

TECHNICAL EFFICIENCY AND PRODUCTION SCALE ANALYSIS IN SMALL-SCALE TUNA HANDLINE FISHERIES IN WEST SULAWESI

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ABSTRACT

Tuna fishing activity in West Sulawesi has intensified in recent years, raising concerns regarding the sustainability of the fishery in the Makassar Strait amid increasing fishing pressure. This study evaluates the capacity utilization and resource use efficiency of small-scale handline vessels by measuring their technical and scale efficiency. A total of 78 tuna handline vessels were analyzed using an output-oriented Data Envelopment Analysis (DEA) model under Variable Returns to Scale (VRS), covering two vessel categories: <5 GT and 5–10 GT. Vessel samples were selected through stratified random sampling from the Banggae and Tinambung sub-districts. The results show that vessels in the 5–10 GT category exhibit higher technical efficiency in utilizing production inputs and fishing capacity, while vessels smaller than 5 GT tend to operate closer to the optimal scale, with most exhibiting increasing returns to scale (IRS). These findings highlight that efficiency improvements in the small-scale segment could be achieved through targeted technological assistance and training, particularly among smaller vessels (<5 GT), while capacity management remains essential in larger vessels (5–10 GT) to prevent excessive fishing effort. Integrating efficiency-based management insights with Indonesia's Measured Catch Policy is critical to support the sustainability of tuna fisheries in the region.

Keywords: DEA, scale efficiency, small-scale fisheries, tuna fishing, technical efficiency

INTRODUCTION

Small-scale fisheries (SSFs) are crucial for food security, income generation, and employment in coastal communities, particularly in developing countries like Indonesia. They contribute significantly to local and regional economies. SSFs are the main source of seafood for coastal populations (Arthur *et al.* 2021; Canty & Deichmann 2022; Villasante *et al.* 2022). In Indonesia, the small-scale tuna handline fishery plays a strategic role, especially in West Sulawesi Province. This region is located adjacent to the ecologically important Makassar Strait, which is part of Fisheries Management Area (WPP) 713 (Gordon *et al.* 2019). Traditional handline tuna fisheries in West Sulawesi are concentrated in Banggae (Majene District) and

Tinambung (Polewali Mandar District), where fishers mainly target skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), and Tongkol (*Euthynnus affinis*) using small vessels (<10 GT) operated independently or in small groups (Khan *et al.* 2020; Syamsuddin 2023).

Despite their importance for local livelihoods, these fisheries face several challenges. These include limited technology, dependence on traditional knowledge, and inefficient use of inputs such as fuel, labour, and fishing effort (Gigentika *et al.* 2016; Liu *et al.* 2021). This situation is echoed by small-scale handline tuna fisheries in the Makassar Strait, which also struggle to optimize resource use due to technological limitations, varying production capacities, and pressures on tuna stock sustainability. Production inefficiencies

may contribute to increasing operational costs, reduced competitiveness (Hatmar & Nelwan 2024; Jurwanto *et al.* 2025), and elevated fishing pressure on tuna stocks (Wicaksono 2019). However, most previous studies have focused on aggregate production indicators or financial assessments (Júnior *et al.* 2016; Krumhansl *et al.* 2017; Wicaksono 2019). This leaves a significant knowledge gap regarding vessel-level technical performance and scale efficiency, which is the level at which fishing decisions are made.

This situation generates an important scientific problem. At present, the technical, scale, and capacity utilisation efficiencies of individual tuna handline vessels remain unknown, particularly between the two dominant vessel-size groups (<5 GT and 5–10 GT). Empirical evidence is also lacking on how variations in input use—such as fuel consumption, crew size, and trip frequency— affect their output performance. This knowledge gap is increasingly critical amid the national agenda to implement the Measured Fishing Policy, which requires accurate assessments of fleet-level fishing capacity and productivity.

Data Envelopment Analysis (DEA) offers a straightforward, non-parametric way to assess relative efficiency from multiple inputs and outputs without assuming a production function (Efendi *et al.* 2020; Muawanah *et al.* 2021; Pascoe & Tingley 2016). DEA estimates technical efficiency (TE)—maximising outputs from inputs—and scale efficiency (SE)—operating at the right scale (Liu *et al.* 2021; Zhaoqun *et al.* 2018; Cao *et al.* 2021). Although DEA has been widely used to assess fisheries efficiency in various contexts (Liu *et al.* 2021; Cao *et al.* 2021; Zhaoqun *et al.* 2018; Muawanah *et al.* 2021; Walden & Atwood 2023; Yang *et al.* 2022), no study has yet evaluated the technical and scale efficiency of the small-scale tuna handline fleet in the Makassar Strait. The lack of DEA studies at the vessel level in this region creates a clear *research gap*. Understanding how vessel size affects technical and scale efficiency is especially important. Prior studies show that small-scale vessels often have underutilised input capacity. Medium-scale vessels, on the other hand, may operate at a non-optimal scale (Gigentika *et al.* 2016; Liu *et al.* 2021; Muawanah *et al.* 2021).

To address these issues, this study applies an *output-oriented* DEA model under *Variable Returns to Scale* (VRS) to estimate pure technical efficiency (TE), scale efficiency (SE), and capacity utilization (CU) for two

vessel-size groups (<5 GT and 5–10 GT). The DEA framework enables vessel-to-vessel comparison and reveals the potential for output expansion given the same level of inputs. Overall, this study provides several key novelties, including: (1) the first DEA-based assessment of tuna handline vessels in the Makassar Strait, (2) a simultaneous evaluation of TE, SE, and CU, offering a comprehensive understanding of fleet performance, (3) new empirical evidence on efficiency disparities across vessel-size groups, which has not been previously reported for central Indonesian tuna fisheries, and (4) direct relevance to capacity management strategies under Indonesia's Measured Fishing Policy. Accordingly, the introduction establishes a strong theoretical, empirical, and methodological foundation for analysing technical and scale efficiency in small-scale tuna handline fisheries in West Sulawesi and their implications for sustainable fisheries governance.

METHODS

Research Procedure

Location and Time of Research

This research was conducted in two sub-districts that are the centers of tuna landing in West Sulawesi Province, namely: Banggae District (Majene Regency) and Tinambung District (Polewali Mandar Regency). Field data collection was conducted during the period (August - December 2022).

Data Type and Source

This research employs a quantitative approach, utilizing data types that include both primary and secondary data. Primary data were collected directly from the field through surveys using structured questionnaires and in-depth interviews with *tuna-handline* fishers, who were selected as the research sample. Primary data collected included technical characteristics of the vessels (such as GT size), operational *inputs* (such as fuel use, number of crew members, and number of trips), catches, and fishermen's perceptions of fisheries conditions and sustainability aspects.

Meanwhile, secondary data were obtained from various official sources, including the Marine and Fisheries Agency, which provided information on the number and distribution of *tuna-handline* fishing vessels in the study area. In addition, secondary data were also collected from fisheries statistical documents published by the Ministry of Marine Affairs and Fisheries (MMAF), as well as from scientific literature, technical reports, and pre-



Figure 1 Research location

Table 1 Allocation of sample size in each stratum

Vessel Size	Population Proportion	Number of Samples
<5 GT	±75%	58 vessels
5-10 GT	±25%	20 vessels
Total	100%	78 vessels

vious research results relevant to the topic of fishing efficiency and capacity in small-scale fisheries. The simultaneous use of primary and secondary data was intended to enhance the validity of the analysis and provide a comprehensive understanding of the operational conditions of the tuna *handline* fishery at the study site.

Sampling Method

The population in this study consisted of 365 *tuna-handline* vessels, which were scattered in the research location (BPS-Statistics of Sulawesi Barat Province 2023). To determine the number of representative samples, the Slovin formula was used, with a 10% *margin of error*, resulting in a total sample of 78 vessels. Sampling was conducted using a stratified random sampling method, based on stratification by vessel size, specifically: <5 GT and 5-10 GT vessels. The proportion in the population based on local government data shows that approximately 75% of vessels are <5 GT and 25% are 5-10 GT (BPS-Statistics Majene Regency 2024). Based on these proportions, the allocation of sample size within each stratum is as seen as Table 1.

Furthermore, the selection of units within each stratum was made purposively, i.e., by selecting vessels that consistently catch tuna and have complete technical and operational data. This approach was chosen to ensure data quality and the relevance of the analysis units in calculating fishing capacity.

Data Analysis

The Data Envelopment Analysis (DEA) method was used to measure technical efficiency and capacity utilization in small-scale fisheries. DEA is a nonparametric technique that estimates the relative efficiency of decision-making units (DMUs) by comparing inputs and outputs. In this study, *output-oriented* DEA is run with two production scale assumptions: *Constant Returns to Scale* (CRS), which assumes that an increase in input results in a proportional increase in output, and *Variable Returns to Scale* (VRS), which accommodates changes in efficiency due to non-constant scale of operations.

These two assumptions are used in parallel to derive three main efficiency measures:

- a) **Technical Efficiency (TE_VRS):** Pure technical efficiency that considers varying scales of operation. The TE_VRS value indicates the extent to which a vessel maximizes output given the inputs used, reflecting the managerial performance of the skipper independent of the vessel's scale.
- b) **Capacity Utilization (CU) or TE_CRS:** Technical efficiency based on the assumption of constant scale of production. TE_CRS is used as a proxy for *capacity utilization*. This measure reflects how well the production capacity is utilized to achieve maximum potential output in the long run, without considering scale constraints.
- c) **Scale Efficiency (SE):** *Scale* efficiency is used to determine whether a particular DMU (specific vessel) exhibits *increasing or decreasing returns to scale*. SE to identify whether inefficiency is due to the scale of operations or technical factors.

The observation period is limited to the August to November 2022 fishing season. This study employs an **output-oriented model** to measure the ability of each fishing unit (Decision Making Unit/DMU) to maximize catch output (y) given the available inputs (x). The *inputs* (x) used are the gross tonnage (GT) capacity, the amount of fuel consumed, the number of crew members, and the number of trips made during the observation period. The observed *output* (y) is the volume of tuna catch per vessel, measured in kilograms (August-November). Assuming there are n fishing units (DMUs). Each DMU uses m inputs to produce s outputs. For the o -th DMU being evaluated, the input vector is denoted as x_o and the output vector as y_o .

The model allows the calculation of relative technical efficiency scores, where an efficiency score of < 1 indicates that the vessel has not yet reached maximum efficiency and still has room to increase *output* without having to increase *inputs*. Conversely, an efficiency score = 1 indicates that the vessel is technically efficient. The output-oriented technical efficiency equation, assuming CRS (Schrobback *et al.* 2023), is written as:

$$\max_{\phi, \lambda} \phi \dots \dots \dots (1)$$

$$s.t \sum_{j=1}^n \lambda_j y_{rj} \geq \phi y_{ro}, \dots \dots \dots (2)$$

$r = 1 \dots, s$ (Output Constraint)

$$\sum_{j=1}^n \lambda_j x_{ij} \leq x_{io}, \dots \dots \dots (3)$$

$i = 1 \dots, m$ (Input Constraint)

$$\lambda_j \geq 0, \quad j = 1 \dots, n$$

The VRS model is added to accommodate production scale variability, an additional constraint:

$$\sum_{j=1}^n \lambda_j = 1 \dots \dots \dots (4)$$

With:

x_{ij} : Amount of i -th input for j -th DMU (GT, Fuel, Crew, Trip).

y_{rj} : Amount of r -th output for j -th DMU (Catch).

ϕ : technical efficiency (TE) score

λ_j : intensity weights to form the efficiency frontier,

y_{ro}, x_{io} : Output and input vectors of the DMU being evaluated.

j : Index for fishing units (DMU), $j = 1 \dots, n$.

r : Index for outputs, $r = 1 \dots, s$.

i : Index for inputs, $i = 1 \dots, m$.

Stages of Analysis DEA Efficiency Analysis:

1. Output-oriented DEA, assuming CRS and VRS, was run in parallel for all business units (vessels) with the help of software DEAP 2.1 (Coelli 1996).
2. TE_CRS values were interpreted as **Capacity Utilization (CU)**. The **Capacity Utilization (CU)** value is obtained from $1/\phi_{CRS}$. A value of CU < 1 indicates the presence of under-utilized capacity.
3. TE_VRS values as pure **Technical Efficiency (TE)**. The **Pure Technical Efficiency (TE_VRS)** value is obtained from $1/\phi_{VRS}$.
4. **Variable Input Utilization (VIU) (λ_j)**: a parameter used to assess input efficiency in this study. VIU is defined as the ratio of optimal input usage to observed input usage. A VIU value of < 1 indicates input congestion or excessive use of resources, such as fuel and labor, relative to the catch obtained.
5. **Scale efficiency (SE)** is calculated from the ratio of CRS to VRS efficiency (Schrobback *et al.* 2023):

$$SE = \frac{TE_{crs}}{TE_{vrs}} \dots \dots \dots (5)$$

With:

SE=1: operating at optimal scale

SE<1: there is scale inefficiency \rightarrow , indicating the need to adjust the scale of production.

6. Analysis of differences in efficiency between ship capacity groups was conducted using the Wilcoxon rank sum test.

RESULTS

Vessel Characteristics

Table 2 presents the descriptive statistics for the tuna handline fleet, stratified into two size classes: vessels under 5 GT (n=58) and vessels 5–10 GT (n=20). The data reveals distinct structural differences between the groups. The **5–10 GT fleet** exhibits significantly higher operational capacity, averaging 6.50 GT with larger crews (5.80 persons) and nearly double the fuel consumption (912.50 liters) compared to the **<5 GT group** (3.21 GT, 4.45 persons, and 542.41 liters). This capacity translates into greater productivity, where larger vessels landed an average catch of 1,074.44 kg from 4.70 trips, substantially outperforming the smaller vessels (354.87 kg

from 2.88 trips). Notably, the high standard deviation in fuel consumption for the <5 GT group (544.05) exceeds its mean, indicating extreme heterogeneity in resource use. This variability underscores the necessity of using Data Envelopment Analysis (DEA) to evaluate the underlying technical efficiency beyond these aggregate averages.

Efficiency indicators

The box plot analysis highlights a distinct trade-off between vessel groups. Vessels **under 5 GT** exhibit high Scale Efficiency (mostly >0.8), indicating optimal physical size, but struggle with low Capacity Utilization (CU) (0.18–0.50) and variable Technical Efficiency (0.26–0.67). Conversely, the **5–10 GT fleet** demonstrates superior managerial performance—evident in higher and more uniform CU and TE scores (predominantly 0.6–1.0)—but shows significant variability in Scale Efficiency, suggesting potential scale mismatches despite their operational capability.

Table 2 Descriptive statistics of tuna handline vessels <5 GT and 5–10 GT in Majene Regency.

Vessel Capacity	<5 GT (n=58)		5–10 GT (n=20)	
Statistics	Mean	Standard Deviation	Mean	Standard Deviation
GT (Gross ton)	3.21	0.69	6.50	1.61
Fuel (liters)	542.41	544.05	912.50	462.79
Crew (person)	4.45	0.96	5.80	1.06
Trip	2.88	2.87	4.70	2.15
Catch (kg)	354.87	481.49	1,074.44	801.68

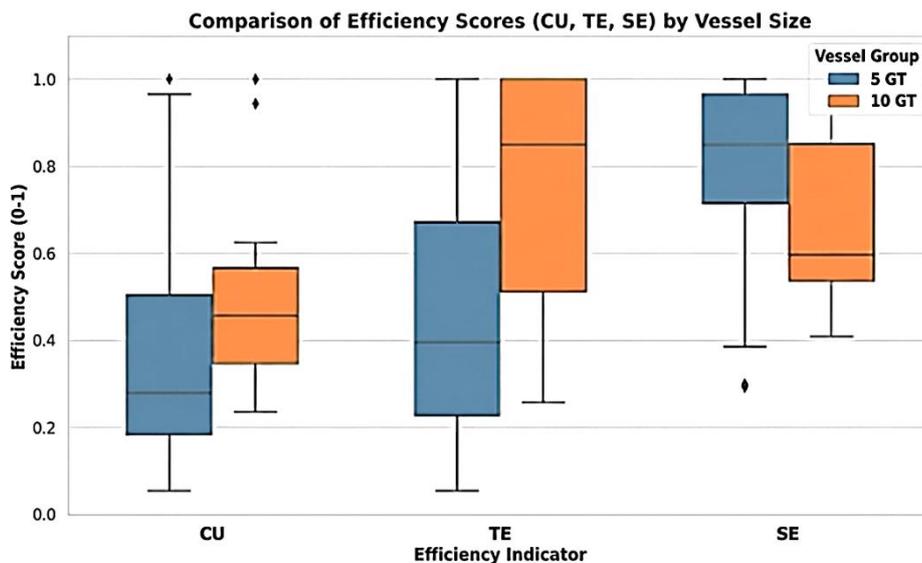


Figure 2 Distribution of capacity utilization rate, technical efficiency, and scale efficiency of vessels <5 GT and 5 - 10 GT on tuna handlines.

Table 3 Mean CU, TE, and SE of tuna *handline* vessels by GT size group

GT group	Mean CU (SD)	Average TE (SD)	Mean SE (SD)
< 5 GT	0.374 (0.276)	0.461 (0.294)	0.815 (0.203)
5-10 GT	0.505 (0.234)	0.756 (0.263)	0.681 (0.201)

Table 4 Mann-Whitney Test Results for Differences in CU, TE, and SE Values Based on Ship GT Size

Comparison	Variable	W statistic	p-value	Conclusion
<5 Gt vs 5-10 Gt	CU	348	0.0081	✔ Significantly different
<5 Gt vs 5-10 Gt	TE	259.5	0.0002	✔ Significantly different
<5 Gt vs 5-10 Gt	SE	812	0.0077	✔ Significantly different

The average **Capacity Utilization (CU)** value for the <5 GT vessel group was 0.374 (SD = 0.276), lower than the 5-10 GT group, which reached 0.505 (SD = 0.234). Similarly, **Technical Efficiency (TE)** shows a considerable difference, with an average value of 0.461 (SD = 0.294) for vessels <5 GT and 0.756 (SD = 0.263) for vessels 5-10 GT. In contrast, **Scale Efficiency (SE)** tends to be higher in the <5 GT group, at 0.815 (SD = 0.203), compared to 5-10 GT vessels, which have an average SE of 0.681 (SD = 0.201).

The Mann-Whitney test revealed significant differences in all three indicators (CU: p = 0.0081; TE: p = 0.0002; SE: p = 0.0077), confirming that vessel size statistically affects technical efficiency, capacity, and scale of production.

Variable Input utilization (VIU)

VIU values for vessels <5 GT vary and are often <1, especially for fuel and Crew, indicating potential technical improvements. Meanwhile, vessels with a gross tonnage of 5-10 GT almost entirely exhibit a VIU of 1, indicating optimal *input* utilization (Figure 3).

Analysis of λ (λ) values for fuel, crew, and trip inputs reveals potential efficiency in input utilization. Vessels <5 GT have an average λ for fuel of 0.887, crew of 0.933, and optimal trip at 1.00. A total of 29 vessels on fuel and crew have $\lambda < 1$, indicating room for input reduction without sacrificing output. The 5-10 GT vessels show λ values close to 1 on all inputs, with only a few vessels having $\lambda < 1$ or > 1 , indicating better input efficiency overall.

This finding highlights the importance of interventions to enhance operational efficiency on small vessels, particularly in managing fuel and labor inputs.

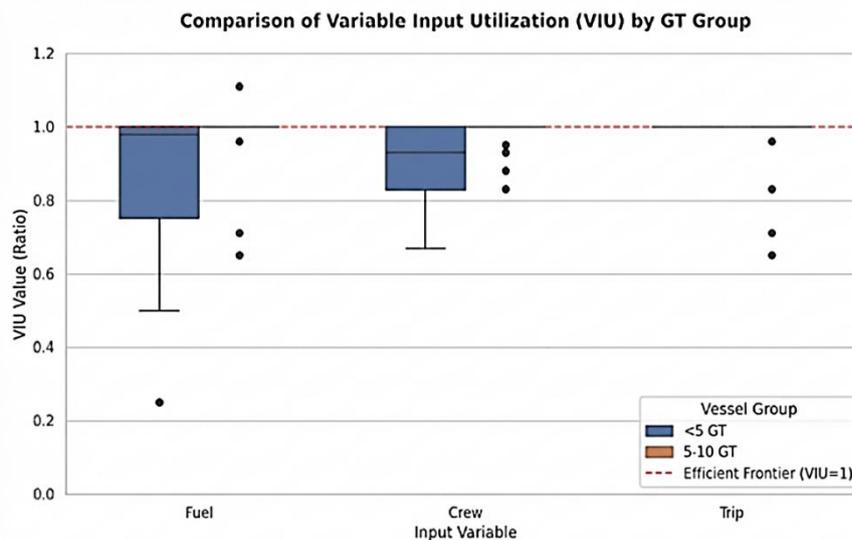


Figure 3 Comparison of VIU values by GT and *input* type

Table 5 Average and Distribution of Lambda (λ) Values for Production Inputs by Vessel Size

vessel capacity	<5 GT (n=58)			<10 GT (n=20)		
inputs	Fuel	Crew	Trip	Fuel	Crew	Trip
mean (λ)	0.887	0.933	1	0.972	0.979	0.958
$\lambda < 1$	29	18	0	4	5	5
$\lambda = 1$	29	40	58	15	15	15
$\lambda > 1$	0	0	0	1	0	0

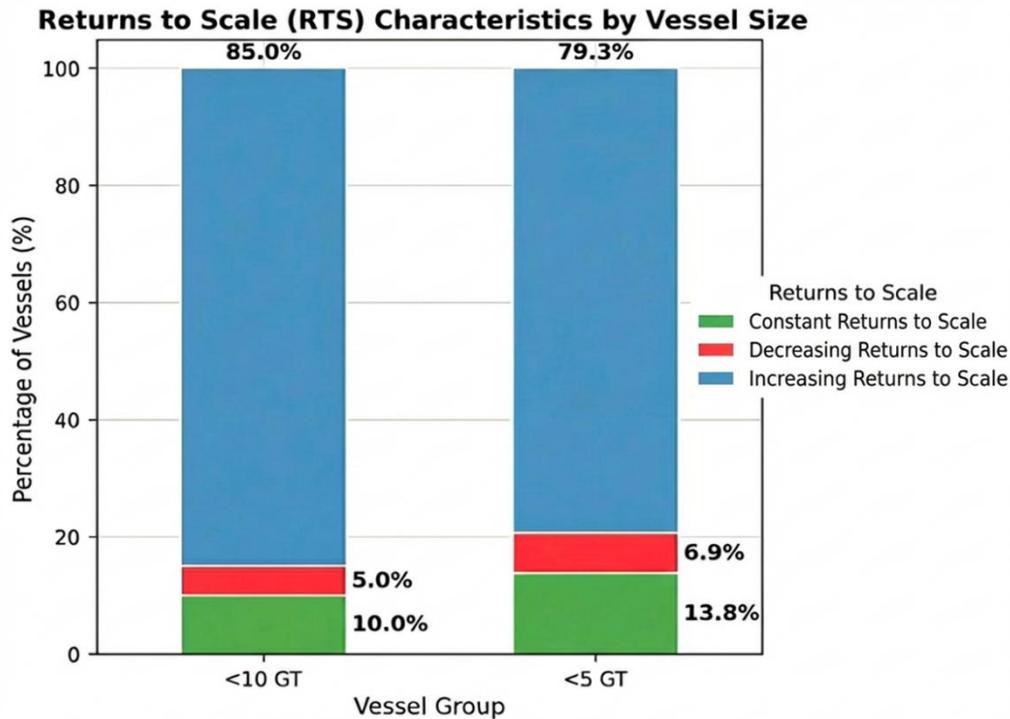


Figure 4 Distribution of Returns to Scale (RTS) per GT group of vessels

Returns to Scale (RTS)

The distribution graph of Returns to Scale (RTS) shows that the majority of vessels in both GT groups operate under increasing returns to scale (IRS) conditions, with approximately 80% of vessels in both the <5 GT and 5-10 GT groups. In contrast, only a small percentage of vessels are in decreasing returns to scale (DRS) or constant returns to scale (CRS).

DISCUSSION

Efficiency Performance of Fishing Units

This study employed an output-oriented DEA model under the VRS assumption (Efendi *et al.* 2020; Kamiyama & Miyata 2023; Siahainenia *et al.* 2017) to evaluate small-scale tuna handline fisheries in West Sulawesi based on Capacity Utilization (CU), Technical Efficiency (TE), and Scale Efficiency (SE) (Figure 2). While previous research reports

general utilization rates ranging from 75% to 100% (Liu *et al.* 2021; Tidd *et al.* 2025), our analysis using Wilcoxon rank-sum tests revealed significant differences across vessel groups for all indicators ($p < 0.01$). This confirms that vessel size fundamentally dictates efficiency outcomes.

1. Capacity Utilization (CU)

Capacity Utilization (CU), defined as the ratio of current production to maximum potential production, remains generally low across the fleet. Vessels <5 GT averaged a CU of only 0.374, while the 5–10 GT group performed better with an average of 0.505. These low values align with trends in Chinese offshore fisheries (Gbigbi 2019) and the Mediterranean (Dong *et al.* 2022), where suboptimal utilization is common. However, the specific cause differs by vessel size in West Sulawesi. For small-scale fishers (<5 GT), the inability to maximize output stems from

structural barriers, including limited access to technology and weak managerial capacity (Al-Siyabi *et al.* 2021; Kasim *et al.* 2021; Siyabi & Bose 2018). Similarly, studies in the Mediterranean and Asia have shown that a lack of capital and outdated technology contribute to inefficiencies (Liu *et al.* 2021; Liu *et al.* 2025; Yang *et al.* 2022). Conversely, the higher CU in the 5–10 GT group suggests that larger vessels benefit from capital investment and operational flexibility (Cooke *et al.* 2021; Walden & Atwood 2023).

2. Technical Efficiency (TE) vs. Scale Efficiency (SE)

A distinct trade-off was observed between technical and scale efficiency across the vessel groups. Vessels under 5 GT demonstrated high Scale Efficiency (average 0.815), indicating they operate near their optimal physical size. However, their Technical Efficiency (TE) was low (average 0.461), with most units concentrated in the 0.2–0.4 range. This disparity suggests that while the physical dimensions of these vessels are appropriate, their operational management—specifically regarding skipper skill and input allocation—remains inefficient.

In contrast, larger vessels in the 5–10 GT category achieved a high TE (average 0.756), a performance level comparable to efficient fleets observed in Maluku (Moniharapon *et al.* 2024) and Gorontalo (Olii *et al.* 2019). Despite this high managerial efficiency, their Scale Efficiency was significantly lower (average 0.681), indicating that they frequently operate outside the efficient scale, a condition likely driven by unplanned expansion or overcapacity relative to the available resources (Kamiyama & Miyata 2023).

The VIU analysis reinforces the TE findings. Vessels 5–10 GT have almost entirely achieved efficient input utilization ($VIU \approx 1$) (Figure 3). In comparison, vessels <5 GT exhibit significant waste, particularly in fuel and labor. The findings confirm that the low technical efficiency (TE VRS) of the <5 GT fleet stems from allocative inefficiencies in fuel and crew management rather than suboptimal vessel size. Therefore, optimization requires technological interventions for fuel economy and the rationalization of crew numbers. This confirms that profitability for small vessels is eroded not by their size, but by inefficient operational practices, such as excessive trip duration relative to catch, a challenge also noted in the Philippines (Digal *et al.* 2017).

Most vessels in both groups exhibited *Increasing Returns to Scale* (IRS) (Figure 4), demonstrating a clear opportunity: output can be increased more than input. This suggests that sustainable fisheries management can best enhance productivity by targeting operational improvements, adopting appropriate technology, and strengthening technical capacity, rather than merely expanding inputs such as vessel numbers or gear. Focusing on operational practices is thus crucial for increasing overall capacity utilization (Kamiyama & Miyata 2023).

Challenges in Optimization and Overcapacity Risks

The findings indicate that most tuna handline vessels in West Sulawesi continue to face significant challenges in optimizing input management. For smaller vessels, low technical efficiency highlights the need for rationalizing input use, particularly fuel, through better operational practices (Gómez & Maynou, 2020). However, high efficiency in larger vessels (5–10 GT) also carries inherent risks; if unmanaged, increased efficiency can lead to overcapacity (Pauly & Zeller 2016). Reducing this capacity is crucial, as overcapacity not only reduces technical efficiency but also threatens resource sustainability and fleet profitability globally (Bell *et al.* 2016; Tidd *et al.* 2023b). Despite its importance, excess capacity persists worldwide, often driven by subsidies and structural governance failures (Hopewell 2022; Rust *et al.* 2016). This issue is exacerbated by climate change, which makes inefficient fleets particularly vulnerable (Tidd *et al.* 2023a). Patterns of overexploitation are widespread: South China Sea resources are 57% overfished (Roberts *et al.* 2017), China faces declining carrying capacity (Colloca *et al.* 2017), and South Korea's octopus fisheries and Egypt's Mediterranean fleet struggle with overcapacity (Sala *et al.* 2018; Liu *et al.* 2021).

Policy Implications for West Sulawesi

In West Sulawesi, the observed low technical efficiency reflects both wasted resources and untapped economic potential. Therefore, governance must shift towards efficiency-based management to strengthen sustainability. To address the specific structural causes of inefficiency identified in this study, policy interventions must be targeted rather than uniform:

- a) **Capacity Building for Small Vessels (<5 GT):** Since these vessels are scale-efficient but technically inefficient, policies should prioritize

output improvements rather than physical expansion. Interventions should focus on training and the adoption of catch-efficiency technologies (modern gear, fish finders) to improve managerial capability and optimize fuel and labor use.

- b) **Effort Control for Medium Vessels (5–10 GT):** For the larger fleet, where technical efficiency is high but scale efficiency is compromised, the primary policy focus must be balancing business capacity with stock availability. To prevent the economic waste associated with scale inefficiency and overcapacity, measures such as catch quotas, limited entry, and catch share systems are recommended (Bertheussen & Vassdal 2022; Ding *et al.* 2022).
- c) **Strengthening Governance.** Addressing these disparities requires proactive policy interventions to reduce stress on stocks (Béné *et al.* 2015; Akinyemi *et al.* 2022). Strategies must include optimizing fishing effort distribution and strengthening regulations against illegal fishing. Excess capacity, if left unaddressed, will undermine regulatory control overfishing effort (Jennings & Yamazaki 2016). Therefore, adaptive, data-driven governance is essential to enhance both the profitability of fishers and the long-term sustainability of tuna resources.

CONCLUSION

Vessel size drives efficiency differences in West Sulawesi's handline fishery. Vessels of 5–10 GT are more efficient in utilizing fishing capacity and production inputs (average TE 0.756 and CU 0.505), while vessels under 5 GT tend to operate closer to the optimal scale (average 0.815 vs. 0.681), with most exhibiting *Increasing Returns to Scale* (IRS). These patterns imply remaining productivity potential, requiring operational improvements for <5 GT vessels and business strengthening with effort control for the 5–10 GT fleet.

RECOMMENDATION

Based on the efficiency trade-offs identified, this study proposes a targeted "two-track" management policy. For the <5 GT fleet, interventions must prioritize output optimization through capacity building—

specifically skipper training and the adoption of modern technologies (GPS, Fish Finders)—rather than physical expansion. Conversely, for the 5–10 GT fleet, strict effort control measures, such as licensing limits or catch quotas, are required to prevent overcapacity. At the practical level, fishers are encouraged to improve fuel-efficient behaviors and form cooperatives to consolidate business costs.

However, this study has limitations related to the availability and depth of data on fishing effort and technical inputs. Additionally, the DEA approach overlooks external environmental and socioeconomic factors that inevitably impact efficiency levels. Therefore, these quantitative results need to be complemented with qualitative analysis and the use of **panel data** in future research to capture seasonal variations and provide a holistic understanding of fishery performance.

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