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Research Article

Skipjack tuna (*Katsuwonus pelamis*) sustainable resource management through fishing vulnerability and some population dynamic analysis in Malang south coast waters, East Java

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Abstract

Skipjack tuna (*Katsuwonus pelamis*) represents an essential fishery resource in the waters off Malang's South Coast in East Java, possessing significant economic and ecological importance. However, escalating fishing pressures and climate variability, particularly fluctuations in sea surface temperature (SST), have raised concerns about the sustainability of its stock. This research aimed to evaluate the fishing vulnerability and population dynamics of skipjack tuna in the area. Data was gathered from January 2021 to October 2021 at the Pondokdadap Coastal Fishing Port (CFP) Malang South Coast Waters, involving the analysis of 1,062 skipjack tuna. The Productivity and Susceptibility Analysis (PSA) was utilized to assess vulnerability, while growth, mortality, and recruitment patterns were examined through length-frequency distribution and the von Bertalanffy growth model. The findings revealed that skipjack tuna had a productivity score of 2.44 and a susceptibility score of 2.33, resulting in a low vulnerability classification (1.44). Nonetheless, the species faces overfishing, as indicated by an exploitation rate (E=0.58) surpassing the sustainable threshold of 0.50. The relationship between SST and catch per unit effort (CPUE) and recruitment patterns showed a low to moderate inverse correlation, indicating that environmental factors affect stock variations. To promote sustainability, it is crucial to implement effective management strategies, including regulations on fishing efforts, size restrictions, and seasonal closures. Adopting ecosystem-based fisheries management (EBFM) approaches incorporating climate adaptation strategies is also advisable. These results offer important insights into the interplay between SST dynamics and skipjack tuna fisheries, aiding future stock management and conservation initiatives.

Introduction

Skipjack tuna (*Katsuwonus pelamis*) is a significant pelagic species with considerable economic importance, emerging as a primary export product for Indonesia due to rising global demand (FAO, 2020). As the world's second-largest fish producer, Indonesia contributes over 16% to the worldwide tuna market, with an estimated annual output of around one million tons (Statista, 2023). The Pondokdadap Coastal Fishing Port (CFP), located in Malang, East Java, serves as a vital center for the landing of large pelagic fish, particularly skipjack tuna (*K. pelamis*), within the Fisheries Management Area (FMA) 573, which is situated in the Indian Ocean (Agustina *et al*., 2019a). In 2021, the marine fisheries yield in the waters off Malang was reported to be between 14,000 and 16,000 tons, with skipjack tuna representing the most significant share at approximately 5,000 tons during September and October (Yani, 2021).

Skipjack tuna is a highly migratory species, subject to various environmental influences such as food availability, oceanographic conditions, and climate variability (Peck *et al*., 2013; Dueri *et al*., 2014). The population density of skipjack tuna in the Indian Ocean correlates with fluctuations in sea surface temperature (SST), with optimal conditions occurring at around 29°C, lower salinity levels, and a preference for depths between 38 and 2,807 meters (Amir *et al*., 2018; Lan *et al*., 2020). This species displays schooling behavior and frequently congregates around fish aggregating devices (FADs), with movement patterns primarily determined by ocean currents and temperature gradients (Zainuddin *et al*., 2013; Chang *et al*., 2022). The open-access nature of Indonesia's fisheries often results in heightened fishing pressure, leading to resource depletion when not managed effectively. Overfishing of skipjack tuna threatens the sustainability of stocks, as excessive harvesting diminishes biomass and disrupts population recruitment dynamics (Hilborn and Walters, 1992; Khatami *et al*., 2018). The concept of vulnerability in fisheries refers to the sensitivity of fish populations to environmental stressors and human-induced pressures (Yonvitner *et al*., 2019). The ramifications of vulnerability extend to productivity and susceptibility, influencing stock resilience and natural mortality rates (Fazli *et al*., 2021).

Climate change further intensifies the vulnerability of skipjack tuna populations by modifying ocean temperatures, current patterns, and primary productivity (Pauly and Cheung, 2018). Variations in SST have a pronounced effect on fish distribution and recruitment, as temperature changes can influence larval survival and spawning success (Islam *et al*., 2019; Pratiwi *et al*., 2020a). Previous studies underscore the necessity of evaluating the vulnerability of skipjack tuna stocks in climate change to facilitate sustainable fisheries management (Dueri *et al*., 2014; Auliyah *et al*., 2021).

A comprehensive understanding of population dynamics is essential for the sustainability of fisheries. Population dynamics involve the changes in fish stocks resulting from growth, mortality, and recruitment processes (Effendie, 2002; Morgan *et al*., 2009). The interplay between recruitment and mortality is crucial in determining population productivity, a fundamental aspect of sustainable fisheries management. A previous study indicates that skipjack tuna production in East Nusa Tenggara has experienced fluctuations over the years, with significant declines noted in 2016, primarily attributed to factors related to population dynamics (Herwaty *et al*., 2021). To ensure the long-term viability of skipjack tuna fisheries, it is imperative to implement effective resource management strategies, including control of fishing efforts and adaptive management practices (Auliyah *et al*., 2021).

This study aimed to evaluate the stock status of skipjack tuna in the coastal waters of Malang by analyzing fishing vulnerability and critical population dynamics parameters. The results will enhance understanding of the relationship between SST fluctuations and skipjack tuna fisheries, thereby aiding in formulating sustainable management strategies in response to environmental changes and fishing pressures.

Materials and methods

Data Collection

This research used simple random sampling on several landing sites on Pondokdadap CFP from January to October 2021 (10 months) as primary data. The data was collected from 16 fishermen representing their fishing vessels who used hooks and lines to catch fish, which had a minimum environmental impact. The samples obtained consist of small, medium, and large-size fish with 1,062 specimens of skipjack tuna. Sea Surface Temperature (SST) secondary data (January- October 2021) were collected from https://www.seatemperature.org/asia/indonesia.

Length Frequency

Length frequency distribution analysis was carried out in several stages: class interval determination, class range, class frequency, and data tabulation on fish length in the frequency class. Then, the data is graphed to show its distribution shift between classes for each month. Finally, length data is converted into length-frequency distribution in Microsoft Excel 2019 (Pauly and David, 1981).

Growth parameter estimation

Skipjack tuna sits in the first place because it is the fastest growing if compared to all other tuna species (Murua *et al*., 2017). Growth parameters often need to be estimated from growth increment data consisting of growth coefficient (K) and asymptotic length (L_∞). The growth coefficient (K) will show how fast the fish reaches the maximum size (Patrick *et al*., 2010). Asymptotic length is the maximum average length of fish that can be achieved during its lifetime (L_∞) (Fayetri *et al*., 2013). The estimation of growth parameters applies to the von Bertalanffy model as follows (Fabens, 1965):

$$L_t = L_\infty\left(1 - e^{-K(t-t_0)}\right) \qquad (1)$$

Where, L_t = fish length at age t (unit of time), L_∞ = asymptotic length, t= fish age at length I, t_0=theoretical age at zero-length

This method uses ELEFAN I (Electronic Length Frequency Analysis), which is connected to the FiSAT II program.

Mortality and exploitation rates

Total instantaneous mortality rate (Z) and natural mortality (M) were estimated using the length converted catch curve method implemented in FiSAT II. While fishing mortality (F) and exploitation rates (E) were calculated using the formula (Gulland, 1971; Pauly, 1984):

$$F = Z - M \quad (2)$$

$$E = F/Z \quad (3)$$

Where, Z= Total mortality, F= Fishing mortality, M= Natural mortality, E=Exploitation rates

Productivity and susceptibility analysis (PSA)

Productivity parameters are variables used to determine whether or not the fish resources can be recovered due to fishing activities. The PSA analysis illustrates the relative vulnerability determined by the combination of productivity (x-axis) and susceptibility (y-axis). Rankings are given a score of 1-3 for high to low productivity, respectively, and 1-3 for low to high susceptibility, respectively (Patrick *et al*., 2010; Sambah *et al*., 2021).

Vulnerability score

Calculation of the vulnerability score from the productivity and susceptibility score was shown on the following formula (Patrick *et al*., 2010; Yonvitner *et al*., 2020):

$$v = \sqrt{(p-3)^2 + (s-1)^2} \quad (3)$$

Where, v= Vulnerability, p= Productivity score, s= Susceptibility score

Vulnerability indicator scores are divided into three levels: low (v≤1.6), moderate (1.6<v<1.8), and high (v≥1.8) (Tables 1 and 2).

Table 1: Productivity *a*ttributes and *s*core.

Productivity Attributes	Score		
	High (3)	Moderate (2)	Low (1)
Maximum size	<60 cm	60-150 cm	>150 cm
Maximum age	<10 year	10-30 year	>30 year
Maturity age	<2 year	2-4 year	>4 year
Natural mortality (M)	>0.40	0.20-0.40	<0.20
Von Bertalanffy growth coefficient (K)	>0.25	0.15-0.25	<0.15
Intrinsic growth rate (r)	>0.5	0.16-0.5	<0.16
Fecundity	>10,000	100-1,000	<100
Recruitment pattern	>75%	10-75%	<10%
Mean trophic level	<2.5	2.5-3.5	>3.5

Source: Patrick *et al*., 2010

Linear regression

Linear regression can be used to determine the correlation between the independent (sea surface temperature) and dependent variables (reproduction and productivity) (Walpole, 1995). A linear regression operated on SPSS 16 software obtained the significance coefficient, determinant coefficient, and correlation coefficient between sea surface temperature and CPUE of skipjack tuna at Pondokdadap CFP in

2021. The linear regression is formulated based on the following equation:

$\hat{y} = a + bx$ (4)

Where, $\hat{y}$= Dependent variable, a= Intercept, b= Slope, x= Independent variable Catch Per Unit Effort (CPUE)

Catch Per Unit Effort (CPUE) is a method that represents the catch in one fishing effort (Sibagariang *et al.*, 2011).

Table 2: Susceptibility attribute.

Susceptibility Attributes	Score		
	High (3)	**Moderate (2)**	**Low (1)**
Management strategy	No catch limits for targeted stocks	Targeted stocks have catch limits in the community	Targeted stocks have catch limits
Fisheries impact on habitat	Absent, minimum, or temporary adverse effect	More than minimum or temporary but mitigated adverse effects	More than minimum or temporary and unmitigated adverse effects
Behavioral responses (Schooling)	Increase in fishing gear catchability	Do not substantially affect fishing gear catchability	Decrease in fishing gear catchability
Fisheries impact selectivity on morphological characteristic	Low	Moderate	High
Economics of fishery value	High	Moderate	Low
Seasonal migration pattern	Increase catchability	Do not substantially affect the catchability	Decrease catchability

Source: Patrick *et al*., 2010

Fishing effort is the number of days at sea or trips. The dynamics of catch production in an area can be seen from the CPUE year fluctuation, as mentioned in the equation below:

$$CPUE = \frac{C}{E} \quad (5)$$

Where, C= Catch (ton), E= Effort (trip), CPUE= Catch per unit effort (kg/trip)

Results

Length Frequency

The length data of skipjack tuna from January to October 2021 were obtained through direct measurements at Pondokdadap CFP. The measurements were taken using fork length. The sample size of skipjack tuna comprised 1,062 specimens. The recorded length of skipjack tuna ranged from 25 to 63 cmFL, with a mean length of 39.68±9.95 cmFL. The modal length class of captured skipjack tuna was 39-40 cmFL with 167 specimens. Conversely, the least frequently observed length class of captured skipjack tuna was 63-64 cmFL with 1 specimen only. In addition, there were no specimens recorded in both length classes 59-60 cm and 61-62 cm (Fig. 1)

Estimation of growth parameter

The asymptotic length (L∞) of the resulting data is 63 cmFL. The growth coefficient (K) is 0.25 year^{-1}. The value of K is classified as low if it is <0.3/year (Bakhtiar *et al*., 2013). A higher growth value indicates that the fish will reach asymptotic length more rapidly (Mahmud *et al*., 2019). Food availability is crucial in determining higher and lower growth rate (K) values. The availability of food for skipjack tuna (fish, debris, squid, and crustaceans) provides energy for fish to grow until they reach their asymptotic fork length (FL∞) (Restiangsih and Amri, 2019). Both internal and external factors affect the growth pattern of fish.

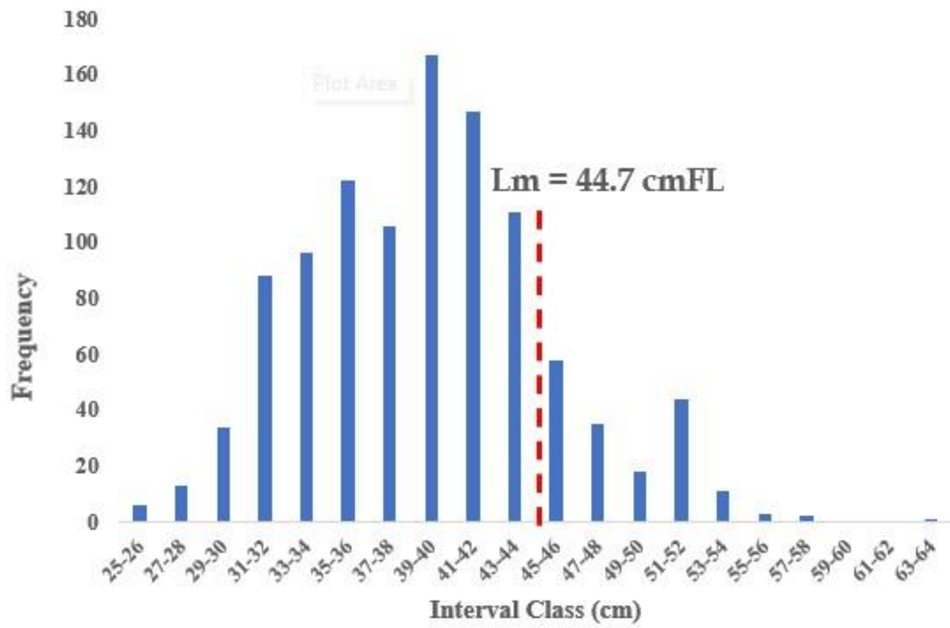

Figure 1: Length frequency of skipjack tuna (*K. pelamis*) on Pondokdadap CFP from January to October 2021.

An internal factor is the presence of diseases and parasites, as when the digestive and other organs of fish are affected, the energy produced from food for growth is reduced due to recovery processes.

Mortality and exploitation rate

Mortality analysis of skipjack tuna based on Pauly's empirical equation in FiSAT indicated that the total mortality coefficient (Z) and natural mortality (M) were estimated to be 1.13 year^{-1} and 0.47 year^{-1}, respectively. Hence, fishing mortality (F) was 0.66 year^{-1}, resulting in the value of the exploitation rate (E) being as high as 0.58. The result of the exploitation level (E>0.5) meant that the skipjack tuna stock was in an overfishing category or that the exploitation rate had exceeded the optimum level (Nguyen and Tran, 2023). The observed increase in the mortality rate was likely attributable to the high intensity of fishing activities, which resulted in the capture of a greater number of fish below the minimum catchable size (Amaliani *et al*., 2022).

Recruitment pattern

The result of the recruitment pattern requires the previously obtained L∞, K, and t_0 values. Based on the results, skipjack tuna is recruited almost every month, although the value is not too high. The high recruitment of skipjack tuna occurred in August, with 16.54% (Fig. 2).

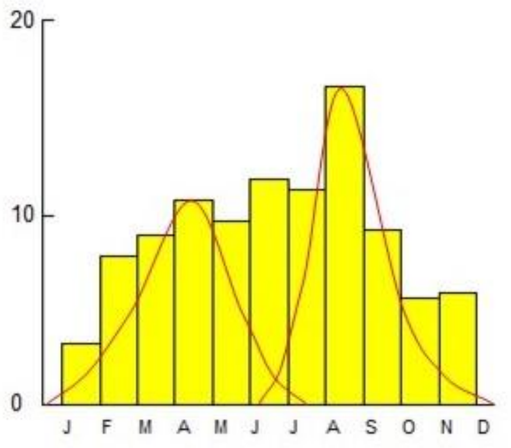

Figure 2: Recruitment pattern of skipjack tuna (*K. pelamis*).

Productivity parameters

Analysis of productivity parameters of skipjack tuna in Malang south coast waters, which constitutes the northern part of the Indian Ocean, demonstrated that values of maximum length, maximum age, and age at maturity were 63 cmFL, 12 years (Webster, 2013), and 1.5 years (Alhassan and Kettey-Tagoe, 2019) respectively. Additional findings revealed that the natural mortality (M) and growth coefficient (K) were 0.47 year^{-1} and 0.25 year^{-1} respectively. The mean trophic level of skipjack tuna in the Indian Ocean, sampled at Pondokdadap CFP in Malang, East Java, was 3.8, categorizing it as a high-level trophic organism due to its piscivorous nature (Yonvitner *et al*., 2020). However, mean trophic level attributes in productivity analysis demonstrate low productivity (Table 3).

Table 3: Productivity parameter attribute results.

Attribute	Unit	Result	Weight	Score	Data quality
Maximum size	cm	63	2	3	1
Maximum age	year	12[1]	2	2	3
Age at maturity	year	1.5[2]	2	3	3
M (natural mortality)	year^{-1}	0.47	2	3	1
K (growth coefficient)	year^{-1}	0.25	2	2	1
r (intrinsic growth rate)		0.743[3]	2	3	3
Fecundity	eggs	74,177 – 1,553,792[4]	2	3	3
Recruitment pattern	%	16.54	2	2	1
Mean Trophic Level		3.8[5]	2	1	3

Sources: 1) Webster (2013); 2) Alhassan & Kettey-Tagoe (2019); 3) Genti *et al*. (2002); 4) Hartaty & Arnenda, (2019); 5) Yonvitner *et al*., (2020)

Susceptibility parameter

The interviews with 16 skipjack tuna fishermen who utilized hand lines revealed that fishing activities are not sufficiently monitored to maintain the fish stock. Seasonal migration demonstrates a moderate impact, as the primary factors affecting skipjack tuna catch efforts are strong waves and winds, which can diminish the effectiveness of fishing operations (Table 4).

PSA analysis

A Productivity-Susceptibility Analysis (PSA) plot illustrates the relative vulnerability determined by the combination of productivity (x-axis) and susceptibility. The productivity and susceptibility parameters analysis graph correlated to skipjack tuna productivity and susceptibility scores at Pondokdadap CFP comprises three lines: blue, indicating low vulnerability; green, indicating moderate vulnerability; and red, indicating high vulnerability. The productivity-to-susceptibility ratio is 2.44 to a susceptibility ratio of 2.33, suggesting a low level of susceptibility for this relationship. The green point denotes high data quality. Conversely, a high susceptibility score indicates that fish are at greater risk of vulnerability (Fig. 3).

Vulnerability score

The susceptibility analysis of skipjack tuna was obtained at 1.44. The score is classified as a low vulnerability because it is ≤ 1.60 (Patrick *et al*., 2010). This can be interpreted because skipjack tuna can maintain the sustainability of its population against fishing activities.

Table 4: Susceptibility parameter attribute results.

Attribute	Results	Weight	Score	Data quality
Management strategy	No catch limits for targeted stocks	2	3	1
Fisheries impact on habitat	The minimum impact caused by fishing gear on the environment	2	1	1
Behavioral responses (Schooling)	Increase in fishing gear catchability	2	3	1
Fisheries impact selectivity on morphological characteristic	High selectivity fishing gear	2	1	1
Economics of fishery value	15,000-20,000 IDR/kg (low economic value)	2	1	1
Seasonal migration pattern	Skipjack tuna migration habits can affect the catch	2	2	1

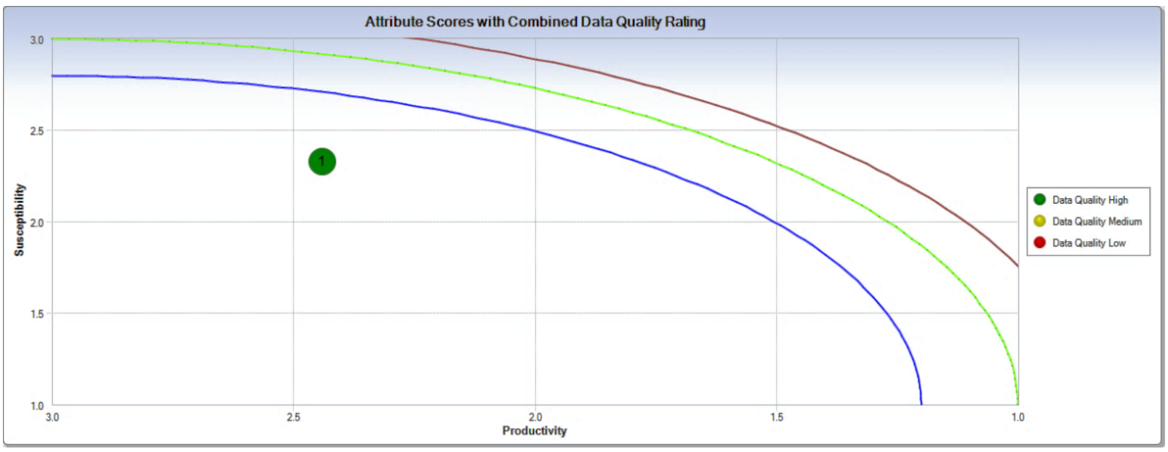

Figure 3: PSA results of skipjack tuna landed at Pondokdadap CFP Malang.

Correlation of SST and CPUE

Sea surface temperatures in the Indian Ocean, specifically in the region south of East Java in 2021, exhibit monthly fluctuations (Figs. 4 and 5). The significance score obtained is 0.337, which indicates no statistically significant effect of sea surface temperature on the CPUE of skipjack tuna in Pondokdadap CFP in 2021, as the significance score exceeds the alpha value (0.337>0.05). The determinant score obtained is 0.116 or 11.6%, suggesting that sea surface temperature fluctuations account for 11.6% of the variation in the CPUE of skipjack tuna at Pondokdadap CFP in 2021. The correlation coefficient between sea surface temperature and CPUE of skipjack tuna at Pondokdadap CFP in 2021 is -0.340, which is classified as the low category and the relationship is inversely proportional.

Correlation of SST and recruitment pattern

The significance score of skipjack tuna in Pondokdadap CFP in 2021 is 0.427, while the determinant coefficient is 0.064.

A significance score higher than alpha (0.427>0.05) indicates a significant effect of sea surface temperature on the recruitment pattern of skipjack tuna in Pondokdadap CFP. The determinant coefficient in 2021 is 0.064 or 6.4%.

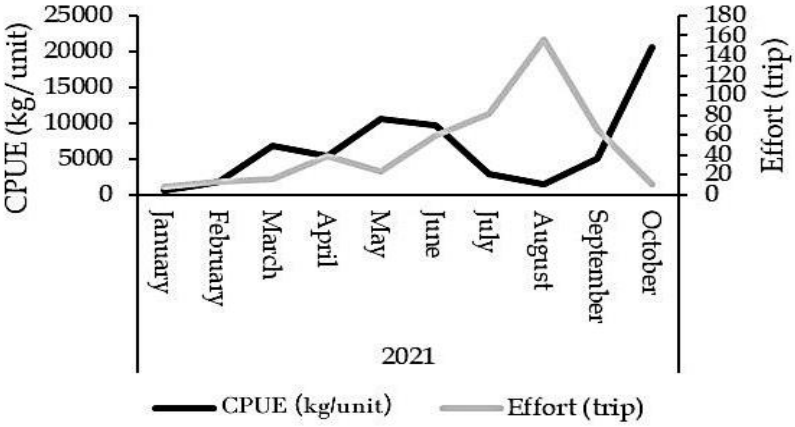

Figure 4: Correlation of CPUE and fishing effort.

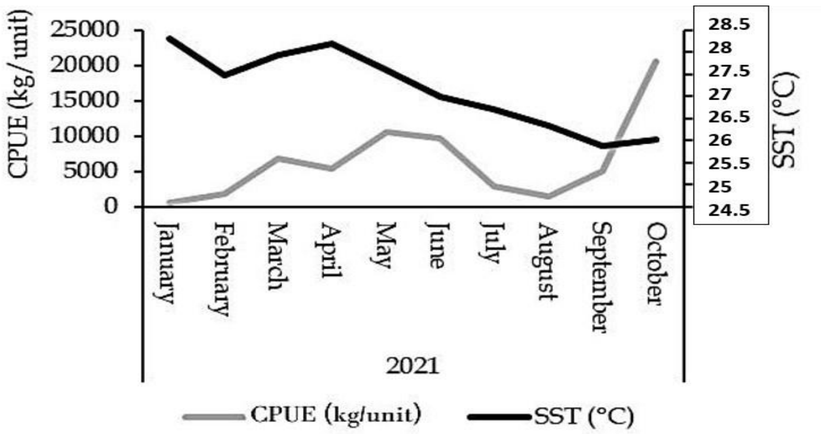

Figure 5: Correlation of CPUE and sea surface temperature.

This coefficient demonstrates the extent to which sea surface temperature influences the recruitment pattern of skipjack tuna, with other factors accounting for the remaining influence. The sea surface temperature variable affects 6.4% of the recruitment pattern of skipjack tuna in Pondokdadap CFP. The coefficient correlation of sea surface temperature between the recruitment pattern of skipjack tuna in Pondokdadap CFP in 2021 is -0.253, classified as a low correlation and is inversely proportional.

Discussion

The results of this research offer a thorough evaluation of the stock status of skipjack tuna (*K. pelamis*) in the waters off the Malang South Coast. The findings reveal that while the species is currently experiencing fishing vulnerability, it still has the potential for recovery if managed appropriately. The Productivity-Susceptibility Analysis (PSA) produced a productivity score of 2.44 and a susceptibility score of 2.33, categorizing the skipjack tuna population as having low vulnerability (Patrick *et al*., 2010). In accordance with this finding, the skipjack tuna is classified as a sturdy species and has high reproduction ability (Julia et al., 2019; Bintoro et al., 2021) However, despite this classification, the species faces overfishing challenges, as evidenced by an exploitation rate of 0.58, surpassing the sustainable fisheries threshold of 0.50 (Pauly, 1984).

The overfishing of skipjack tuna has been extensively documented across various regions, with heightened fishing efforts leading to stock depletion (Herwaty *et al*., 2021). In this study, a notable proportion of catch (79.64%) was below the maturity length of 44.7 cmFL, indicating significant exploitation pressure before fully realizing their reproductive capacity (Agustina *et al*., 2019b). Similar patterns have been noted in other areas of the Indian Ocean, where uncontrolled fishing intensity has resulted in changes to population dynamics and stock instability (Dueri *et al*., 2014; Khatami *et al*., 2018). Effective management strategies, such as regulating fishing efforts and implementing size-selective fishing practices, are essential to ensure the sustainability of fish stocks (Hilborn and Walters, 1992).

Climate change represents another factor impacting skipjack tuna populations, primarily through variations in sea surface temperature (SST) (Pauly and Cheung, 2018). The study's results indicate a low-to-moderate inverse correlation between SST and catch per unit effort (CPUE) (-0.340), suggesting that changes in SST affect fish availability (Lan *et al*., 2020). Additionally, the recruitment pattern showed a weak correlation with SST fluctuations (-0.253), supporting the idea that alterations in oceanographic conditions influence spawning success and larval survival (Peck *et al*., 2013; Islam *et al*., 2019). Previous research has shown that temperature-induced changes in fish distribution and primary productivity can affect recruitment patterns (Dueri *et al*., 2014; Pratiwi *et al*., 2020b).

The dynamics of skipjack tuna populations are shaped by growth, mortality, and recruitment patterns (Effendie, 2002; Morgan *et al*., 2009). The finding of this study which indicated a the growth coefficient (K) of 0.25 year-1 was in line with data found by Murua *et al*. (2017) with the range of the growth coefficient (K) of tuna species as big as 0.05 $year^{-1}$ – 0.95 $year^{-1}$. In addition, growth coefficient (K) as part of growth model and parameter is one of the reference points to justify stock status and proper sustainable fisheries management tool (Kolody *et al.,* 2016; Murua *et al*., 2017). The estimated natural mortality rate (M) was 0.47 $year^{-1}$, while fishing mortality (F) was recorded at 0.66 $year^{-1}$, further confirming trends of overexploitation (Kartini *et al*., 2017). To maintain population resilience, sustainable fisheries management must prioritize stock assessments and adaptive management strategies (Auliyah *et al*., 2021). The peak recruitment period for fish occurs in August (16.54%), indicating that targeted management actions during spawning seasons could enhance stock sustainability (Webster, 2013). Implementing seasonal closures or restrictions during peak recruitment times may help reduce excessive captures of juveniles and improve overall fishery productivity (Hartaty and Arnenda, 2019).

Given the current state of overfishing and environmental pressures, an ecosystem-based fisheries management (EBFM) approach should be adopted to align fishery regulations with climate adaptation strategies (Hilborn and Walters, 1992; Suryaman *et al*., 2017). Potential management strategies may include:

1. Effort Control through fishing quotas and licensing systems establishment to manage fleet size and fishing intensity (Khatami *et al*., 2018);
2. Size Limitations by applying minimum fish landing sizes to prevent recruitment overfishing and allow juvenile fish to reach reproductive maturity (Herwaty *et al*., 2021);
3. Seasonally closed areas by creating conservation zones such as Marine protected areas (MPAs) to protect critical fish habitats and spawning grounds (Peck *et al*., 2013);
4. Monitoring and Compliance by enhancing surveillance and data collection efforts to improve the accuracy of stock assessments (Patrick *et al*., 2010); and
5. Climate adaptation strategies can be implemented by modifying fishing practices based on oceanographic forecasts and SST trends to optimize catch efficiency while minimizing ecological impacts (Dueri *et al*., 2014).

Conclusions

This study underscores the urgent need for improved management strategies to ensure the sustainability of skipjack tuna populations in the Malang South Coast waters. The findings indicate that although the species has a low vulnerability score, the ongoing trend of overfishing requires immediate action. Additionally, the effects of climate variability highlight the necessity for adaptive fisheries management. Future research should concentrate on refining stock assessment models and investigating ecosystem-based management frameworks to secure the long-term viability of skipjack tuna fisheries resources.

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Conflicts of Interest

The authors declare that there are no conflicts of interest.

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