Int. J. Aquat. Biol. (2026) 14(3): 136-147
ISSN: 2322-5270; P-ISSN: 2383-0956
Journal homepage: www.ij-aquaticbiology.com

Original Article

Quantifying the effect of trolling speeds on catch composition, CPUE, and fuel consumption in Teluk Tamiang, Indonesia

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Abstract: Trolling speed is an operational factor that can influence catch performance and fuel use in small-scale pelagic fisheries, yet its quantitative effects remain insufficiently documented in Indonesian waters. This study evaluated the influence of towing speed on catch composition, catch per unit effort (CPUE), and fuel consumption during trolling operations in Teluk Tamiang, Indonesia. A total of 32 fishing operations were conducted at two towing speeds (4 and 8 knots), each repeated 16 times, resulting in 264 fish dominated by narrow-barred Spanish mackerel (*Scomberomorus commerson*), trevally (*Caranx tille*), and barracuda (*Sphyraena jello*). Although total biomass did not differ significantly between speeds, species-specific responses were evident: faster towing favored highly active predators such as mackerel, whereas slower speeds attracted opportunistic feeders, including trevally and barracuda. Mean CPUE at 8 knots (5.45 kg trip^{-1}) was approximately 1.5 times higher than at 4 knots (3.62 kg trip^{-1}) and improved distance-based fuel efficiency; however, it required 35-40% higher hourly fuel consumption. Conversely, the lower speed produced smaller catches but greater catch-per-liter efficiency, indicating clear trade-offs between fishing performance and fuel use. These findings highlight towing-speed optimization as a practical operational strategy for balancing catch productivity and energy efficiency in small-scale trolling fisheries.

Article history:
Received 26 March 2026
Accepted 7 May 2026
Available online 15 June 2026

Keywords:
Fuel efficiency
Lure behavior
Sustainability
Towing speed
Trolling fishery

Introduction

Trolling (troll line fishing) is a common method employed in artisanal and small-scale marine fisheries throughout tropical and subtropical regions (FAO, 2024). It is a fishing technique in which a boat moves through the water, dragging a line with hooks, lures, or bait near the water's surface. The line is set at a specific depth to target certain fish species, which are attracted to the bait and move towards the hooks (Eighani et al., 2019). The catch efficiency and species composition of trolling operations are influenced by multiple factors, including lure type, hook size and type, fishing area, sea conditions, towing speed, and biological aspects of the fish target (Annida et al., 2021; Manjunathan et al., 2023).

Troll line fishing is crucial to coastal livelihoods in Indonesia, targeting species such as mackerel, tuna, and skipjack (Suharyanto et al., 2020). However, research on the most favorable towing speed for small-scale fleets is lacking, with most studies focusing on commercial fisheries that operate differently (Anggawangsa et al., 2023). Local knowledge of fish movements and distribution is key to success, making it challenging to apply commercial findings to small-scale fisheries like those in the Kotabaru Regency of South Kalimantan Province.

Boat speed plays a critical role in determining lure behavior and fish response (Jones et al., 2008). Fast-moving lures tend to attract active, fast-swimming species such as mackerel and tuna, whereas slower speeds are more effective for ambush predators like trevally. Understanding this relationship is essential for maximizing catch efficiency while minimizing fuel consumption and bycatch (FAO, 2024).

Optimizing towing speed is particularly important in regions where small-scale fisheries are central to food security and livelihoods (Stacey et al., 2021). Even minor variations in towing speed can

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DOI: https://doi.org/10.22034/ijab.v14i3.2856

substantially influence catch rates, species composition, and fuel usage. For example, adjustments to hook depth and towing speed in troll-line fisheries have been shown to affect the catchability of target species (Kebede et al., 2016). Higher speeds will also increase fuel consumption costs compared to slower speeds (Bastardie et al., 2022). Establishing an optimal range of towing speeds and fuel can therefore improve both efficiency and species selectivity, contributing to more sustainable fishing practices.

In this study, the term "optimal" is defined in relation to operational performance indicators, specifically catch rate, CPUE, and fuel use, rather than broader ecological or economic sustainability considerations. Although towing speed affects these operational metrics, improved performance under specific speed conditions should not be interpreted as evidence of sustainable exploitation, as this is influenced by additional factors, including stock condition, size selectivity, and economic returns, which are not examined in the present analysis.

Our research seeks to inform evidence-based management practices for sustainable small-scale troll line fisheries. We describe the technical characteristics of troll line gear, analyze species-specific responses to varying towing speeds, and evaluate the relationship between operational speed and fuel efficiency. By integrating biological, technical, and economic perspectives, this research provides valuable insights into the trade-offs between fishing performance and energy use. The findings are expected to contribute to the development of sustainable fishing guidelines and enhance the resilience of small-scale coastal fisheries in Indonesia and other developing countries.

Materials and Methods

Study site: The study was conducted in the coastal waters of Teluk Tamiang (4°05′S, 116°06′E), located in Kotabaru Regency, South Kalimantan, Indonesia (Fig. 1). This semi-enclosed bay forms part of the southern Makassar Strait ecosystem, characterized by mixed oceanographic influences from the Java Sea and the Flores Sea. The area features shallow marine habitats dominated by coral reef complexes, sandy bottoms, and scattered seagrass beds, with a high diversity of pelagic and reef-associated fish species.

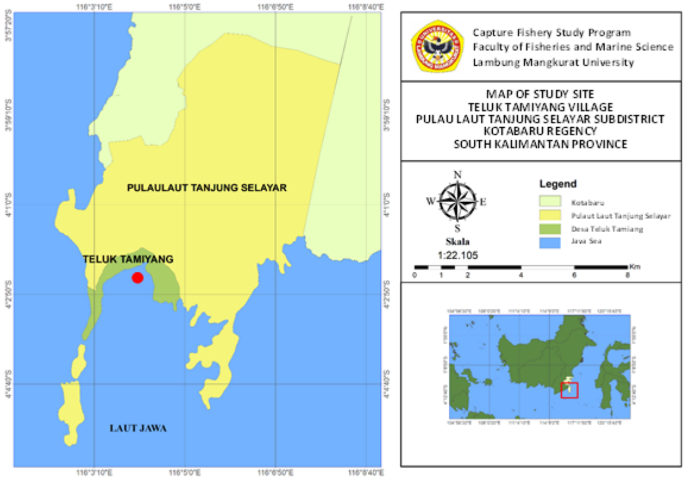

Figure 1. Map of Teluk Tamiang village in Kotabaru Regency, Indonesia.

Local fisheries in Teluk Tamiang are dominated by small-scale artisanal operations using 3 GT wooden motorized boats (L×B×D = 10×1.8×1 m), equipped with a 24 HP single-cylinder Dongfeng diesel engine (Fig. 2). These vessels typically operate within 9-12 nautical miles from the shore and conduct daily fishing trips of 4-8 h duration. The region is a representative site for troll line fishing in South Kalimantan, where local communities rely heavily on pelagic fish resources for both subsistence and income generation. Research activity was conducted from April to July 2023, including field surveys, experimental fishing, and data analysis.

Fishing gear and experimental design: The troll line gear construction (Fig. 3) consisted of a 6-m bamboo rod (70 mm diameter), a 40-m of nylon monofilament main line (1 mm diameter), stainless steel upper and lower swivels, a 15-m iron steel wire leader (0.6 mm diameter), a 5-m nylon monofilament lower line (0.4 mm diameter), PVC artificial lures (12 cm length, 20 mm width), and stainless-steel hooks (5 cm length, 20 mm width). The gear specification was presented in Table 1.

Two towing speed treatments were tested: 4 knots and 8 knots, representing the typical operational range

Table 1. Gear specifications for troll-line fishing in Teluk Tamiang.

Gear Components	Materials	Length (m)	Width (cm)	Diameter (mm)
Rod	Bamboo	6	-	70
Main line	Nylon Monofilament	40	-	1
Upper swivel	Stainless steel	0.04	1.5	-
Wire leader	Iron steel	15	-	0.6
Lower swivel	Stainless steel	0.02	0.5	-
Lower line	Nylon Monofilament	5	-	0.4
Hook (J-hook)	Stainless steel, No. 7	0.05	2	-
Artificial lure	PVC	0.12	2	1

Figure 2. Equipment and a fishing boat used for trolling line operation.

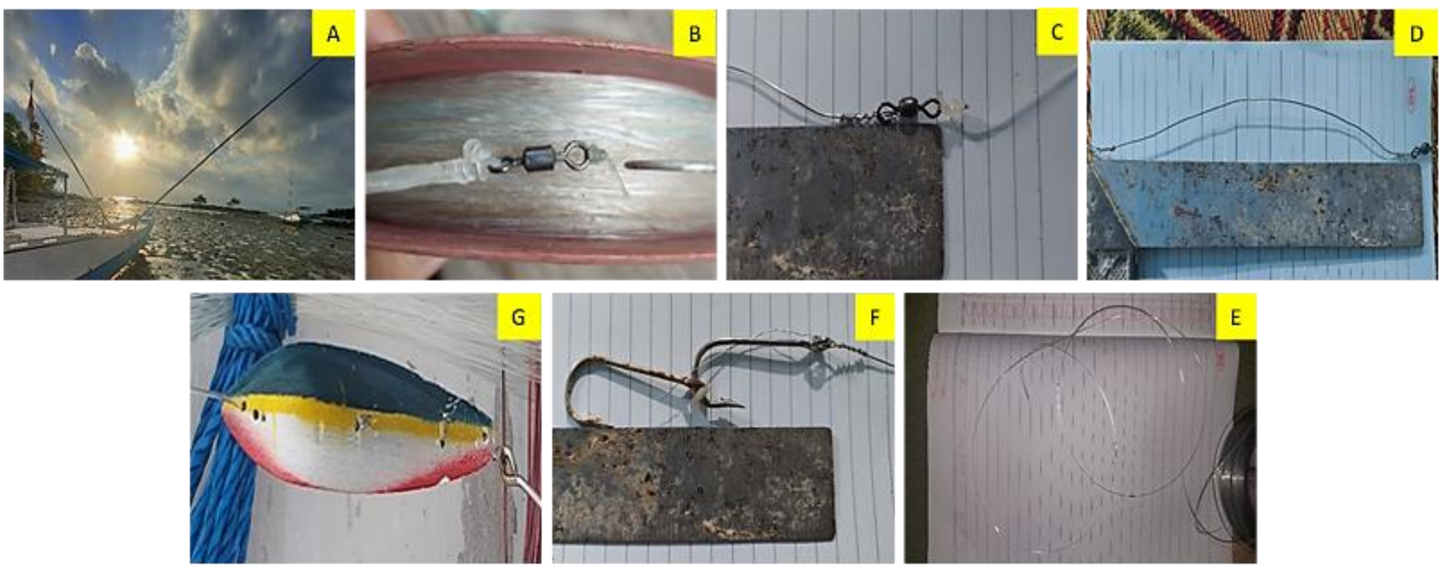

Figure 3. Gear components of the troll line used for catching pelagic species in Teluk Tamiang. (A) Rod, (B) Main line and upper swivel, (C) Lower swivel, (D) Wire leader, (E) lower line, (F) Hook, and (G) Artificial lure.

used by local troll line fishers. Daily catch data were collected from troll line operations on 16 independent fishing trips for each towing speed treatment. Each trip was treated as a single replicate, resulting in a total of 32 observations. Fishing was conducted during daylight hours (06:00-14:00), following randomized treatment order (e.g., 8 → 4 → 8 → 4 knots) to minimize temporal or environmental bias. All trips were conducted under comparable sea states and weather conditions. Environmental parameters, including sea surface temperature (28.5-29.5°C), salinity (33-35 ppt), and depth (20-50 m), were meticulously recorded to capture potential fluctuations. To account for potential temporal variation in weather and sea conditions, the experimental design employed a Randomized Block Design (RBD), with each day constituting a distinct block, and speed treatments were randomly assigned to minimize bias and ensure robust comparisons.

All trolling operations were performed under consistent sea conditions (e.g., wave height < 0.5 m and wind speed < 15 km.h^{-1}) to minimize environmental variability. The same vessel, crew, and carefully planned fishing route were maintained across all treatments to ensure comparability and reliability of the results. The trolling lines were deployed approximately 30-50 m astern of the vessel to allow natural lure movement and reduce noise disturbance from the propeller, thereby increasing the chances of successful fishing.

Data collection and analysis: We identified all caught fish to species level based on White et al. (2013). Each specimen was then counted, weighed to the nearest 0.1 kg using a digital scale, and measured for length to the nearest mm using a measuring tape. No size-selective sorting was performed to ensure full representation of the species composition and actual fishery output. Catch data was standardized to Catch per unit effort (CPUE) in kg trip^{-1} to compare fishing efficiency. Effect size was calculated using Cohen's *d* formula (Cohen, 1988) of $d = (M_1\text{-}M2) / S_p$, which quantifies the standardized difference between the mean catches of the two towing-speed treatments, where M_1 is the mean catch at 8-knot towing speed, M_2 is the mean catch at 4-knot towing speed, and S_p is the pooled standard deviation (S_1, and S_2) of both treatments that is calculated as:

$$S_p = \sqrt{\frac{(n_1 - 1)\, S_1^2 + (n_2 - 1)\, S_2^2}{n_1 + n_2 - 2}}$$

Cohen's *d* is commonly interpreted using the following thresholds: 0.2 indicates a small effect; 0.5 indicates a medium effect; 0.8 indicates a large effect; and values greater than 1.2 indicate a very large effect. The proportion of catch composition was calculated using the formulas (Krebs, 1989; Kurnia et al., 2023) of $P = ni/N \times 100\%$, where *P* is the proportion of the fish species caught by the troll line (%), *ni* is the number of catches of the *i*-th fish species (individual or kg), and *N* is the total catch (individual or kg).

Fuel consumption for troll line boats operating at different towing speeds was quantified through direct measurement during field observations in Teluk Tamiang waters. Fuel usage was recorded using a calibrated flow meter installed between the fuel tank and engine, with readings taken at two controlled towing speeds: 4 knots and 8 knots. The total volume of fuel consumed (L.h^{-1}) was divided by the distance traveled (kmh^{-1}) to determine the fuel consumption rate per kilometer (L.km^{-1}). These data were then averaged across trips to obtain representative values for each speed category, allowing comparison of energy efficiency between lower and higher towing speeds.

To ensure comparability between treatments, fishing effort was operationally standardized at the trip level. Each trolling trip was conducted over a comparable duration (4-5 h), along similar fishing routes, and within consistent spatial ranges (9-12 nautical miles from shore). The same vessel, crew, and gear configuration were maintained across all operations. Although towing speed influences the distance covered per unit time, CPUE in this study is expressed on a per-trip basis (kg.trip^{-1}), reflecting the practical unit of effort commonly used in small-scale fisheries. Therefore, the results should be interpreted as relative catch performance per fishing operation, rather than strictly effort-normalized catch rates in terms of swept area or distance.

Although the experimental design followed a randomized block structure (with day as a blocking factor), the relatively small number of observations per block limited the application of a full two-way or mixed-effects model. Therefore, statistical comparisons were conducted using independent *t*-tests to evaluate overall differences between towing-speed treatments. This approach provides a simplified assessment of treatment effects, and the results should be interpreted as indicative rather than fully accounting for potential day-to-day variability.

Data analysis followed standard statistical procedures (Zar, 2009). Normality of residuals was assessed using the Lilliefors test, and homogeneity of variance was evaluated with Levene's test. Differences in mean catch and CPUE between treatments were analyzed using independent *t*-tests at a 95% confidence level (P<0.05). All analyses were conducted using Microsoft Excel and SPSS version 18.0.

Results

Catch composition: A total of 264 individuals of three pelagic species were captured during the experimental trolling operations: the narrow-barred Spanish mackerel *(Scomberomorus commerson*), trevally *(Caranx tille*), and barracuda (*Sphyraena jello*). These species are common inhabitants of the semi-enclosed coastal waters of Teluk Tamiang and represent the principal targets of the local small-scale troll line fishery.

The data clearly showed that trolling speed is a key determinant of the target species, with some species consistently striking fast-moving lures while others prefer slower presentations. At 8 knots, catches were dominated by Spanish mackerel (69 fish; 212.1 kg). This speed produced the highest overall biomass (263.1 kg). While the slower 4-knot trolling speed successfully targeted trevally (71 fish; 35.6 kg) and barracuda (38 fish; 53.5 kg). Despite barracuda being slightly heavier and more numerous at this speed, the overall biomass remained lower (178.8 kg). The total biomass recorded across all operations amounted to 441.9 kg (Table 2). The study also recorded significant size variation among the species: Spanish mackerel averaged the largest at 75 cm (3.1 $kg.fish^{-1}$), followed by barracuda at 50 cm (1.4 $kg.fish^{-1}$), and travelly at 32.5 cm (0.5 $kg.fish^{-1}$).

Trolling speed and catch analysis: The independent *t*-test (Table 3) revealed a significant difference in mean daily catch between 4 knots and 8 knots (P<0.001). The 8-knot towing speed resulted in substantially higher catches compared to 4 knots. The results also indicate that trolling speed significantly affects CPUE in the troll line fishery (Table 4). The mean CPUE at 8 knots (5.45 $kg.trip^{-1}$) was approximately 1.5 times higher than at 4 knots (3.62 $kg.trip^{-1}$), indicating improved catch performance at higher speeds, particularly for fast-swimming species such as mackerel. However, these differences should be interpreted in light of the operational definition of effort applied in this study. Although trips were standardized in duration and fishing conditions, higher towing speeds inherently increased the distance covered per trip. As a result, the elevated CPUE at 8 knots likely reflects a combined effect of greater encounter probability and speed-related catchability, rather than the influence of towing speed alone.

The daily catch differed markedly between the two

Table 2. Catch composition of troll line fishing at different towing speeds in Teluk Tamiang.

Catch and Length size	4 knots				8 knots				Total Catch			
	ind.	**%**	**kg**	**%**	**ind.**	**%**	**kg**	**%**	**ind.**	**%**	**kg**	**%**
Mackerel 70–80 cm	29	21.01	89.7	50.17	69	54.76	212.1	80.62	98	37.12	301.8	68.30
Trevally 30–35 cm	71	51.45	35.6	19.91	28	22.22	12.7	4.83	99	37.50	48.3	10.93
Barracuda 45–55 cm	38	27.54	53.5	29.92	29	23.02	38.3	14.56	67	25.38	91.8	20.77
Total	138	100	178.8	100	126	100	263.1	100	264	100	441.9	100

Table 3. Statistical analysis of troll line catch data using the t-test.

t-test: Two-Sample Assuming Unequal Variances	Variable 1	Variable 2
Mean	10.85	16.34375
Variance	5.72	20.74
Observations	16	16
Hypothesized Mean Difference	0	
df	23	
t Stat	-4.27214	
$P(T \leq t)$ two-tail	0.00029	
t Critical two-tail	2.06866	

Table 4. CPUE comparison of troll line fishing at different towing speeds.

Catch number (kg)		Total effort (trip)	CPUE (kg.trip^{-1})	
4 knots	8 knots		4 knots	8 knots
84.3	211.3	16	5.27	13.21
34.6	13.1	16	2.16	0.82
54.7	37.1	16	3.42	2.32
57.87	87.17	16	3.62	5.45
173.6	261.5	-	10.85	16.34

Table 5. Comparison of fuel consumption at 4 and 8 knots in Teluk Tamiang.

Parameter	Unit	4 Knots	8 Knots (+35%)	8 Knots (+40%)
Boat speed	km.h^{-1}	7.408	14.816	14.816
Fuel consumption per hour	L.h^{-1}	2.500	3.375	3.500
Fuel consumption per kilometer	L.km^{-1}	0.337	0.228	0.236

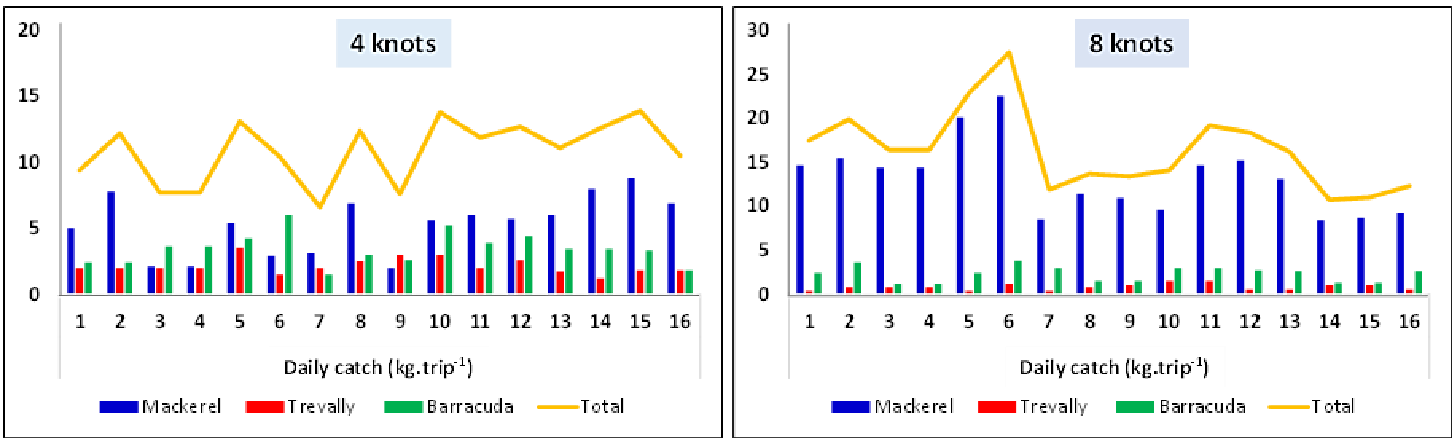

Figure 4. Daily catch distribution by species as a function of two different towing speeds across the 16 trolling operations.

towing-speed treatments. The 8-knot treatment produced consistently higher catch values (10.7-27.5 kg.trip^{-1} with a mean of 16.3±4.4 kg.trip-1) compared to the 4-knot treatment (6.6-13.9 kg.trip-1 with a mean of 10.9±2.1 kg.trip^{-1}). Mackerel accounted for the majority of biomass in both treatments, while trevally and barracuda remained small fractions of the total catch. The difference in total performance is visually represented by the trend lines (Fig. 4). The steeper and more variable yellow trend line associated with the 8-knot setting indicates consistently elevated catch rates compared to low-speed treatment, which produced consistent but modest yields over the 16 fishing trips.

Figure 5 clearly demonstrates a separation between the two towing-speed treatments. The 8-knot treatment exhibited a markedly higher median daily catch and a broader interquartile range (IQR) than the 4-knot treatment. In contrast, the 4-knot treatment showed a lower median catch with a narrower IQR, reflecting more consistent but reduced catch performance. Collectively, these patterns suggest that increasing towing speed to 8 knots enhances catch yield while also increasing variability in daily catches.

Cohen's d effect size: The calculated effect size (Cohen's d = 1.51) indicates a very large practical difference between the two towing-speed treatments. While the results confirmed significant differences in mean catch, the effect size quantifies the magnitude of these differences, demonstrating that they are not only detectable but substantial. Values of d > 1.2 are typically classified as very large effects, indicating that the 8-knot treatment consistently yielded higher catches than the 4-knot treatment, with minimal overlap between their respective distributions. This confirms that the observed difference is both ecologically and operationally meaningful.

Fuel efficiency and operational performance: Fuel consumption estimates were derived from flow meter

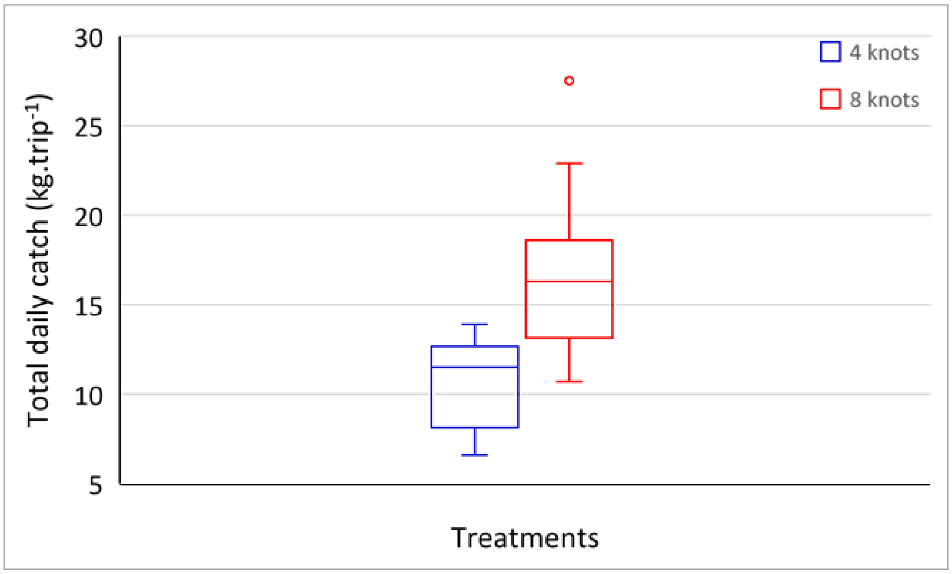

Figure 5. Comparison of the total daily catch between the 4-knot and 8-knot towing speed treatments, showing a higher median and wider IQR at 8 knots.

measurements conducted under controlled towing conditions at both speeds. Average fuel use at 4 knots was 2.5 $L.h^{-1}$, while estimates for 8 knots ranged from 3.38 to 3.50 $L.h^{-1}$, corresponding to an increase of approximately 35-40% (Table 5). When standardized by distance traveled, fuel consumption was lower at 8 knots (0.228-0.236 $L.km^{-1}$) compared to 4 knots (0.337 $L.km^{-1}$). However, these estimates represent averaged operational values rather than continuous real-time measurements across all fishing trips.

Discussions

The present results indicate that trolling speed is a critical operational parameter influencing catch performance and fuel consumption in a small-scale troll line fishery. Higher towing speed (8 knots) increased CPUE, particularly for fast-swimming pelagic species such as Spanish mackerel, while lower speed (4 knots) reduced catches but lowered fuel consumption. These findings demonstrate clear trade-offs between fishing performance and fuel efficiency, rather than identifying a universally optimal or sustainable towing speed.

The observed catch composition is consistent with local fishers' experiential knowledge, who routinely adjust trolling speed according to target species and sea conditions. The significantly higher catches at 8 knots suggest that increased trolling speed enhances lure action and expands the effective fishing area, thereby increasing encounter rates with the target species. Faster towing likely generates stronger hydrodynamic disturbance and increased lure activity, which may enhance visibility and stimulus cues for fast-swimming pelagic species such as mackerel (Mittelbach et al., 2014). However, these mechanisms were not directly measured in the present study and should be considered as plausible explanations rather than demonstrated effects. Comparable patterns have been reported in Indian troll line fisheries, where higher towing speeds resulted in increased mackerel catch rates (Manjunathan et al., 2023). However, the mackerel captured in the present study were smaller than those reported from the Gulf of Oman (Eighani et al., 2019), likely reflecting differences in stock structure, fishing grounds, or gear configuration.

In contrast, the lower yields at 4 knots suggest that lure motion at reduced speeds may fall below the optimal stimulus threshold required to trigger mackerel strikes, while also limiting the horizontal area swept per unit effort. At slower speeds, lures may exhibit less dynamic movement, potentially reducing their attractiveness to highly mobile predators, although this behavioral response was not directly quantified. The strong differences observed confirm trolling speed as a critical operational factor influencing catch performance, speed-dependent hydrodynamic, and behavioral mechanisms in pelagic fisheries. Kebede et al. (2016) demonstrated that increased towing speed enhances lure vibration frequency and strike rates in visually oriented predators such as hairtail and mackerel. Nevertheless, excessively high speeds may reduce catchability for species with limited burst-swimming capacity, underscoring the need for speed optimization. Experimental evidence linking fish swimming behavior to hydrodynamic indicators further supports these mechanisms (Liu et al., 2023).

Although towing speed significantly influenced species composition and catch rates, the ecological implications of these differences cannot be fully assessed within the scope of the present study. No information on stock status, population structure, or exploitation levels was available, limiting inference regarding sustainability. While individual fish lengths were measured, size-at-speed comparisons were not explicitly analyzed and therefore cannot be used to evaluate potential effects of towing speed on size selectivity or stock dynamics. Consequently, the observed differences in catch composition should be interpreted as operational outcomes rather than indicators of ecological sustainability.

A key limitation of this study relates to the standardization of fishing effort. Although trip duration, vessel, gear, and environmental conditions were controlled, towing speed inherently influences the distance covered and the effective fishing area. Consequently, CPUE expressed on a per-trip basis reflects a combination of catchability and spatial effort. This should be considered when interpreting the higher CPUE observed at 8 knots, which may partly result from increased encounter rates rather than solely improved fishing efficiency.

Although CPUE is widely used as an indicator of fishing performance (Mulia et al., 2024; Ahmadi and Ghanem, 2024), its application as a proxy for stock condition or sustainability remains debated, particularly in small-scale fisheries with high spatial and operational variability (Setyadji et al., 2016; Ohshimo et al., 2021). In this context, the differences in CPUE observed here are more likely driven by towing speed and species-specific behavioral responses than by changes in stock abundance. Therefore, the higher CPUE at increased speed should be interpreted as reflecting variation in catchability, rather than evidence of improved stock status or sustainable exploitation, consistent with the caution emphasized by Kunimatsu et al. (2025).

Another limitation relates to the statistical treatment of the experimental design. Although the study used a randomized block design, the analysis did not explicitly account for block effects (i.e., day-to-day variability). As a result, potential temporal heterogeneity in environmental conditions may not be fully accounted for. Future studies should apply mixed-effects or two-way ANOVA models to better isolate treatment effects from temporal variation.

The very large effect size, together with strong statistical significance, underscores towing speed as a dominant driver of catch variation. The wide separation between treatment means relative to the pooled standard deviation, combined with the minimal overlap in their 95% confidence intervals. This suggests that towing speed is an important operational factor influencing catch outcomes, although its relative contribution compared to other factors (e.g., fish distribution and environmental variability) cannot be fully isolated in the present study. This pronounced effect demonstrates that towing at 8 knots confers a clear advantage in catch efficiency, consistent with the observed differences in mean catch and the distributional patterns shown in the descriptive analyses. The magnitude of the effect further highlights the central role of towing speed in shaping gear performance and fish encounter rates, likely through enhanced lure dynamics and increased probability of interaction with target species (Liu et al., 2023).

The present analysis, which revealed a large effect size (Cohen's *d*), demonstrates that higher towing speeds substantially increase daily catches and highlights towing speed as a key operational parameter influencing CPUE in troll-line fisheries. This finding supports best-practice recommendations emphasizing the importance of reporting effect magnitude and precision to facilitate meaningful interpretation of biological relevance and to inform a priori power analyses in future studies (Goulet-Pelletier and Cousineau, 2018; Bakker et al., 2019).

In the present study, artificial lures shaped to resemble small fish and incorporating diverse color patterns proved effective in capturing mackerel, trevally, and barracuda. The lures' visual form and motion closely mimicked natural prey, eliciting predatory responses from these visually oriented species. Lure color also played an important role, as visibility and contrast vary with water clarity, depth, and ambient light conditions (Moraga et al., 2015; Hehanussa et al., 2023). Niam et al. (2013) reported that red-colored lures are more effective than green or blue alternatives in attracting pelagic predators such as skipjack and tuna, underscoring species-specific differences in color perception and foraging behavior. Such insights support the development of adaptive operational guidelines for small-scale troll line fisheries, enabling fishers to adjust lure characteristics, color, and towing speed in response to target species behavior, environmental conditions, and prevailing fishing circumstances.

Consistent with earlier studies, the present results indicate that variations in towing speed influenced lure behavior: higher speeds increased lure lift and activity in the water column, whereas lower speeds promoted more stable movement but reduced spatial coverage. These findings support the view that trolling line configuration strongly affects lure depth, stability, and natural movement, thereby shaping strike probability and catch outcomes. Effective control of hook depth through coordinated adjustments of towing speed, warp line length, and sinker weight is therefore essential under the variable current and sea conditions of Teluk Tamiang, as also suggested by Miyamoto et al. (2006). The absence of significant differences among certain treatments further highlights the complex interactions among fish behavior, gear configuration, and environmental variability inherent in small-scale fisheries, emphasizing the need for adaptive strategies rather than fixed operational settings to maintain effective lure presentation (Kebede et al., 2016).

Future research should integrate additional approaches, such as acoustic monitoring, systematic testing of lure colors, and controlled-depth experiments, to better elucidate the mechanisms underlying catch variability. Moreover, operational innovations, including the strategic deployment of fish aggregating devices (FADs) (Anggawangsa et al., 2023) and the adoption of labor-saving technologies such as hydraulic trolling haulers (Park et al., 2015), offer promising pathways to enhance efficiency, reduce physical workload, and improve the sustainability of small-scale troll line fisheries.

Fuel consumption estimates in this study are subject to several limitations. Measurements were obtained under controlled conditions and averaged across trips, rather than continuously monitored during all fishing operations. As a result, variability arising from engine load, vessel maneuvering, and changing sea conditions may not be fully represented. Therefore, the reported values should be regarded as approximations of relative energy use between towing speeds rather than precise measures of operational fuel efficiency. From an operational standpoint, increasing towing speed to 8 knots increased hourly fuel consumption while enhancing catch rates and distance-based fuel efficiency. However, these outcomes do not directly imply economic advantage. The lack of data on species-specific prices, size-based valuation, and overall profitability limits the ability to assess net economic returns under different speed regimes. Moreover, higher fuel expenditures at increased speeds may offset gains in catch volume, particularly in small-scale fisheries that are highly sensitive to fuel price fluctuations. Consequently, the economic implications of towing speed should be interpreted cautiously and understood as context-dependent.

When normalized by fuel consumption, catch-per-liter efficiency was marginally greater at the lower speed, indicating that moderate trolling speeds may offer a more balanced operational trade-off between catch performance and fuel consumption under certain conditions (Byrne et al., 2021; Anggawangsa et al., 2023). In addition, lower towing speeds may reduce mechanical stress on engines and fishing gear, potentially lowering maintenance costs and extending vessel service life (Bastardie et al., 2022). Reduced turbulence at lower speeds may also decrease fish avoidance behavior and limit unintended interactions with non-target species, contributing to lower bycatch rates (Abubakar et al., 2022). However, such operational balance does not inherently imply sustainability. Sustainable fishing outcomes depend on broader factors, including stock status, exploitation rates, and economic returns (Annida et al., 2021; Manjunathan et al., 2023), which were not directly addressed in this study.

These results underscore the importance of integrating energy-efficiency considerations into fishing operations, particularly in small-scale fisheries that often have limited financial resilience and are highly sensitive to fuel price fluctuations. Encouraging fishers to operate at moderate trolling speeds may help reduce fuel expenditures and greenhouse gas emissions while maintaining acceptable catch rates and profitability, although broader sustainability outcomes cannot be directly inferred from the present study. Such strategies align with the FAO Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries, which emphasize energy optimization and operational efficiency as key pathways toward long-term socio-economic and environmental sustainability (FAO, 2015).

The present results, which emphasize the role of fuel efficiency in operational performance, support earlier studies that highlight the importance of vessel design for fishing efficiency. Over the past decade, troll line boat design has evolved considerably, driven by the need for improved fuel economy and enhanced comfort for fishers, with newer vessels becoming lighter, more hydrodynamically efficient, and better adapted to local sea conditions (Mulyadi et al., 2021). In several regions, fiberglass vessels are gradually replacing traditional wooden boats; however, wooden troll line boats remain widely used in areas such as East Lombok (Setyadji et al., 2016), Sukabumi (Apriliani et al., 2021), and Teluk Tamiang. The growing adoption of fiberglass vessels indicates their potential as a practical alternative for small-scale troll-line fisheries, offering advantages in durability, fuel efficiency, and reduced maintenance requirements.

Several mechanistic interpretations presented in this study, including those related to lure behavior, hydrodynamic effects, and fish response, are based on established literature but were not directly measured. Therefore, these explanations should be interpreted as conceptual frameworks that support the observed patterns rather than as empirical findings derived from this study. The outcomes of this study are derived from a localized experimental setting and should therefore be interpreted within that spatial and operational context. While towing speed clearly influenced catch composition, CPUE, and fuel use in Teluk Tamiang, translating these findings into broader management recommendations requires consideration of additional biological, ecological, and socio-economic dimensions. Integrating future towing-speed experiments with stock status evaluations, size-structure assessments, and economic valuation analyses would strengthen the evidence base for assessing ecological and economic sustainability and for formulating more robust operational guidance for troll line fisheries.

Conclusion

The present findings highlight the importance of context-specific decision-making in troll line fisheries, rather than identifying a single universally sustainable towing speed. Operating at 8 knots increased CPUE and improved distance-based fuel efficiency but also resulted in higher hourly fuel consumption, whereas 4 knots produced lower CPUE but greater catch-per-liter efficiency, indicating a performance trade-off rather than a single optimal speed, depending on the operational efficiency metric prioritized. No information on stock status, population structure, or exploitation levels was available, limiting inference regarding sustainability. Future research integrating stock assessments, size-based analyses, and market value data is required to evaluate the broader ecological and economic implications of towing speed and to inform comprehensive management guidance for small-scale troll line fisheries.

Acknowledgments

The authors thank the Lambung Mangkurat University, Faculty of Fisheries and Marine Science, for administrative support, and the fishermen of Teluk Tamiang Village for their cooperation during trolling operations. This research received no external funding.

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