents representing the total 105 grouper farming households in coastal Lamongan. Livelihood assets were assessed through scoring and index analysis, technical efficiency was estimated using Stochastic Frontier Analysis (SFA), and the determinants of inefficiency were examined through Tobit regression with robust standard errors. The results found that the average livelihood asset index was 0.47 (moderate), with financial capital being the weakest component. Technical efficiency averaged 0.83, indicating efficient use of inputs while still allowing room for improvement. Natural capital (land area and water resources) and financial capital (income and savings) significantly affected technical inefficiency, whereas human, social, and physical capital did not. These findings emphasize the importance of strengthening the financial capital and the management of natural resources optimally to promote the efficiency and sustainability of grouper aquaculture in coastal Lamongan, Indonesia.



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Keywords: Sustainable Livelihood Framework; grouper aquaculture; efficiency analysis; Stochastic Frontier Analysis; livelihood-efficiency linkage; sustainability

1. Introduction

The aquaculture sector has developed into one of the main pillars of global food security [1–3]. According to FAO [4], nowadays more than 50% of the global fish supply derives from aquaculture, and Asia contributes nearly 90% of the total production. This growth not only increased the availability of animal protein but also provided jobs for more than 20 million coastal households in developing countries. However, at this figure, there

is a disparity in productivity between large and small-scale businesses. Many small-scale farmers have very limited access to capital, technology, and knowledge, preventing them from achieving optimal technical efficiency [5]. In the context of grouper aquaculture, global production has reached at least 155,000 tons valued at USD 630 million, with Indonesia contributing approximately 11% of total production [6]. Despite this economic significance, the sector faces sustainability challenges, including dependence on wild-caught seed and inefficient resource utilization.

In the pond-based grouper aquaculture in coastal Lamongan, Indonesia, a similar phenomenon occurs where high productivity is not always aligned with production efficiency. The core issue in this aquaculture is the limited livelihood assets owned by the farmers. According to the Sustainable Livelihood Framework, these assets form an “Asset Pentagon” where five capitals interact and influence each other in shaping livelihood outcomes [7,8]. These interrelated resources consist of human capital (education, skills, experience, and health), natural capital (land area, water resources, water availability, and climate change), social capital (social networks, participation in groups, access to information, and social support), financial capital (income, savings, credit/loans, and debt), and physical capital (land status, home status, equipment, vehicles). Research conducted by Ismail et al. [9] indicates that the sustainability of livelihood assets around conservation areas was not very high, with financial capital scoring only 23% and natural capital 29%, which directly contributed to the low productivity of fishermen. For grouper aquaculture in Indonesia, these capital limitations restrict farmers’ capacity to adopt eco-friendly technology and manage disease risks, leading to technical inefficiencies.

The Asset Pentagon concept emphasizes that these capitals do not function in isolation but rather interact dynamically—for instance, strong social capital can partially compensate for limited financial capital through mutual support networks and collective resource pooling, while high human capital enhances the effective utilization of physical capital. The disparity in both the availability and synergistic utilization of these assets for livelihood has led to differences in the efficiency of the farmers [10]. Understanding these asset interactions is critical because farmers with balanced and complementary assets may achieve higher efficiency than those with abundant but isolated resources.

Technical efficiency (TE) is defined as the capacity of a producer to extract the maximum output from a given mix of inputs [11]. In aquaculture contexts, studies have shown that TE can be influenced by multiple factors, including stocking density, feed management, water quality, and technology adoption. For instance, research in Indian shrimp farming reported an average TE of 0.90, indicating 10% potential for output increase without additional inputs [12], while a bioeconomic study in Taiwan revealed that environment-friendly technologies increased grouper productivity by 18.6 tons/ha while reducing power consumption by 1510 kWh/ha monthly [13]. These findings underscore the importance of technological innovation and efficient resource management in achieving optimal technical efficiency.

The situation of lower technical efficiency signifies that there is a waste of inputs, and that the production costs are high, which causes lower profit margins and, thus, the weakening of economic security for the farmers [11]. In addition, inefficient aquaculture practices could lead to further environmental pressures, such as water pollution, the degradation of pond ecosystems, and increased challenges for farmers in adapting to climate change [13]. These problems indicate that technical efficiency should be improved first if one wants to reach the goal of sustainable aquaculture in the coastal area [12].

A number of empirical studies have been attempting to determine the main factors of technical efficiency in the aquaculture industry. Islam et al. [14] discovered that the technical efficiency of Malaysian aquaculture systems was largely influenced by the farmers’

experience and training, as well as the quality of the seeds used. Ogundari [15] reported that education, training, stocking density, and access to loans contributed significantly to technical efficiency in Nigerian pond-based aquaculture, with an average TE of 81%, confirming the role of human and financial capital in increasing productivity. Adetoyinbo and Otter [16] reported that membership in a producer group had a positive influence on the technical efficiency of traditional fishermen in Nigeria by making it easier to get market information and technology, demonstrating that social capital, such as farmer groups and cooperatives, can serve as strategic tools to improve technical efficiency. These findings implicitly demonstrate the interactive nature of livelihood assets, where social capital (group membership) facilitates access to information and technology, thereby enhancing human capital and ultimately improving technical efficiency. However, Mitra et al. [17] noted that variations in efficiency among farmers can also be attributed to differences in aquaculture environment, including water quality and cultivation systems, suggesting that natural capital plays a crucial role alongside human and social factors.

However, all these studies are still limited to capturing fisheries or non-grouper aquaculture. The link between livelihood assets and their interactive effects on technical efficiency for grouper commodities in brackish pond systems is still rarely studied [6]. This indicates that there is a crucial research gap to fill given the differences in ecological, social, and economic factors between grouper aquaculture and other fisheries commodities.

This study provided a detailed picture of the connection between the farmers' livelihood capacity and the technical efficiency of pond-based grouper aquaculture systems in coastal Lamongan. The research has the objective to measure the livelihood assets of coastal pond-based grouper farmers in coastal Lamongan, to determine the technical efficiency of aquaculture businesses, and to examine how the balance and interaction among livelihood assets influence the technical efficiency of aquaculture. By employing the Asset Pentagon framework, this study investigates not only the individual contribution of each capital but also how assets interact synergistically, for instance, how social capital can compensate for financial capital constraints, or how human capital enhances the effective utilization of physical and natural resources. To this end, the research will be an empirical basis for the development of policies and interventions in fisheries that are focused on strengthening assets, fostering asset synergy, improving efficiency, and managing marine resources in a sustainable way. Moreover, it will be a useful addition to the literature on the uncharted area of the relationship between livelihood assets interactions and technical efficiency in aquaculture [18]. The research results will be highly significant for local governments, financial institutions, and fisheries training institutions in their quest for creating comprehensive and sustainable productivity enhancement strategies for small-scale farmers in Indonesia. Understanding these asset interactions will enable stakeholders to design more effective interventions that leverage existing strengths to compensate for resource limitations [19]. Also, this research, in turn, will provide a real contribution to enhancing the economic performance and social-ecological sustainability of the grouper aquaculture sector through the channeling of livelihood assets as a base for reinforcing the farmers' capacity, reducing production inefficiencies, and drawing up coastal fisheries development policies.

2. Methods

A quantitative method was employed in this research to examine the association between livelihood assets and technical efficiency in grouper fish farming in ponds. The reason for this methodology was that it enables an objective evaluation of the efficiency level and a ranking of farmers' technical performance based on different types of livelihood assets. Scoring and index were the methods used to evaluate the Livelihood assets [20], then Stochastic Frontier Analysis (SFA) to determine the technical efficiency, and finally,

Tobit regression with robust standard errors was used to investigate the effect of livelihood assets on technical efficiency.

2.1. Time and Location of Research

The study was conducted in June 2025 in Lamongan, East Java, Indonesia, popularly referred to as “Kampung Kerapu”. This area is recognized as the largest and one of the most important places for pond-based grouper aquaculture on the Java north coast and also in Indonesia. The research area was about ± 76 ha, from the pond to the beach was approximately 50–300 m. The chosen sites were based on the intensity of aquaculture activities, various technical practices, and the existence of production infrastructure such as water transport, access roads, and distribution facilities. The high concentration of research activities in this particular area allowed the researcher to carry out a thorough observation with respect to the aquaculture households and their aquaculture activities. The detailed location of the study area is presented in Figure 1.

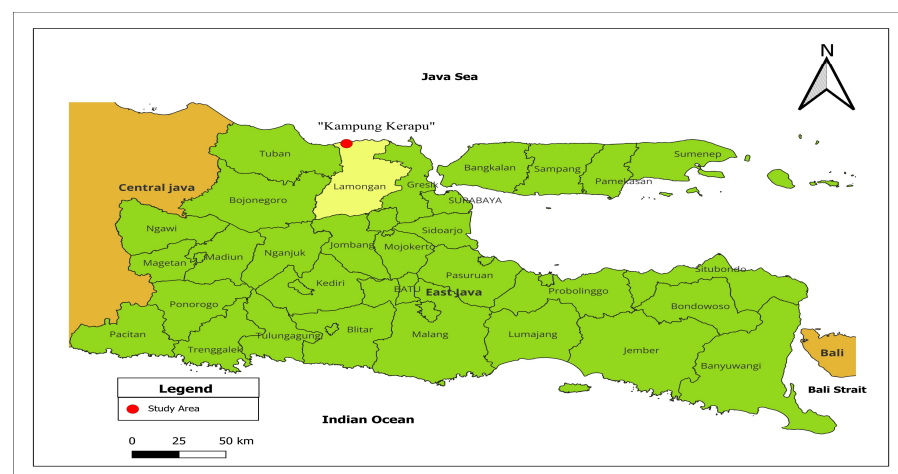


Figure 1. Location of Research.

2.2. Type and Source of Data

The primary and secondary data were the two kinds used for this research. Primary data in the case of this research was obtained through structured interviews and direct observation in the field with the main respondents—the farmers cultivating hybrid grouper (*Epinephelus fuscoguttatus* $\times$ *Epinephelus lanceolatus*). A structured questionnaire was the research instrument that included the indicators of livelihood assets derived from the Sustainable Livelihood Framework [7,8] as well as production input–output variables. On the other hand, the secondary data came from publications by the Ministry of Maritime Affairs and Fisheries, the Central Bureau of Statistics of East Java Province, and academic reports of current scientific journals that were relevant to the issue at hand.

2.3. Population and Sample

The population for this study consisted of all the grouper farmers’ households located within the research area, which comprised a total of 105 fishery household units. The sampling method used was simple random sampling, which allows every element of the population to have an equal chance of being selected as a sample [21]. This choice of method was made in order to eliminate any biases in the distribution of the respondents and to ensure that the representation was proportional. The sample size was determined using the Slovin formula with an error rate of 5% [22], leading to 83 respondents being selected. This sample size was considered sufficient for statistical estimation with a high degree of confidence.

2.4. Instruments and Data Collection

The research tool was a structured questionnaire that had three major sections: (1) the identity of the respondent and characteristics of the business, (2) measures of livelihood resources such as human, natural, social, financial, and physical capital, and (3) input–output data of pond production. Data collection was done by direct interviews in the field, observation of pond conditions, and getting relevant documents from the concerned institutions.

2.5. Data Analysis Method

This analysis is conducted in several interrelated sections, and the analysis is as follows:

a. Livelihood Assets Analysis

The Livelihood assets analysis aimed to determine the capability of farmers in five main aspects: human, natural, social, financial, and physical capital [8]. Each capital was calculated by averaging the scores of the MSI transformation results and then normalizing them to an index scale of 0–1 with the formula

$$I = \frac{(Xi - Xmin)}{Xmax - Xmin}$$

where I is the livelihood asset index, Xi represents the MSI-transformed score of each indicator, $Xmin$ is the minimum observed value, and $Xmax$ is the maximum observed value. The index values have been categorized into five groups: very low (0–19.99%), low (20–39.99%), moderate (40–59.99%), high (60–79.99%), and very high (80–100%). The index values for each capital were shown in the form of an asset pentagon diagram, where the further a point is from the center, the higher the access to that particular asset. This method is similar to the Sustainable Livelihood Framework concept of Scoones [7] and Ellis [23], which underlines the collaboration of capitals in attaining economic security.

b. Technical Efficiency Analysis (Stochastic Frontier Analysis/SFA)

The evaluation of technical efficiency was done via the Stochastic Frontier Production Function with the Maximum Likelihood Estimation (MLE) approach. This particular model works on the principle of partitioning the random error term (v) and the inefficiency component (u), which helps in knowing the degree of a production unit's deviation from the efficiency frontier [24]. We employed a Cobb–Douglas functional form for the stochastic production frontier due to its parsimony, ease of interpretation, and consistency with previous aquaculture efficiency studies. The Cobb–Douglas specification assumes constant elasticities of production and allows for straightforward estimation of input contributions to output. The basic formula of the model is presented as follows:

$$\ln Y_i = \ln \beta_0 + \beta_1 \ln X_1 + \beta_2 \ln X_2 + \beta_3 \ln X_3 + \beta_4 \ln X_4 + \beta_5 \ln X_5 + \beta_6 \ln X_6 + v_i - u_i$$

where the log-linear specification represents the Cobb–Douglas functional form, the output of grouper production (Y_i) is measured in kilograms, where (X_1 – X_6) refers to the input parameters such as land area (ha), number of seeds (units), amount of feed (kg), amount of diesel fuel (lt), amount of lime (kg), and labor (man-days). The coefficients β_1 through β_6 represent the elasticities of output with respect to each input. The parameter estimation was done using STATA software version 17.0 MP—Parallel Edition, and the Technical Efficiency (TE) value was computed as follows:

$$TE = y_i / (y_i^*) = \exp(-u_i)$$

with the limit of $0 \leq TE \leq 1$. A TE value of 1 means full efficiency; on the other hand, $TE < 1$ means technical inefficiency. The selection of the Cobb–Douglas functional form over more flexible specifications (e.g., the Translog model) was supported by likelihood ratio tests and considered appropriate given the sample size and the technological characteristics of pond-based grouper aquaculture.

c. Analysis of the Effect of Livelihood Assets on Technical Efficiency

The relationship among livelihood assets and technical efficiency was tested through Tobit regression with the dependent variable in the form of technical inefficiency (u_i) estimated by SFA. The Tobit model is appropriate because the dependent variable (technical inefficiency) is censored, bounded between 0 and 1. The model equation can be written as follows:

$$u_i = \delta_0 + \delta_1 Z_1 + \delta_2 Z_2 + \delta_3 Z_3 + \delta_4 Z_4 + \delta_5 Z_5 + \delta_6 Z_6 + \delta_7 Z_7 + \delta_8 Z_8 + \delta_9 Z_9 + \delta_{10} Z_{10} + \delta_{11} Z_{11} + \delta_{12} Z_{12} + \delta_{13} Z_{13} + \delta_{14} Z_{14} + \delta_{15} Z_{15} + \delta_{16} Z_{16} + \delta_{17} Z_{17} + \delta_{18} Z_{18} + \delta_{19} Z_{19} + \delta_{20} Z_{20} + w_i$$

where (Z_1 – Z_{20}) consists of indicators for each of the livelihood assets (education, skills, experience, health, land size, water source, water availability, climate change, social network, participation in organizations, access to information, social support, income, savings, credit/loans, debt, land status, house, equipment, and vehicle). Initially, classical assumption tests comprising normality, multicollinearity, and heteroscedasticity tests were carried out to validate the model. Robust standard errors were employed to address potential heteroscedasticity in the Tobit regression. The analysis results were interpreted using the coefficient value and significance level (p -value) with STATA software assistance. This method is in line with the previous studies of Allison and Ellis [25], which highlighted the significance of livelihood assets in enhancing managerial and technical efficiency within the small-scale fisheries sector.

This study did not employ generative artificial intelligence tools in the research design, data collection, data analysis, or interpretation of findings. ChatGPT (GPT-5.2, OpenAI) was used exclusively during manuscript preparation for the purpose of identifying relevant literature to support the reference list.

3. Results

3.1. Level of Livelihood Assets

The analysis of the livelihood assets level on pond-based grouper farmers in coastal Lamongan presented a complete picture of the farmers' capacity to draw on different livelihood assets for the purpose of supporting their business sustainability. The assessment covered the five main components of livelihood assets, which are human capital, natural capital, social capital, financial capital, and physical capital, and regarded them as a whole, determining the productivity and economic security of farmers against environmental and market pressures. The discrepancy between capitals can have a positive or negative impact on the effectiveness of the livelihood strategy and the sustainability of the aquaculture system, thus making this evaluation significant. The analysis results are that the farmers' livelihood assets level was moderate with varying strengths and weaknesses in each capital type as shown in Table 1.

Table 1 regarding the livelihood assets of the farmers has led to the conclusion that the livelihood conditions of the farmers are in the moderate category, with an average index of 0.47. The value represents the relative ability of farmers to access and utilize five key livelihood assets: human capital, natural capital, social capital, financial capital, and physical capital [25]. Among the five types of assets, physical capital scored the highest by 0.55, with farmers predominantly owning their homes and aquaculture equipment, and using motor-

cycles as the main vehicle type. Land tenure showed diverse arrangements among farmers, including self-owned, rented, and other forms of access. Furthermore, human capital (0.50) also took an important position because farmers with secondary education, adequate skills in pond management, and more than 10 years of experience can support in enhancing the business efficiency. Good family health also enhanced the productivity and sustainability of grouper aquaculture. Meanwhile, natural capital obtained a value of (0.46), indicating a moderate link between land area, water sources, water availability, and the impact of climate change in supporting grouper aquaculture. While the land size is relatively small, the good quality and availability of seawater are key factors in sustaining the production. However, the threat of climate change poses a risk of fish diseases, and therefore water quality management and aquaculture adaptation are key to maintaining productivity and business security. Social capital (0.45) reflected the mutually reinforcing links between social networks, participation in organizations, access to information, and social support. Good interaction between the farmers drives knowledge exchange, while participation in groups expands access to training and assistance [26]. Access to information and family support also strengthen socioeconomic security, although organizational involvement still needs to be improved to strengthen business sustainability [27]. Whereas financial capital is the weakest aspect, with an index of only 0.37, representing the relationship between income, savings, loans, and debts in supporting the sustainability of aquaculture businesses. A stable income reflected a strong financial capacity to support production, but limited savings indicated the need for better financial management. Low credit and debt activity signified financial prudence, but also indicated the potential for improvement through more efficient financial management. Low financial capital also has an impact on the limited ability to expand production, adopt new technologies, and bear the risk of harvest failure [28,29].

Table 1. Index of Livelihood Assets.

No	Types of Livelihood Assets	Average Score	Average Index	Classification
1	Human Capital	3.01	0.50	Moderate
2	Natural Capital	2.86	0.46	Moderate
3	Social Capital	2.79	0.45	Moderate
4	Financial Capital	2.48	0.37	Low
5	Physical Capital	3.19	0.55	Moderate
Total			0.47	Moderate

This finding emphasizes that the level of livelihood assets of grouper farmers was moderate, with variations between assets reflecting the balance between individual capacity and access to resources. Physical and human capital were dominant in sustaining business efficiency and sustainability, while natural and social capital served as a support for environmental and socio-economic security. On the contrary, financial capital was a key limiting factor as a result of poor savings accumulation and access to finance. This finding is consistent with the literature stating that a combination of livelihood assets, instead of only one type, strengthens the capacity of small-scale aquaculture businesses [30], but comprehensive asset management is also needed to support the security and sustainability of fishery businesses [31].

From a theoretical perspective, the findings provide backing to the Sustainable Livelihood Framework (SLF) introduced by DFID [8], which underlines the interaction of livelihood assets among each other when facing external vulnerabilities like price fluctuations, environmental changes, and production risks. An imbalance between capitals, such as high

physical capital not accompanied by adequate financial and social capital, may limit farmers' ability to adapt and optimize their resource use. Therefore, the grouper aquaculture business development strategy should adopt a multi-capital approach that equally distributes investment among infrastructure, human capacity building, and access to finance and social services. In this way, the development of the livelihood assets will not only be aimed at economic growth but will also embrace social empowerment and environmental sustainability as part of sustainable coastal development [7,32].

3.2. Level of Technical Efficiency

The technical efficiency level of hybrid grouper (*Epinephelus fuscoguttatus* × *Epinephelus lanceolatus*) aquaculture in ponds has been the primary indicator to determine how far the farmers used their production resources to give the maximum output. Technical efficiency reflected the effectiveness of the input use combinations such as land area, quantity of seeds, amount of feed, amount of diesel fuel, amount of lime, and amount of labor, in producing a productive and sustainable harvest. In pond management, high efficiency indicates the ability of farmers to reduce costs, reduce wastage, and maintain productivity stability despite facing various environmental conditions. On the contrary, low technical efficiency indicates potential improvements in management, technology, or human resource capacity. In general, this efficiency analysis provides an overview of the economic and technical performance of hybrid grouper (*Epinephelus fuscoguttatus* × *Epinephelus lanceolatus*) aquaculture businesses at the farmer level, which serves as the basis for formulating sustainable aquaculture development policies. The technical efficiency levels are described in Table 2 and Figure 2.

Table 2. Distribution of Technical Efficiency Value.

Value	Number of Farmers (People)	Percentage (%)	Interpretation of Business Performance
<0.70	3	3.61	Inefficient; non-optimal use of inputs
≥0.70–<0.80	14	16.87	Moderately efficient; there is still potential for improvement
≥0.80–<0.90	54	65.06	Efficient; the majority of businesses utilize the effective inputs
≥0.90	12	14.46	Highly efficient; close to maximum efficiency
Total	83	100	
Average TE			0.83
Standard Deviation (σ)			0.06
TE Minimum Value			0.59
Maximum Value TE			0.94

Note: TE, Technical Efficiency; σ , the standard deviation of technical efficiency scores.

The analysis results of the technical efficiency of hybrid grouper (*Epinephelus fuscoguttatus* × *Epinephelus lanceolatus*) aquaculture show that the majority of farmers have achieved high production and are close to maximum efficiency. Based on the measurement results with the Stochastic Frontier Analysis (SFA) approach, the average technical efficiency was 0.83 with a range of values between 0.59 and 0.94. This value indicated that, in general, grouper farmers have been able to utilize about 83% of the existing optimal input potential. The efficiency distribution showed that 65.06% of respondents were in the efficient category (0.80–0.90), while 14.46% were classified as highly efficient (≥0.90). Only a small number

(3.61%) were still below the minimum efficiency threshold (<0.70). The above chart illustrates the dominance of the efficient category as the peak of the distribution, indicating that the distribution of technical efficiency among farmers is relatively balanced with a positive trend towards high efficiency, indicating the homogeneity of input management practices and technology in the research area [33].

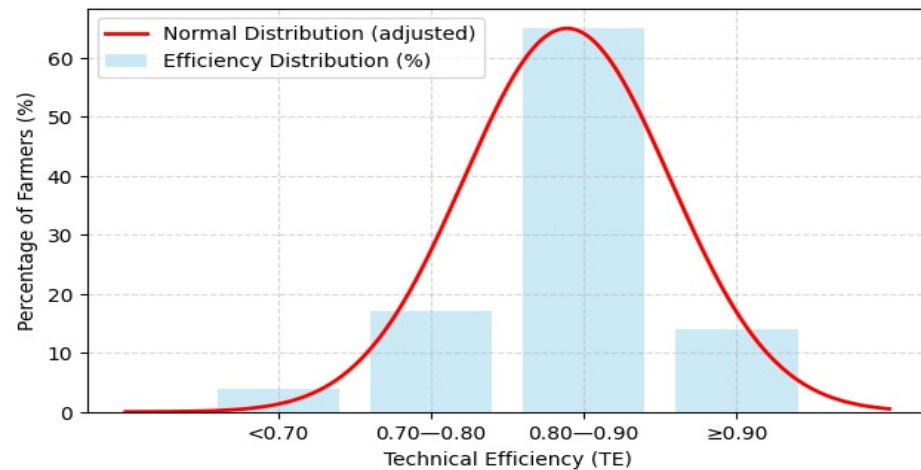


Figure 2. Distribution of Technical Efficiency Level.

3.3. The Effect of Livelihood Assets on the Technical Efficiency

The effect of livelihood assets on the technical efficiency of pond-based grouper aquaculture in coastal Lamongan showed how the various assets owned by farmers, including human, natural, social, financial, and physical capital, play a role in determining the level of productivity and the ability to manage resources efficiently. Such assets not only reflected the economic and technical capacity but also described the adaptive capacity of farmers in the face of environmental and market dynamics. In the grouper aquaculture business, the balance between asset types is key in reducing production inefficiencies and business sustainability. For this reason, this analysis was performed to identify the relative contribution of each asset to technical inefficiency and the relationship between variables affecting business performance. The results regarding the effect of each livelihood asset on the technical inefficiency of aquaculture are described in Table 3 and Figure 3.

Based on the estimation results of Tobit regression with robust standard errors, the links between livelihood assets and technical inefficiency indicate that there is a variation in the contribution of each asset component to the production efficiency of grouper farmers. From the table of estimation results and the bar graph, we can see that most variables hold positive coefficients with various significance levels. From the natural capital aspect, the land size variable ($\delta_5 Z_5$) has a negative coefficient of -0.0373 and is significant at the 5% level ($p = 0.012$), implying that the larger the land size, the lower the level of technical inefficiency. It means that farmers with wider land ownership tend to be able to utilize production inputs more optimally. This particular result supports the findings of Coelli [24] and Kumaran [12], who reported that land size is the most important factor in the growth of technical efficiency in aquaculture and agriculture [15]. On the other hand, the water source variable ($\delta_6 Z_6$) has a positive coefficient of 0.0284 and is significant at the 1% level ($p = 0.001$), suggesting that water source capacity to increase inefficiency, which implies that the more the reliance on one water source, the more the potential for technical efficiency decrease. Regarding financial capital, the Z income ($\delta_{13} Z_{13}$) and Z savings ($\delta_{14} Z_{14}$) variables are significant at the 1% level ($p = 0.001$ and $p = 0.008$). This implies that the higher the income and savings of farmers, the higher the level of technical inefficiency or the lower

the technical efficiency. This condition may occur as farmers with high income and savings tend to reduce production costs or do not allocate resources optimally.

Table 3. Estimation of the Effect of Livelihood Assets on Technical Inefficiency.

Variables	Parameter	Tobit vce (Robust) Regression Analysis			
		Coefficient	Std.Err.	t	$p > t $
_Cons	$\delta_0 Z_0$	0.3450292	0.1378352	2.50	0.015
Education	$\delta_1 Z_1$	0.010581	0.0108216	0.98	0.332
Skills	$\delta_2 Z_2$	0.0004108	0.0100828	0.04	0.968
Experience	$\delta_3 Z_3$	−0.0004468	0.0125811	−0.04	0.972
Health	$\delta_4 Z_4$	0.0172567	0.0146496	1.18	0.243
Land Area	$\delta_5 Z_5$	−0.037339 *	0.0144101	−2.59	0.012
Water source	$\delta_6 Z_6$	0.0284048 **	0.0085174	3.33	0.001
Water availability	$\delta_7 Z_7$	−0.007971	0.0172092	−0.46	0.645
Climate change	$\delta_8 Z_8$	−0.0057031	0.0111866	−0.51	0.612
Social network	$\delta_9 Z_9$	0.0107716	0.0094441	1.14	0.258
Participation in organization	$\delta_{10} Z_{10}$	−0.0075363	0.0075957	−0.99	0.325
Access to information	$\delta_{11} Z_{11}$	−0.0098654	0.0082784	−1.19	0.238
Social support	$\delta_{12} Z_{12}$	0.0055162	0.0082678	0.67	0.507
Income	$\delta_{13} Z_{13}$	0.046687 **	0.0127666	3.66	0.001
Savings	$\delta_{14} Z_{14}$	0.0441468 **	0.0159923	2.76	0.008
Credit/loan	$\delta_{15} Z_{15}$	−0.0002958	0.004694	−0.06	0.950
Debt	$\delta_{16} Z_{16}$	0.0023344	0.0046509	0.50	0.617
Land Status	$\delta_{17} Z_{17}$	−0.0062853	0.0076213	−0.82	0.413
Home	$\delta_{18} Z_{18}$	0.0297134	0.0232653	1.28	0.206
Equipment	$\delta_{19} Z_{19}$	0.0161212	0.0232052	0.69	0.490
Vehicle	$\delta_{20} Z_{20}$	−0.0014296	0.0060986	−0.23	0.815
Log pseudolikelihood	139.60253				
Prob > F	0.0001				

Note: vce (robust), robust estimator; Std.Err., standard error; t, t-statistic; $p > |t|$, significance; $\delta_0 Z_0 \dots \delta_{20} Z_{20}$, regression coefficients; Prob > F, overall model significance (* $p < 0.05$, and ** $p < 0.01$).

On the contrary, other variables for human capital (education, skills, experience, health); natural capital (water availability, climate change); social capital (social networks, participation in organizations, access to information, social support); financial capital (credit, debt); and physical capital (status of land, houses, equipment, vehicles) showed no significant effect ($p > 0.05$). This indicated that the capital dimension has yet to make a real contribution in explaining variations in technical inefficiency among the farmers, meaning that its role in improving the effectiveness of input use is relatively limited. In summary, it emphasizes that technical inefficiency is affected by the characteristics of natural and financial capital, while other capital has not made significant contributions in increasing or lowering the inefficiency.

The core findings of this analysis showed that the livelihood assets component contributed differently to the technical efficiency of grouper aquaculture. Natural capital, primarily land area, was a great contributor to the reduction of the technical inefficiency, while the reliance on water sources led to increased inefficiency. In the case of financial capital, high income and savings were linked to an increase in inefficiency, probably because of the poor allocation of resources. Human capital, social capital, and physical capital had no effect, which might mean that they were not contributing much to efficiency due to either respondent uniformity or inefficient asset use. Therefore, the technical efficiency improvement is mainly dependent on the co-operation of productive natural and financial capitals, which is further supported by the integration of human, social, and physical capacities.

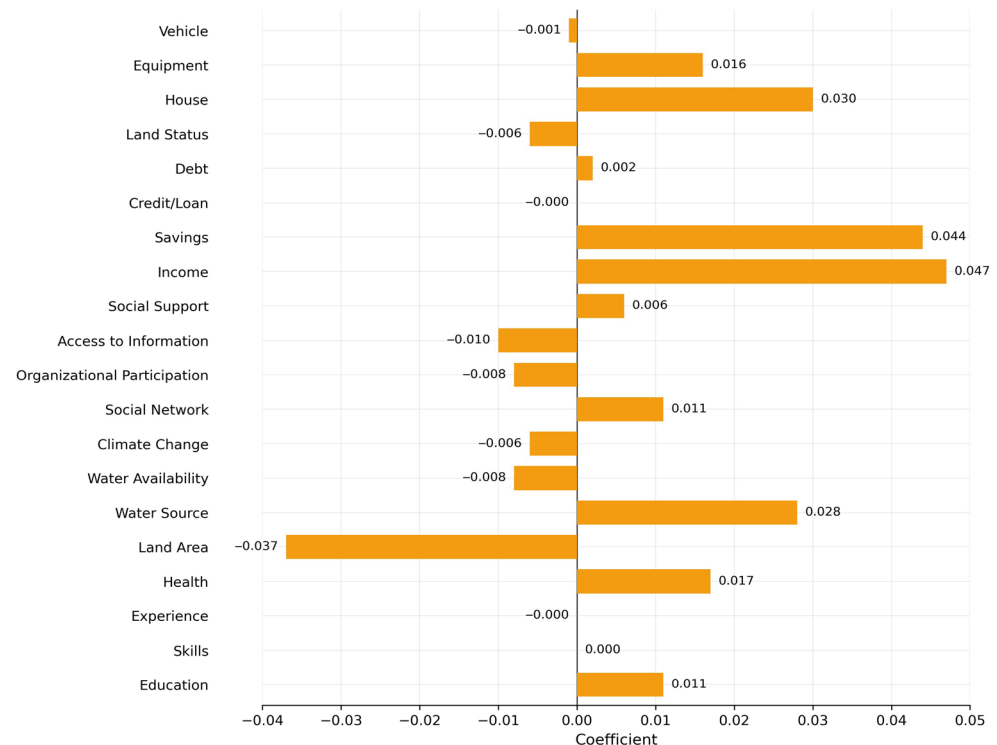


Figure 3. Estimated Coefficients of Livelihood Asset Variables Related to Technical Inefficiency.

The particular finding is in line with the Sustainable Livelihood Framework [7,8] that underlines that the sustainability of households and the efficiency of the economy depend on the optimal mix of the five capital inputs: human, social, natural, financial, and physical. Thus, the study results or findings revealed that multiplying one income source and having lots of assets actually determined the technical efficiency. Also, natural and financial capital brought in as direct factors accessed while human and social capital were regarded as the supporting factors. Thus, essentially, the notion in Chambers and Conway [34] is that no or little welfare can be achieved without the interaction between assets and livelihood strategies. Theoretically, the positive links between income, savings, and technical efficiency illustrate the principle of livelihood resilience, which is the ability of the livelihood system to maintain productivity despite external pressures such as fluctuating feed prices or climate change. On the other hand, the negative links between credit and technical efficiency indicate the presence of financial vulnerability, where debt burden without productivity improvement might reduce the overall efficiency. The research results, therefore, have not only added to the literature regarding the significance of livelihood assets in the small-scale fishery economies [1], but also pointed out the major role of financial and natural capitals as the key enhancers of technical efficiency, the necessity for social empowerment and human capacity development as the supporting elements. Technical efficiency improvement schemes will not only depend on the supplying of assets but also on asset management, integration, and adaptive utilization to achieve long-term sustainability [18,35].

4. Discussion

The findings of this research confirmed that the measurement of livelihood assets showed that farmers' livelihood conditions were in the "moderate" category with an average index of 0.47, which indicated a relative balance between capitals but with a significant weakness in the financial capital. Human and physical capital earned the highest scores, then came natural and social capital, while financial capital was the weakest point. This answers the first research question that variations among livelihood assets

are the major factor in pond aquaculture sustainability. The absence of financial capital limits the farmers' capacity to access technology and increase production. This finding aligns with the Sustainable Livelihood Framework [7,8] which points out the necessity of capital balance. On the other hand, the study's contribution lies in its verification that financial deficits paving the way for livelihood imbalances may limit productivity even with relatively large human and physical capital, a situation that is not often pointed out in aquaculture studies in Southeast Asia.

The analysis of the technical efficiency of pond-based grouper aquaculture in coastal Lamongan, Indonesia, was classified as high, with an average technical efficiency (TE) value of 0.83. This number indicates that the majority of farmers have optimized input use to 83% of the maximum available potential. This outcome answers the second research question that the grouper aquaculture system in the research area is relatively technically efficient, and there is still an opportunity to increase by 17% without additional new inputs. The equal distribution of efficiency also reflected the homogeneity of technical and managerial practices among farmers. This confirms the argument that the factors of feed management, water quality control, and the use of semi-intensive technology are key to successful pond efficiency [23]. Accordingly, these results showed that while the majority of farmers are still operating on a small scale, their ability to manage resources is close to best practice at the local level.

The high level of technical efficiency in grouper aquaculture can be attributed to several factors, including farmers' ability to consistently manage seed stocking densities and the support of semi-intensive technology [36], as supported by research studies [12] and [37]. On the other side, low-efficiency farmer groups generally encounter a shortage of working capital, a lack of input diversification, and a poor technical knowledge of water quality management. This condition confirms that an increase in technical efficiency is not the result of using large amounts of inputs, but rather the ability to allocate inputs optimally according to the conditions of the aquaculture environment [24,33]. The symmetrical normal distribution of efficiency scores indicates that the variation in efficiency between farmers is relatively small, suggesting that most business units are operating at near-optimal production capacity.

The findings from this study showed that the pond-based hybrid grouper (*Epinephelus fuscoguttatus* × *Epinephelus lanceolatus*) aquaculture business is technically efficient, and it will be able to enhance productivity through management optimization. The average efficiency level of 0.83 implied that there was still an opportunity to increase production by around 17% without the need to increase production inputs, only by improving governance and technological innovation [38]. Moreover, the high level of efficiency distribution showed that external factors such as infrastructure availability, institutional support, and access to technological information played a role in maintaining the stability of farmers' technical performance [39]. Thus, the technical capacity building through training, technology assistance, and facilitation of access to finance is a vital strategy to eliminate the difference in efficiency that is still there among the farmer groups. This is the same view as that of Farrell [40], who differentiated between technical, allocative, and economic efficiency in production. In this research, technical efficiency describes the extent to which farmers can maximize output from a given combination of inputs without regard to price or cost structure. A high level of efficiency indicated the success of the cultivation system in achieving the optimal input–output combination under certain technological conditions. In addition, this finding is also consistent with the frontier production function theory developed by Aigner et al. [41], stating that variations in efficiency among farmers represent the influence of managerial factors, experience, and technology application on production performance. Consequently, it can be concluded that a high level of technical efficiency in

pond-based hybrid grouper (*Epinephelus fuscoguttatus* × *Epinephelus lanceolatus*) aquaculture not only reflects successful management of production factors, but it is also an indicator of the sector's readiness to deal with the modernization of sustainable aqua-culture.

Tobit regression with robust standard errors provided empirical evidence of the effect of livelihood assets on the technical efficiency of grouper aquaculture. The findings show that land area has a significant negative effect on technical inefficiency [42], indicating that more land can help farmers optimize resource utilization and thus improve efficiency [43]. Other assets, such as human, social, and physical capital, did not show significant effects, which may be the result of the homogeneity of the respondents or the limited utilization of these assets in aquaculture practices. This finding contradicts the research of Ogundari [15] and Adetoyinbo and Otter [16], who ranked human and social capital as the key factors of efficiency. This dissimilarity can be explained by highlighting the weakness of human, social, and physical capital, hence the need for effective management and optimization of natural and financial capital to improve efficiency in grouper aquaculture, as well as providing strategic directions for capacity building of farmers to optimize various capitals as a whole.

The theoretical contribution of this research is in the strengthening and development of the Sustainable Livelihood Framework (SLF) concept in explaining the linkages between livelihood assets and technical efficiency in the aquaculture sector. The research results emphasized that a balance between assets or the five main capitals (human, natural, social, financial, and physical) is a pre-condition to achieve a sustainable production efficiency. The imbalance between assets, especially the poor financial capital despite the relatively strong human and physical capital, showed that efficiency depends not only on the availability of assets, but also on the synchronized function of capital in supporting the production performance and sustainability of aquaculture businesses [44].

The practical implications of this research showed that the enhancement of technical efficiency in pond-based grouper aquaculture in coastal Lamongan should be directed at strengthening and balancing livelihood assets. Local governments and stakeholders need to prioritize the enhancement of access to microfinance and the financial management of farmers to strengthen their weak financial capital. In addition, technical training support, institutional strengthening of groups, and better production facilities and water infrastructure provision will lead to the rise of the capital's human, social, and physical effectiveness. This integrative approach is important to make it possible for all livelihood assets to work together in a positive way that will increase the technical efficiency, productivity, and sustainability of aquaculture businesses in coastal areas.

From the methodological perspective, the major merit of this research lies in utilizing a combination of Stochastic Frontier Analysis (SFA) and Tobit regression with robust variance that allows for a simultaneous assessment of technical inefficiency and its associated factors [45]. This method provides a better degree of accuracy in estimation than nonparametric approaches like DEA since it has the capability of distinguishing random errors from inefficiency components [39,41,46]. Nonetheless, its limitation is the cross-sectional character of the data, which cannot depict the efficiency dynamics across periods and the possibility of bias introduced by the environmental variables that have not been completely accounted for. Moreover, even though the livelihood assets index was standardized, assessments based on respondents' perceptions may contain subjectivity. Therefore, further research using panel data and integrating biophysical data is recommended to strengthen the analysis model [47].

Overall, this research opens up new paths in the study of technical efficiency in aquaculture by positioning livelihood assets as an important factor. While most aspects of human, social, and physical capital did not contribute significantly due to the similarity

of respondent characteristics, natural and financial capital greatly influenced technical efficiency. As the scarcity of research testing the role of capital in dynamic efficiency, it is suggested that future research should combine spatial approaches and panel models to understand climate change and the role of local institutions in promoting the concept of asset-based sustainability, assessing the social, economic, and ecological resilience of coastal communities in an integrated manner.

5. Conclusions

This research suggested that the analysis of livelihood assets of farmers was in the moderate category with an index of 0.47, where human, natural, social, and physical capital were relatively moderate, while financial capital was still low. Technical efficiency was high, with an average efficiency of 0.83, reflecting the optimization of inputs up to 83% of the maximum potential. The key factors affecting the efficiency were seedling management and semi-intensive technology support. The results of the Tobit regression with robust standard errors showed that financial capital (income and savings) and natural capital (land size and water resources) had a significant effect on technical efficiency, while human, social, and physical capital did not have a significant impact. These findings support the theory of asset-based efficiency in aquaculture and emphasize the importance of enhancing the natural and financial capital for sustainable productivity in coastal areas.

To enhance the business sustainability and technical efficiency of pond-based grouper aquaculture in coastal Lamongan, there is a need for policies focusing on access to low-interest microfinance, financial literacy, and diversification of family income sources. Local governments need to strengthen irrigation systems and pond water quality management. Moreover, educational and extension institutions need to provide more extensive technical and managerial training. Social institutions such as cooperatives and farmer groups need to be optimized as information-sharing and market collaboration platforms. This research has its limitations since it used cross-sectional data that did not capture the time changes and micro-environmental aspects. Future research is recommended to use panel data and spatial approaches to assess interactions between assets in the context of climate change and to integrate local institutions into technical efficiency models.

Overall, this research contributes to the study of technical efficiency in aquaculture by positioning livelihood assets as an important factor. While human, social, and physical capital did not show significant direct effects due to respondent homogeneity, natural and financial capital greatly influenced technical efficiency. Given the scarcity of research examining the role of livelihood assets in dynamic efficiency, future research should combine spatial approaches and panel models to understand climate change impacts and the role of local institutions in promoting asset-based sustainability, while assessing the social, economic, and ecological resilience of coastal communities in an integrated manner.

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was collected from all respondents before the commencement of the research. Additionally, the participants were informed about the purpose, methodology, and expected results of the research, including confidentiality guarantees. The participation was voluntary; moreover, the possibility to withdraw at any time without consequences is provided. No personal information identifying the respondents is included in the publication of the results for privacy reasons.

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