Bio-economic model of mackerel tuna fisheries (*Euthynnus affinis*) in the northern waters of Aceh

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Abstract. The production of mackerel tuna (*Euthynnus affinis*) at the Kutaraja Ocean Fishing Port has fluctuated due to variations in fish availability and fishing effort. This study aims to evaluate the management of mackerel tuna by comparing actual fishing conditions with three key management reference points: Maximum Sustainable Yield (MSY) represents the highest level of catch that can be maintained over time without compromising the reproductive capacity of the stock, Maximum Economic Yield (MEY) reflects the optimal level of fishing effort that maximizes economic returns while ensuring resource sustainability, and Open Access (OA) describes a situation with unrestricted fishing access, which typically results in excessive exploitation and the degradation of fishery resources. Additionally, it evaluates the utilization level of mackerel tuna by determining the number of permitted catches in the northern waters of Aceh. The results indicate that under the MSY regime, total production within 10 years reached 425.09 tons, with a fishing effort of 2,270.31 trips and an economic rent of IDR 4.115 million. Under the MEY regime, total production was 414.40 tons, with a fishing effort of 1,910.35 trips and an economic rent of IDR 4.266 million. Meanwhile, in the OA regime, total production declined to 226.84 tons, with a fishing effort of 3,820.71 trips and no economic rent (IDR 0). Based on the bioeconomic analysis and comparisons with actual conditions, it can be concluded that the management of mackerel tuna at the Kutaraja Ocean Fishing Port has led to both biological and economic overfishing. The utilization level of mackerel tuna was 171.1% of the total allowable catch (TAC), indicating an urgent need for policies to regulate fishing effort and catch limits.

Key Words: Gordon-Schaefer bioeconomy model, mackerel tuna, overfishing, utilization level.

Introduction. Mackerel tuna (*Euthynnus affinis*) is one of Indonesia's most significant pelagic fish species and a key export commodity for various international markets. Due to its high demand and economic value, this species plays a crucial role in the global seafood industry (Syah et al 2020). In Aceh, mackerel tuna is primarily caught using purse seine, although more sustainable fishing methods, such as longline and handline techniques, have been recommended to maintain stock levels (Chaliluddin 2021). Fishers operating in the northern waters of Aceh typically land their catches at the Kutaraja Ocean Fishing Port. Over the years, the production of mackerel tuna at this port has fluctuated, with total landings increasing from 529.58 tons in 2011 to 894.11 tons in 2014. Despite a decline in subsequent years, production rebounded to 811.83 tons in 2020 (Badan Pusat Statistik 2022).

The potential of mackerel tuna, like other economically valuable fish species, is critical for human consumption, trade, and export. Indonesia is one of the world’s leading suppliers of tuna, contributing significantly to both domestic and global seafood markets (Baihaqi et al 2024). However, the open-access nature of fishery resources presents a major challenge, as it can lead to overfishing, resource depletion, environmental degradation, and economic instability among local fishers (Halim et al 2017). Overfishing occurs when fishing activities exceed the maximum sustainable yield (MSY), causing declines in fish populations and economic losses for coastal communities (Cánovas-Molina et al 2021).

Concerns about the sustainability of mackerel tuna resources have been increasing. According to Fauzi & Anna (2005), balancing the biological and economic aspects of resource utilization is crucial in preventing fishery depletion. Sustainable fisheries management should include catch limits, seasonal fishing restrictions, and the adoption of eco-friendly fishing technologies (Rochmat et al 2023). Additionally, ensuring long-term sustainability requires analytical approaches such as bioeconomic analysis, which integrates biological conservation with economic efficiency (Clark 2010).

This study aims to evaluate the management of mackerel tuna resources in northern Aceh by analyzing their current status under different management scenarios, including MSY, maximum economic yield (MEY), and open access (OA). While previous studies, such as those by Auliyah (2021), have focused on the bioeconomic modeling of tuna fisheries in Indonesia, and Harahab et al (2021) have examined the economic and ecological sustainability of the tuna industry, this research provides a localized perspective specific to northern Aceh. By assessing the sustainability of fishing practices and the effectiveness of regulatory frameworks, this study aims to provide data-driven recommendations for fisheries management. Additionally, it seeks to determine the allowable catch limits needed to maintain ecosystem balance and ensure long-term economic benefits for fishers. Effective fisheries management policies are essential for Aceh to continue benefiting from its rich marine resources while safeguarding the sustainability of mackerel tuna populations for future generations.

Description of the study sites. This study was conducted at the Kutaraja Lampulo Ocean Fishing Port in Banda Aceh from November to December 2024. Data collection consisted of both primary and secondary sources.

Primary data were obtained through direct observations at the research site. These data included the cost structure of fishing operations and the market prices of fishery resources, which were gathered through interviews with fishers.

Secondary data were collected from various sources, including the Department of Maritime Affairs and Fisheries (DKP) of Aceh Province, the Central Statistics Agency (BPS), and the Kutaraja Lampulo Ocean Fishing Port. Additional information was acquired from books, academic journals, online databases, and other relevant literature. The secondary data included historical records of mackerel tuna catches between 2011 and 2020 in the northern waters of Aceh (Figure 1), fishing effort data, trip counts by gear type, and other supporting information.

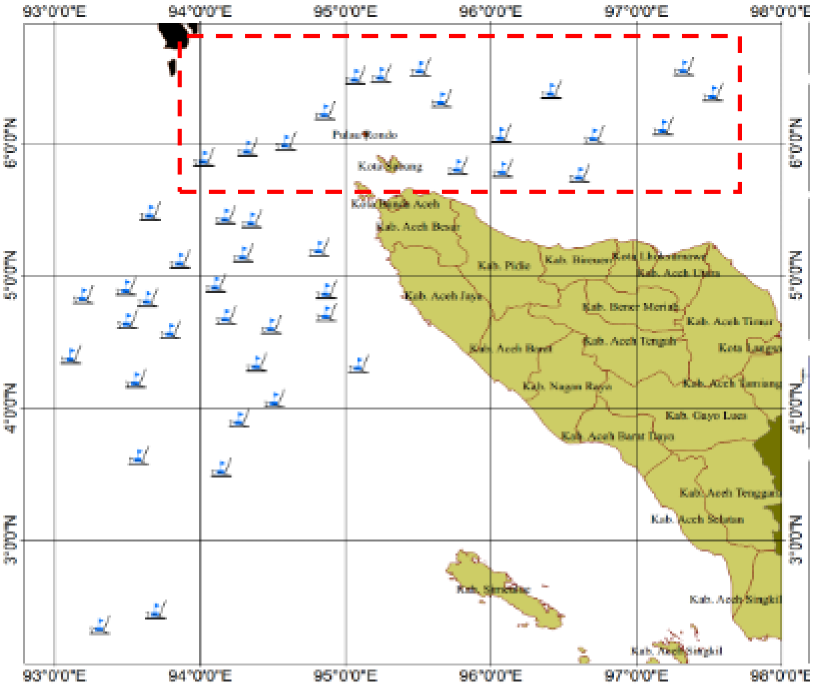

Figure 1. Aceh's nothern's waters of fishing area (Bahri et al 2017).

***Statistical analysis**.* The bioeconomic analysis of mackerel fisheries management was conducted using the Gordon-Schaefer model to determine the level of resource utilization by calculating the MSY, MEY, and OA values. Additionally, biological parameters were estimated using the Clarke-Yoshimoto-Pooley (CYP) method.

The analysis employed both MSY calculations and Gordon-Schaefer bioeconomic modeling, methods widely used in previous studies (Susanto et al 2015; Aprianty et al 2019; Irnawati et al 2019; Dutta et al 2021). The MSY was calculated following the approach proposed by Fauzi (2006), which is expressed as:

$$h_{msy} = qKE - \left(\frac{q^2K}{r}\right) E^2 \qquad (1)$$

where: h_{msy} = maximum sustainable yield production; r = intrinsic growth; q = catchability coefficient; K = carrying capacity; and E = fishing effort.

Furthermore, the biological parameters in the equation can be estimated using the Fox Algorithm estimation model (Aprianty et al 2019; Rasheed 2020; Indra et al 2021, 2022; Arief et al 2023):

$$x = \left[\left(\frac{z}{U_t}\right) + \left(\frac{1}{\beta}\right)\right] \qquad (2)$$

$$y = \left[\left(\frac{z}{U_{t+1}}\right) + \left(\frac{1}{\beta}\right)\right] \qquad (3)$$

$$z = \left[\left(-\frac{a}{b}\right) - \left(\frac{E_t + E_{t+1}}{2}\right)\right] \qquad (4)$$

$$q = \left[\prod_{t=i}^{n} ln\left(\frac{x/y}{z}\right)\right]^{1/t} \qquad (5)$$

$$K = \frac{\alpha}{q} \qquad (6)$$

$$r = \frac{Kq^2}{\beta} \qquad (7)$$

where: x and y = measure the relative stock condition before and after exploitation between time periods; Ut = CPUE (catch-per-unit-effort) at the time (biomass proxy); Et = effort at time t; β = biological parameter; a, b = regression coefficients, q = catchability coefficient; z = represents how close the stock level is to the point of collapse (critical effort threshold); α = intercept; K = carrying capacity; r = the intrinsic growth rate.

The profit obtained was the difference between total revenue and total cost used. Mathematically, it was written below (Fauzi 2006):

$$\begin{aligned} \pi &= TR - TC \\ &= p \times h - c \times E \\ &= p \times q \times K \times E \times \left(1 - \frac{q \times E}{r}\right) - c \times E \qquad (8) \end{aligned}$$

where: TR was total revenue (IDR), TC was total cost (IDR), π was profit (IDR), p was the average fish price (IDR), h was catch (kg), c was capture cost unity effort (IDR), and E was effort (trip). By obtaining the values of the biological parameters (r, q, K) and economic parameters (p, c), a bioeconomic approach can be applied to manage mackerel tuna fisheries under the MEY, MSY, and OA conditions. The optimal management solutions for mackerel tuna fisheries based on a static optimization model are presented in Table 1. Statistical analyses were conducted using Microsoft Excel.

Table 1

Regime solution for optimal management of skipjack tuna

Variable	*Regime*		
	MEY	*MSY*	*OA*
Biomass (x)	$\frac{K}{2}\left(1+\frac{c}{p.q.K}\right)$	$\frac{K}{2}$	$\frac{c}{p.q.}$
Catch (h)	$\frac{r.K}{4}\left(1+\frac{c}{p.q.K}\right)\left(1-\frac{c}{p.q.K}\right)$	$\frac{r.K}{4}$	$\frac{r.c}{p.q}\left(1-\frac{c}{p.q.K}\right)$
Effort (E)	$\frac{r}{2q}\left(1-\frac{c}{p.q.K}\right)$	$\frac{r}{2q}$	$\frac{r}{q}\left(1-\frac{c}{p.q.K}\right)$
Economic rent (π)	$p.q.K.E\left(1-\frac{q.E}{r}\right) - c.E$	$ph_{MSY} - cE_{MSY}$	$ph_{OA} - cE_{OA}$

Sources: Fauzi (2010); Dutta et al (2021).

Results. Generally, fishermen use purse seines and angling gear to catch large pelagic fish such as mackerel tuna. At the Kutaraja Ocean Fishing Port, mackerel tuna production is predominantly carried out using purse seine fishing gear, which recorded its highest production in 2014, reaching 894.11 tons, while the lowest production was observed in 2016, with only 206 tons.

According to Simanjuntaki et al (2018), fluctuations in catch levels are primarily influenced by the availability of fish, which is strongly affected by fishing effort and seasonal variations. The level of production is determined by the extent of fishing effort, which depends on factors such as vessel capacity, type of fishing gear, number of operational days, and technology used (Nelwan et al 2015).

The fishing effort for mackerel tuna using purse seine gear is significantly higher compared to handline fishing gear. An analysis of catch per unit effort (CPUE) for both fishing methods indicates that purse seines yield the highest CPUE values relative to handlines. Consequently, purse seine fishing is considered the most productive gear type and serves as the standard fishing method for mackerel tuna.

The findings of this study indicate that actual fish production in the research area has exceeded sustainable production levels (Figure 1).

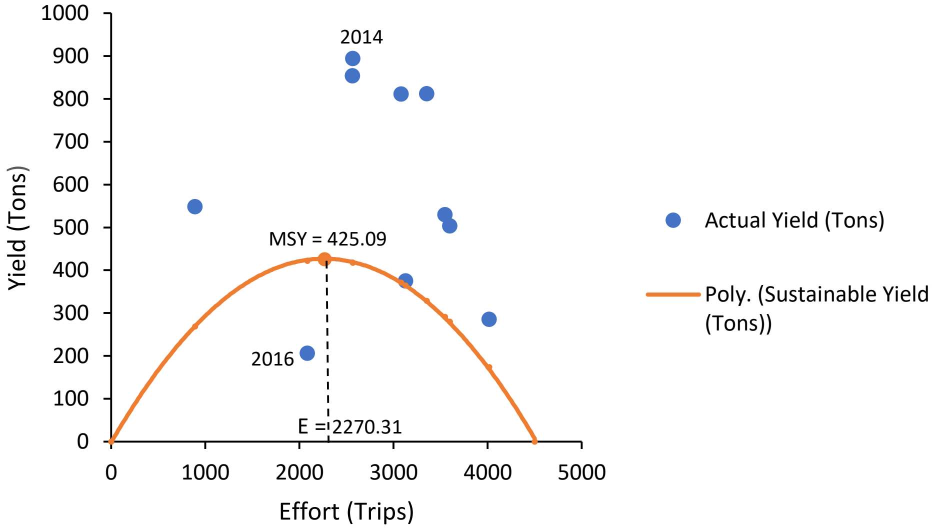

Figure 1. Yield effort curve of makarel tuna.

The Figure 1 illustrates the relationship between fishing effort, measured in trips, and fish yield, measured in tons. The x-axis represents the number of fishing trips, while the y-axis indicates the corresponding fish yield. Blue dots denote actual recorded yields at various effort levels, whereas the orange curve models the sustainable yield, typically following a parabolic shape characteristic of classic fisheries models. This shape reflects the principle that yield initially increases with fishing effort but eventually declines due to overexploitation (Froese & Proelß 2010).

A critical feature of the graph is the MSY, identified at 425.09 tons, occurring at an effort level of 2,270.31 trips. Beyond this threshold, increased fishing pressure leads to reduced yields, likely due to stock depletion and recruitment overfishing, where juvenile fish lack sufficient time to mature and reproduce. This concept aligns with studies on biological overfishing, demonstrating that excessive effort beyond sustainable limits results in declining CPUE and long-term fishery degradation (Pauly & Zeller 2016).

Fluctuations in actual yield data, such as higher yields in 2014 and lower yields in 2016, may indicate temporary stock abundance due to favorable environmental conditions or improved fishing efficiency, and potential overfishing or ecological changes affecting fish availability, respectively. These variations highlight the inherent variability in fisheries, influenced by environmental factors, fishing technology, and regulatory interventions (Hilborn & Ovando 2014).

The graph in Figure 1 underscores the necessity of scientifically informed fisheries management to prevent stock collapse and ensure long-term productivity. Regulatory measures such as effort limitations, seasonal closures, and gear restrictions are commonly implemented to maintain fishing pressure at sustainable levels. Adherence to global fisheries management frameworks, including the precautionary approach advocated by the United Nations Food and Agriculture Organization (FAO) and the principles of ecosystem-based fisheries management, is crucial. By following these principles, fisheries can optimize yields while preserving marine biodiversity and ensuring economic stability for fishing communities (Worm et al 2009; Zhou et al 2012).

Once the biological parameters are estimated using the Clarke-Yoshimoto-Pooley (CYP) approach and the economic parameters are obtained, the model enables a bioeconomic evaluation of the fishery under alternative management regimes, including maximum economic yield (MEY), maximum sustainable yield (MSY), and open access (OA). Furthermore, the three conditions may be compared with the calculation results obtained under real conditions. In the current (actual) exploitation regime, the fishery yields 581.88 tons of catch from 2,882.61 fishing trips, producing an estimated economic rent of IDR 5.822 million. Subsequently, the biomass (x), harvest (h), fishing effort (E), and economic rent (п) for the alternative management scenarios - MSY, MEY, and OA - are derived using the Gordon-Schaefer bioeconomic model. The results of the calculation are therefore given in Table 2.

Table 2

Bioeconomic analysis in various management regimes of mackerel tuna

Varibles	*Model of management*		
	MSY	*MEY*	*OA*
x (ton)	443,87	514,24	140,75
h (ton)	425,09	414,40	226,84
E (trip)	2270,31	1910,35	3820,71
п (IDR millions)	4.115	4.266	0

In this study, all three fisheries management regimes were analyzed. Table 2 presents the differences in key values for each regime. MSY represents the highest level of catch that can be harvested sustainably without depleting fish populations. It serves as the benchmark for sustainable fisheries management. MEY refers to the optimal economic benefit derived from fisheries resources, achieved by maximizing profit while minimizing fishing effort. OA describes a fishing scenario with no regulatory restrictions, often leading to excessive fishing pressure, resource depletion, and diminished economic returns.

Discussion. The comparison of the three management regimes reveals that MSY conditions resulted in the highest production among the three, reaching 425.09 tons. Under MEY conditions, production was slightly lower at 414.4 tons, while OA conditions resulted in the lowest production at 226.84 tons. However, the actual production recorded in the study area exceeded the MSY threshold, with a total production of 581.88 tons. This discrepancy suggests that mackerel tuna resources in the Kutaraja Ocean Fishing Port have been exploited beyond sustainable levels.

The level of fishing effort also varied across the management regimes. The MEY regime had the lowest fishing effort at 1,910.35 trips, whereas the OA regime exhibited the highest effort, reaching 3,820.71 trips due to the absence of regulatory restrictions. The actual fishing effort recorded in the study area was 2,882.61 trips, which was lower than the OA level but higher than the MSY threshold of 2,270.31 trips. Given that the number of trips in actual conditions exceeded the MSY limit, it can be concluded that biological overfishing has occurred in the study area. According to Atmaja et al (2011), biological overfishing is a combination of growth overfishing and recruitment overfishing, occurring when fishing effort surpasses the MSY threshold, leading to stock depletion.

Economic analysis of management regimes. Economic rent varied across different management regimes. Under OA conditions, no economic rent was generated, meaning that fishers did not receive any net financial benefit. In contrast, the MSY regime produced an economic rent of IDR 4.115 million, while the MEY regime yielded the highest economic rent at IDR 4.266 million. However, actual economic rent exceeded both these values, reaching IDR 5.822 million as showed in Figure 2.

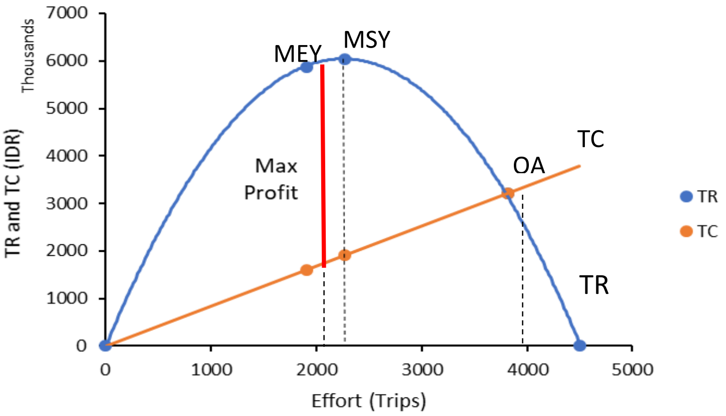

Figure 2. Bioeconomics in various management regimes of mackerel tuna.

Despite this, further analysis reveals that the economic rent per trip in actual conditions was lower than that of the MEY regime. Under the MSY regime, the economic rent per trip was IDR 1.8 million, whereas under the MEY regime, it was IDR 2.2 million per trip, making it the most efficient. In actual conditions, the economic rent per trip was IDR 2.0 million, which is lower than that of MEY. This finding suggests that economic overfishing has occurred, where excessive fishing effort reduces profitability per trip. According to Atmaja et al (2011), economic overfishing is characterized by a higher fishing effort than MEY and lower benefits per unit effort than those obtained under optimal economic conditions. Fauzi (2010) also defines economic overfishing as a situation where fishing activities should generate positive economic rent, but due to excessive input usage (effort), economic rent approaches zero.

Implications for fisheries management. The MEY regime represents the optimal economic condition for fisheries management, where fishing effort is kept at an efficient level to maximize profits while preserving fish stocks. Under MEY conditions, economic rent is maximized, and input factors are utilized more efficiently, resulting in higher profitability per trip and more sustainable biomass levels. This concept, introduced by Gordon (1954), remains a foundational principle in fisheries economics.

Conversely, in an OA regime, fisheries operate under unregulated conditions, leading to excessive fishing effort. This results in an equilibrium where total revenue equals total cost (TR = TC), eliminating economic rent. Despite high fishing effort, catch levels remain low, making resource utilization inefficient. Hardin (1968) highlighted this phenomenon in his "Tragedy of the Commons" theory, explaining how open-access exploitation leads to long-term depletion of resources and reduced economic returns.

The findings indicate that both biological and economic overfishing have occurred in the northern waters of Aceh Province, particularly around the Kutaraja Ocean Fishing Port. While the total economic rent under actual conditions was higher than that under the MEY and MSY regimes, the profit per trip was lower, suggesting inefficiencies in resource utilization. To achieve sustainable and economically viable fisheries, it is essential to implement effective management interventions.

Limiting fishing effort is a crucial strategy to prevent overfishing. This can involve regulating the number of fishing vessels, restricting the number of fishing days, or implementing seasonal closures to allow fish populations to replenish. These measures are designed to manage the amount of effort expended in fishing activities, thereby controlling the pressure on fish stocks (FAO 2002).

Setting catch quotas based on MEY and MSY thresholds ensures that fish harvests remain within sustainable limits. Output controls, such as total allowable catches (TACs), directly limit the quantity of fish that can be harvested, aligning fishing activities with conservation and economic objectives (FAO 2002).

Adopting a precautionary approach in fisheries management involves implementing measures that account for uncertainties in fish stock assessments and environmental variability. This approach aims to prevent serious or irreversible damage to marine ecosystems, even when full scientific certainty is lacking (FAO 1995).

Engaging local communities in the management process can lead to more effective and sustainable outcomes. Community-based fisheries management places local stakeholders at the center of decision-making, promoting sustainable practices, fostering stewardship, and strengthening the social and economic resilience of fishing communities.

Implementing these management interventions can help balance ecological preservation with economic needs, ensuring the long-term viability of fishery resources in the region.

Recent studies have further refined the MEY concept. For instance, research has incorporated nonlinear catchability into bioeconomic models, providing a more accurate representation of fisheries dynamics (Pan 2021). Additionally, integrating economics into fisheries science has progressed, emphasizing the importance of considering economic factors in fisheries management decisions (Anderson et al 2015).

In summary, achieving MEY is crucial for sustainable and profitable fisheries management, whereas open-access regimes often lead to economic inefficiencies and resource depletion.

Analysis of the utilization level of tuna (2014-2023). From the Table 3, it is evident that the utilization level of mackerel tuna at the Kutaraja Ocean Fishing Port during the 2014-2023 period mostly exceeded the TAC of 340.07 tons per year, with an average utilization rate of 171.1%. This indicates that tuna exploitation in Aceh waters has exceeded the recommended limit for sustainable resource management.

a. Evidence of persistent overfishing. Between 2014 and 2018, the utilization rate consistently exceeded 100%, with the highest level recorded in 2017 at 262.92%. The only exception occurred in 2019, when the utilization rate dropped to 60.58%, falling below the TAC. This decline may have been influenced by environmental variability, regulatory changes in the fishing sector, or adverse weather conditions that limited fishing operations.
b. Short-term reduction in exploitation (2019-2022). Following the peak in 2017, the utilization rate gradually declined, reaching 83.90% in 2022. This pattern may reflect the delayed biological consequences of earlier overfishing, where stock depletion reduces catchability, even if fishing effort remains relatively high (Hilborn et al 2020).
c. Resurgence of exploitation in 2023. In 2023, production rose substantially again (238.73%), as illustrated in Figure 3, suggesting a renewed intensification of fishing pressure.

Table 3

The utilization level of tuna at the Kutaraja Ocean Fishing Port in 2014-2023

Year	*Actual production (tons)*	*TACs (ton)*	*Utilization (%)*
2014	529.58	340.07	155.73
2015	811.34	340.07	238.58
2016	854.02	340.07	251.13
2017	894.11	340.07	262.92
2018	548.51	340.07	161.29
2019	206.00	340.07	60.58
2020	374.58	340.07	110.15
2021	503.54	340.07	148.07
2022	285.32	340.07	83.90
2023	811.83	340.07	238.73

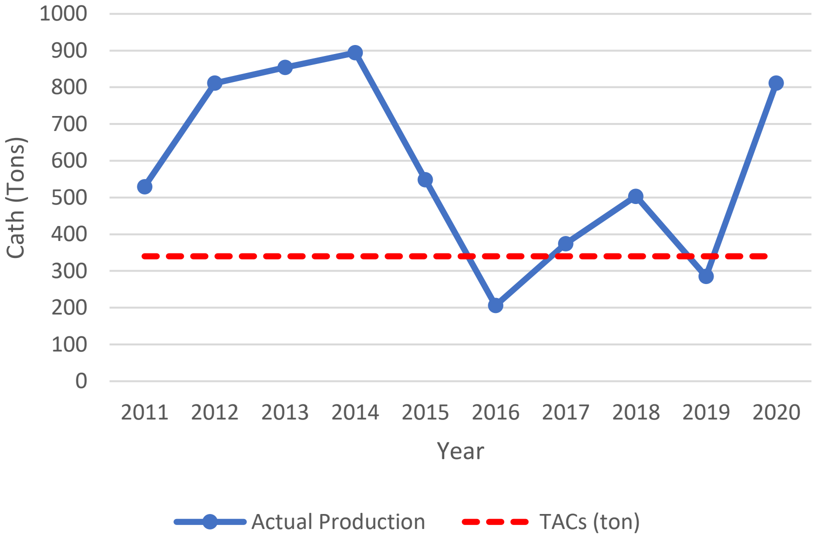

Figure 3. Tuna catch trend vs total allowable catches (TACs).

Implications for fisheries management

a. Strong indications of overexploitation. Utilization rates ranging from 60.58% to 262.92% show that, in most years, the fishery has been operating at levels consistent with overfishing. If this pattern persists without proper management intervention, the mackerel tuna stock is at risk of further biological depletion (Froese et al 2016).

b. Urgent need for stronger regulatory measures. To prevent stock collapse, stricter management is required through both input controls (such as limiting the number of vessels and fishing gear) and output controls (such as establishing catch quotas aligned with MSY and MEY targets).

c. Socioeconomic implications**.** Continued overfishing inevitably reduces biomass availability, which in turn diminishes long-term profitability for fishing communities. The decrease in production observed from 2019 to 2022 likely reflects declining stock abundance in Aceh’s northern waters, driven by the prolonged effects of previous overexploitation.

The data suggest that fisheries management in Kutaraja faces significant challenges in balancing utilization and resource sustainability. More effective bioeconomic-based management strategies are needed to reduce excessive exploitation, such as implementing conservation zones and science-based catch restrictions ((Hilborn et al 2020)).

Conclusions. The bioeconomic analysis of mackerel tuna (*Euthynnus affinis*) resources in the northern waters of Aceh, particularly at the Kutaraja Ocean Fishing Port, revealed that under the maximum sustainable yield (MSY) management regime, total production reached 425.09 tons, with a fishing effort of 2,270.31 trips and an economic rent of IDR 4.115 million.

Under the maximum economic yield (MEY) regime, total production was 414.40 tons, with 1,910.35 fishing trips and a higher economic rent of IDR 4.266 million, indicating a more efficient economic outcome. Meanwhile, in the open access (OA) regime, total production dropped significantly to 226.84 tons, with 3,820.71 trips, resulting in zero economic rent due to excessive fishing pressure.

Comparing these management regimes with actual conditions, the results indicate that the current management of mackerel tuna at Kutaraja Ocean Fishing Port has led to both biological and economic overfishing. The utilization level of mackerel tuna resources was 171.1%, exceeding the total allowable catches (TACs) threshold. This suggests an urgent need for regulatory policies to limit fishing effort and control catch levels to ensure the long-term sustainability of the fishery.

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Conflict of interest. The authors declare that there is no conflict of interest.

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