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Unveiling the status of *Trichiurus lepturus* (Actinopterygii, Scombriformes, Trichiuridae) stocks in the southern Java waters, Indonesia: A biological and length-based assessment approach

Prihatiningsih PRIHATININGSIH[1], Tirtadanu TIRTADANU[1], Muhammad TAUFIK[1], Rosmiati ROSMIATI[1], Erfind NURDIN[1], Anthony Sisco PANGGABEAN[1], Duranta Diandria KEMBAREN[1], Nurulludin NURULLUDIN[1], Umi CHODRIJAH[1], Ralph Thomas MAHULETTE[1], Budi NUGRAHA[1]

1 *Research Center for Fishery, National Research and Innovation Agency, Cibinong, West Java, Indonesia*

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Corresponding authors: Prihatiningsih Prihatiningsih (prih002@brin.go.id); Rosmiati Rosmiati (rosm005@brin.go.id)

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Abstract

The southern Java waters are characterized by a strong upwelling process, making the region a potential hotspot for fishing activities, including the largehead hairtail, *Trichiurus lepturus* Linnaeus, 1758. This study provides data on various aspects of *T. lepturus* in the southern Java waters, including reproductive biology, growth parameters, mortality rates, spawning potential ratio (SPR), and yield per recruit (Y/R). The results are intended to help sustain the management of *T. lepturus* fisheries in the southern Java waters. A total of 19 587 fish specimens were collected monthly between January 2019 and December 2021 from fishermen's catches in the southern Java waters at the Palabuhanratu Archipelago Fishing Port, West Java Province, Indonesia. The data collected involved information on length, weight, sex, and gonads. Length-frequency data were analyzed using various fisheries assessment models. A length–weight relationship follows a positive allometric growth pattern. The sex ratio was slightly female-biased. Gonadal maturity stages (GMS) and the gonadosomatic index (GSI) indicated a prolonged spawning period. The length at first maturity (L_{m50}) males and females was estimated at 84.5 cm and 77.0 cm, respectively. The von Bertalanffy growth equation of *T. lepturus* in southern Java waters is $L_t = 131.67(1 - e^{-0.22(t + 0.5094)})$. Total mortality ($Z$), natural mortality ($M$), and fishing mortality (F) were 1.60 year^{-1}, 0.44 year^{-1}, and 1.16 year^{-1}, respectively. The spawning potential ratio (SPR) was 26%, and the yield per recruit (Y/R) analysis suggested that the current fishing effort is above the maximum sustainable yield level. *Trichiurus lepturus* in southern Java waters is experiencing high fishing pressure, which may compromise its reproductive potential and long-term sustainability. Management measures should be implemented to regulate the fishing effort and ensure the sustainable exploitation of this vital fishery resource.

Keywords

largehead hairtail, mortality rates, overfishing, spawning season, sustainable fisheries

Introduction

The southern Java waters, located within the Indian Ocean, are characterized by a large upwelling area. A large upwelling area that brings nutrient-rich water from the depths influences fish reproduction and growth positively, making the region a potential hotspot for fishing activities (Diogoul et al. 2021; Wen et al. 2023). One of the commercially important fish species found in this area is the largehead hairtail, *Trichiurus lepturus* Linnaeus, 1758, which has high economic value due to its delicious taste and high nutritional profile, providing essential amino acids and healthy polyunsaturated fatty acids (Ding et al. 2022). *Trichiurus lepturus* is a benthopelagic species representing the family Trichiuridae and the order Scombriformes. It is widely distributed in tropical and subtropical waters worldwide, including the Indian, Atlantic, and Northwestern Pacific Oceans (Sun et al. 2020; Cheng et al. 2022; Clain et al. 2023a; El-Bakary et al. 2023).

The largehead hairtail is of paramount economic importance, serving domestic needs and contributing significantly to export revenue for Indonesia (Meriem et al. 2011). Major export destinations include China, the United States, Malaysia, Japan, Vietnam, Thailand, South Korea, Italy, Taiwan, and Singapore. Over the past five years (2017–2021), the export volume of *T. lepturus* reached 43 894 tons, reflecting a substantial increase of 25.26 percentage points (Anonymous 2022). The high demand for *T. lepturus* in both local and international markets is expected to increase the intensity of fishing activities in the southern Java waters (Airlangga et al. 2018; Clain et al. 2023a). If this situation continues without proper management, it is feared that the *T. lepturus* resources will be overexploited. Currently, data and information on *T. lepturus* resources in the southern Java waters are limited, and the assessment of fish stocks in this area faces challenges due to the vast research area and the high costs associated with holistic approaches like demersal trawl surveys (Khan 2006; Kurnia et al. 2022; Martins and Haimovici 1997). Analytical models directly applicable to tropical waters are also hindered by seasonal variations, multispecies dynamics, and diverse fishing methods (Sparre and Venema 1998).

To address this gap, we employed a data-driven approach, utilizing length-frequency time series and life history data for stock assessment of *T. lepturus*, in the southern Java waters covered by the presently reported study. The data were collected, including age, growth, mortality rate, and exploitation rate (Abdussamad et al. 2006; Khan 2006; Shih et al. 2011; Liang and Pauly 2017; Amador and Aggrey-Fynn 2020; Clain et al. 2023b; Santos et al. 2022;) as well as its reproductive biology (Martins and Haimovici 2000; Al-Nahdi et al. 2009; De la Cruz-Torres et al. 2014; Ghosh et al. 2014; Rajesh et al. 2015; Al Nahdi et al. 2016; Clain et al. 2023a). The presently reported study was intended to investigate various aspects of *T. lepturus* in the southern Java waters, including reproductive biology, growth parameters, mortality rates, spawning potential ratio (SPR), and yield per recruit (Y/R). Given the high demand for *T. lepturus* in global markets, continuous unregulated fishing could lead to over-exploitation. Therefore, a comprehensive understanding of the stock status is essential for crafting effective fisheries management policies and ensuring the sustainability of *T. lepturus* populations.

Materials and methods

Data collection. Total length frequency data of the largehead hairtail, *Trichiurus lepturus* were collected from fishermen's catches in the southern Java waters, especially in the Fisheries Management Area (FMA) 573 of the Indian Ocean. The data were collected at the landing site in Palabuhanratu, West Java Province, Indonesia (Fig. 1). The dominant fishing gears used to catch *T. lepturus* were the handline and bottom longline, utilizing hook sizes 7, 8, and 9, with operations at depths between 10 and 100 m. The data collected involved information on length, weight, sex, and gonads. Length measurements were taken monthly from 2019 to 2021.

Meanwhile, the length, weight, and gonad characteristics of the fish were observed at the Research Institute for Marine Fisheries Laboratory, Ministry of Marine Affairs and Fisheries in 2019. The total length of the *T. lepturus* was measured, which is the length from the anterior extremity of the lower jaw to the tip of the tail (Clain et al. 2023a), with an accuracy of up to 0.1 cm. The weight measurements were recorded to the nearest 0.01 g.

Data analysis. The total length frequency data of *T. lepturus* collected from January 2019 to December 2021 were shown as a histogram with a 5.0 cm class interval. Furthermore, the relationship between the length and weight of *T. lepturus* was analyzed using a growth equation described by Al Nahdi et al. (2016):

$$W = aL^b$$

where W expresses the total weight [g], L represents the total length [cm], a is a constant, and b is the growth coefficient. The male and female *T. lepturus* numbers were compared to obtain the sex ratio. This analysis was then examined using the Chi-square test to determine whether the sex ratio was balanced.

The gonadal maturity stage (GMS) in *T. lepturus* was determined through morphological (macroscopic) observations, which involved monitoring the ovarian shape size, filling in the body cavity, color, and egg size and color monthly. Ovarian development was classified into five stages, namely stage I (immature), stage II (developing), stage III (mature/ripe), stage IV (spawning/running ripe), and stage V (spent) (Martins and Haimovici 2000; Amador and Aggrey-Fynn 2020; Clain et al. 2023a). The gonadosomatic index (GSI) was calculated using the ratio between the total weight of the gonad (G) and the total weight of fish (W) in each individual using the equation of Hasan et al. (2020)

$$\mathrm{GSI} = \frac{G}{W} \times 100$$

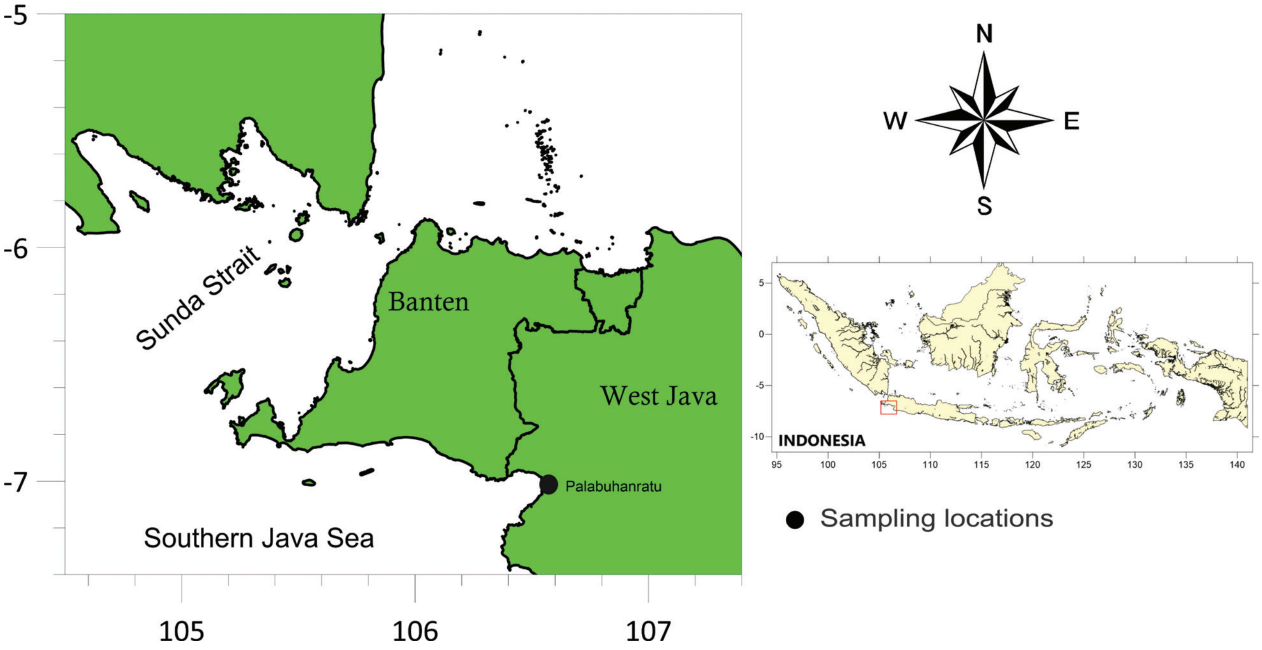

Figure 1. Map of sampling locations for *Trichiurus lepturus* in the waters southern Java, Indonesia.

The length at maturity is made up of 50% (L_{m50}) of adult fish, depending on the circumstances surrounding reproduction. The length (L) of the proportion (Q) of a sexually mature individual can be fitted using a logistic curve of King (2007)

$$Q = \frac{1}{(1 + \exp[-r(L - L_{m50})]}$$

where r is the slope of the curve and L_{m50} is the mean length at sexual maturity, or the length that amount to a percentage of 0.5 (or 50%) in reproductive condition. The probability of the binomial distribution was maximized to fit this logistic model. The SOLVER tool in Microsoft Excel was used to do the analysis. The size at first capture (L_{s50}) was estimated using the trawl-type selection curve in the FiSAT based on the equation from Pauly (1983)

$$In\left(\frac{1}{P_l} - 1\right) = S1 - S2(L),$$

where P_l is the capture probability for length L, and L_{s50} was calculated using $S1/S2$.

The growth parameters were estimated using the von Bertalanffy growth function (Sparre and Venema 1998)

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

where L_t is the total length at age t; L_∞ is asymptotic length; K is the growth coefficient; and t_0 is the theoretical age at zero length. Asymptotic length (L_∞) and growth constant (K) were calculated using the Electronic Length Frequency Analysis/ELEFAN I in TropFishR packages from R Program (R Development Core Team 2008; Mildenberger et al. 2017). We performed parameter selection based on a goodness-of-fit index (R_n) of the data against the von Bertalanffy model indicated by the R_n value. From the results using the growth data of *T. lepturus* in southern Java, the ELEFAN optimize method showed a higher R_n ($R_n = 0.27$) than using ELEFAN SA ($R_n = 0.26$) and ELEFAN GA ($R_n = 0.25$). Thus, the optimize method from TropFishR was performed as the more robust fitness with the length frequency data of *T. lepturus*.

Furthermore, the theoretical age at length zero (t_0) of the *T. lepturus* was calculated using the Pauly (1983) equation

$$\mathrm{Log}(-t_0) = (-0.3922) - 0.2752\ \mathrm{Log}(L_\infty) - 1.038\ \mathrm{Log}(K)$$

Longevity or maximal age (t_{max}) was estimated using the equation proposed by Alagaraja (1984)

$$t_{max} = -\frac{1}{K}ln(1 - \frac{0.99L_\infty}{L_\infty})$$

The mortality parameters, including the total (Z), natural (M), and fishing (F) mortalities, were calculated based on Zhang and Megrey (2006)

$$M = \frac{bK}{e^{K(C_i - t_{max} - t_0 - 1)}}$$

where M is natural mortality; C_i is 0.302 as the coefficient for demersal fishery; K is growth constant; t_0 is theoretical age at zero length; t_{max} is maximum age; b is the exponent from the length–weight relationship. Furthermore, the total mortality (Z) was calculated using the linearized length converted catch curve equation of Sparre and Venema (1998)

$$ln\frac{C(L1, L2)}{\Delta t(L1, L2)} = C - Z_t z\left(\frac{L1 + L2}{2}\right)$$

where C is the frequency of length class. Fishing mortality (F) and exploitation rate (E) were calculated using the equations below:

$$F = Z - M$$

$$E = \frac{F}{Z}$$

The optimal length at first capture was estimated using yield per recruit analysis based on some length at first capture scenarios. The yield per recruit was calculated using the equation (Beverton and Holt 1957)

$$\frac{Y}{R} = F(\propto L\infty^{\beta})\left[\frac{L_\infty - L_c}{L_\infty}\right]^{\frac{M}{K}}\left[\frac{L_\infty - L_r}{L_\infty}\right]^{\frac{M}{K}}\sum_{n-0}^{3}\frac{Un\left[\frac{L_\infty - L_c}{L_\infty}\right]^{n}}{F+M+nK}$$

where *Y*/*R* is the yield per recruit; *a* and *b* are the length–weight relations, *M* is natural mortality; and *K* is the growth constant. U_n contains $U_0 = 1$, $U_1 = -3$, $U_2 = 3$, and $U_3 = -1$. Maximum fishing mortality ($F_{\max}$) was also used as a biological reference point in the yield per recruit analysis (Beverton and Holt 1957). The spawning potential ratio (SPR) was defined as the ratio of spawning stock biomass per recruit in the exploited species ($\text{SSBR}_{exploited}$) to spawning stock biomass per recruit in the absence of fishing ($\text{SSBR}_{F=0}$) (Hordyk et al. 2016).

$$\text{SPR} = \frac{\text{SSBR}_{\text{exploited}}}{\text{SSBR}_{F=0}}$$

$F_{40\%}$ was estimated based on the length-based spawning potential ratio analysis, which gave 40% stock biomass per recruit (Prince et al. 2015).

Results

Length distribution and length–weight relationship. We studied 19 587 individual largehead hairtail, *Trichiurus lepturus*, captured in southern Java, Indonesia, over three years (2019–2021). This fish was 69.0–107.0 cm TL with the mean length of 82.05 ± 7.52 cm TL (Mean ± SD) for females, 68.9–101.5 cm TL the mean length of 80.00 ± 5.95 cm TL for males and 7.0–135.0 cm TL, with the mean length of 78.33 ± 8.35 cm TL for all individuals. The length distribution graph showed a mode at 79.0 cm TL and maximum length at 135.0 cm TL (Fig. 2A–C).

Based on *t*-test analysis, the growth pattern of female ($n = 97$), male ($n = 178$) and all individuals ($n = 353$) hairtail fish exhibited positive allometric growth, where weight increased at a faster rate than length, as indicated by the equations:

$W = 0.0001L^{3.2994}$ for females,

$W = 0.00005L^{3.5557}$ for males and

$W = 0.0002L^{3.2747}$ for all individuals, with correlation coefficients (R^2) of 0.8122, 0.8798, and 0.9322, respectively (Fig. 3A–C).

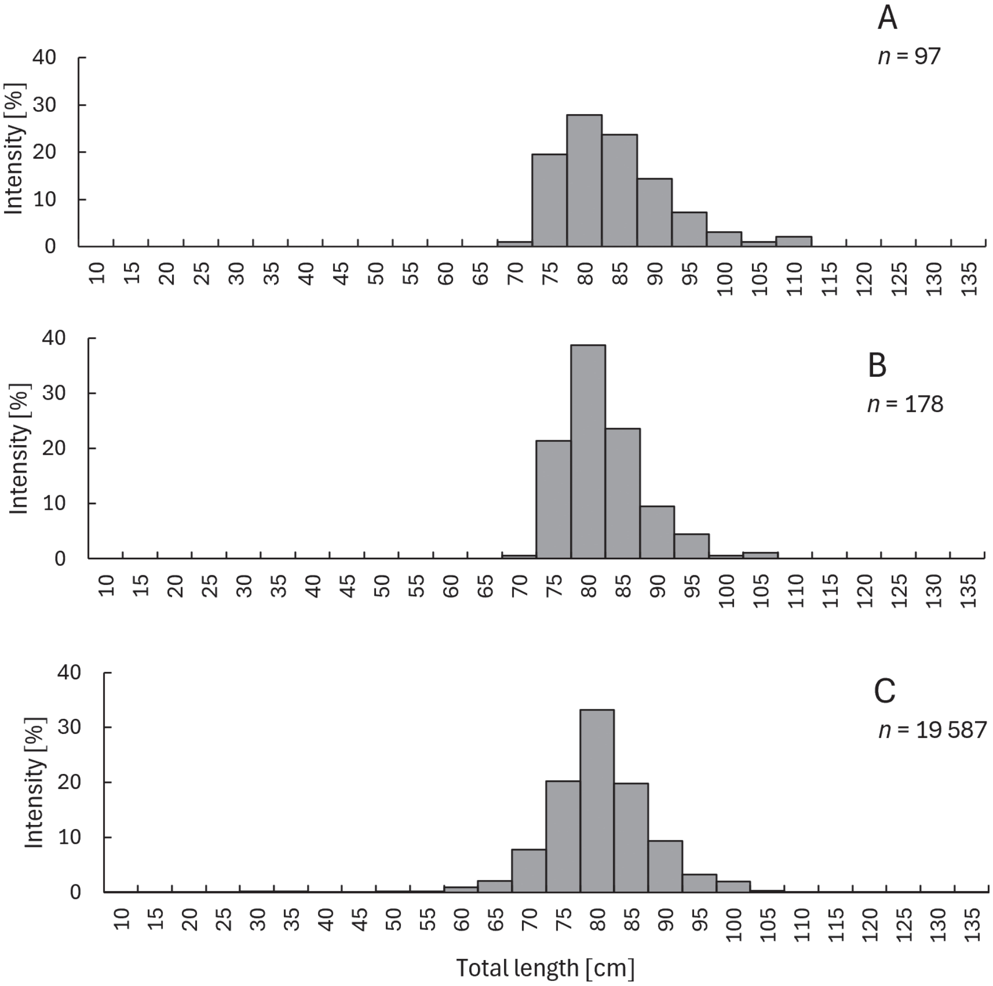

Figure 2. Length distribution of *Trichiurus lepturus* from the waters southern Java, Indonesia; females (**A**), males (**B**), and all individuals (**C**).

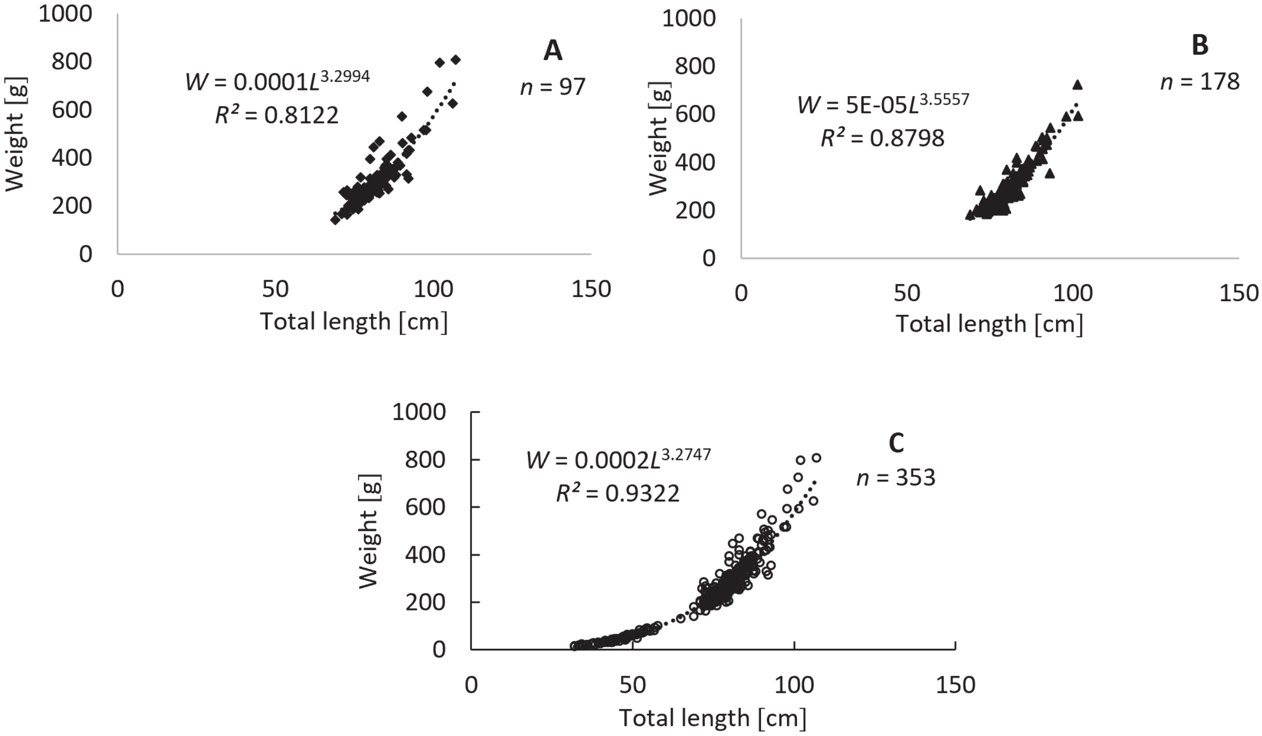

Figure 3. Length–weight relationship of *Trichiurus lepturus* from the waters southern Java, Indonesia; females (**A**), males (**B**), and all individuals (**C**).

Sex ratio. The sex ratio of *T. lepturus* was assessed during the study, and it was found that there were 214 (57%) males and 163 (43%) females. The data analysis revealed that in certain months (February, May, October, and November), the sex ratio of males to females was not significantly different. This was statistically based on the calculated chi square value which lower than the chi square table, ($\chi^2_{\text{value}} < \chi^2_{\text{table}}$), indicating the ratio of male and female was equal (1:1). In June, July, August, and December, however, the sex ratio of males to females was significantly different ($\chi^2_{\text{value}} > \chi^2_{\text{table}}$) from a 1:1 ratio (≠ 1:1), indicating an imbalance in the sex ratio. Overall, the chi-square test results showed that the large head hairtail fish population was dominated by males and that the sex ratio was out of balance (Table 1).

Spawning season. The spawning season of *T. lepturus* was determined by observing gonadal maturity stages (GMS) and gonadosomatic index (GSI). The study found that females exhibited GMS stages I to IV, with the highest frequency of GMS I observed in February (56%) and November (72%), GMS II in August (100%) and October (63%), GMS III in June (57%), and GMS IV in July (75%) (Fig. 4A). Males showed the highest frequency of GMS stage I in February (42%) and October (57%), GMS stage II in May (70%) and June (51%), and GMS stages III and IV in July (63% and 18%) (Fig. 4B).

The GSI (mean ± SD) values in females and males fluctuated during observation. The GSI in females ranged from 0.10 ± 1.0 to 21.59 ± 16.34, while in males it ranged from 1.00 ± 0.75 to 5.13 ± 2.33. Generally, the GSI values in females were higher than in males. The highest GSI values for males and females occurred in July, with respective values of 5.13 and 21.59 (Fig. 5).

Selectivity and maturity. The estimated length of 50% of fish capture (L_{s50}) or length selectivity was examined using the logistic function. The L_{s50} of *T. lepturus* has an 81.0 cm TL. Maturity analysis of males (L_{m50}♂) and females (L_{m50}♀) of *T. lepturus* was 84.5 cm TL and 77.0 cm TL, respectively (Fig. 6). To calculate the maturity proportions, the length group of mature males and female fishes was divided by the total sample (adults and immatures combined) for each length class. A logistic function was used to modify each fish's maturity percentage based on its length, and the model was fitted by maximizing the likelihood of binomial distribution. The length at 50% selectivity (L_{s50}) of *T. lepturus* is higher than the estimated average length at 50% maturity females ($L_{\text{s50}} > L_{\text{m50}}$♀) but smaller than length at 50% maturity males ($L_{\text{s50}} < L_{\text{m50}}$♂) (Fig. 6). These results shed light on the size of *T. lepturus*, a species that is harvested carefully and matures sexually.

Growth parameter, longevity, mortality, and exploitation rate. The research computed several growth characteristics for *T. lepturus*, such as the growth rate (K) of 0.22 year^{-1}, the asymptotic length (L_∞) of 131.67 cm TL, and the theoretical age (t_0) of –0.5094 year at which the fish length is zero. The von Bertalanffy growth equation for this species in southern Java was derived based on these parameters, namely, $L_t = 131.67(1 - e^{-0.22(t + 0.5094)})$ (Fig. 7). The longevity or $t_{\max}$ (age at 95% of asymptotic length) of *T. lepturus* was estimated at 14 years of age.

Table 1. Sex ratio of *Trichiurus lepturus* from the waters southern Java, Indonesia, based on observation time.

Month	Males (M)	Females (F)	Total	Sex ratio (M:F)	χ^2_{value}	χ^2_{table}	$P = 0.05$
February	21	23	44	0.9:1.0	0.09	3.84	Significant
May	24	33	57	0.7:1.0	1.42	3.84	Significant
June	37	7	44	5.28:1.0	20.45	3.84	Not significant
July	22	8	30	2.75:1.0	6.53	3.84	Not significant
August	41	7	48	5.85:1.0	24.08	3.84	Not significant
October	33	19	52	1.73:1.0	3.77	3.84	Significant
November	28	44	72	0.63:1.0	3.56	3.84	Significant
December	8	22	30	0.36:1.0	6.53	3.84	Not significant
Pooled	214	163	377	1.31:1.0	6.90	3.84	Not significant

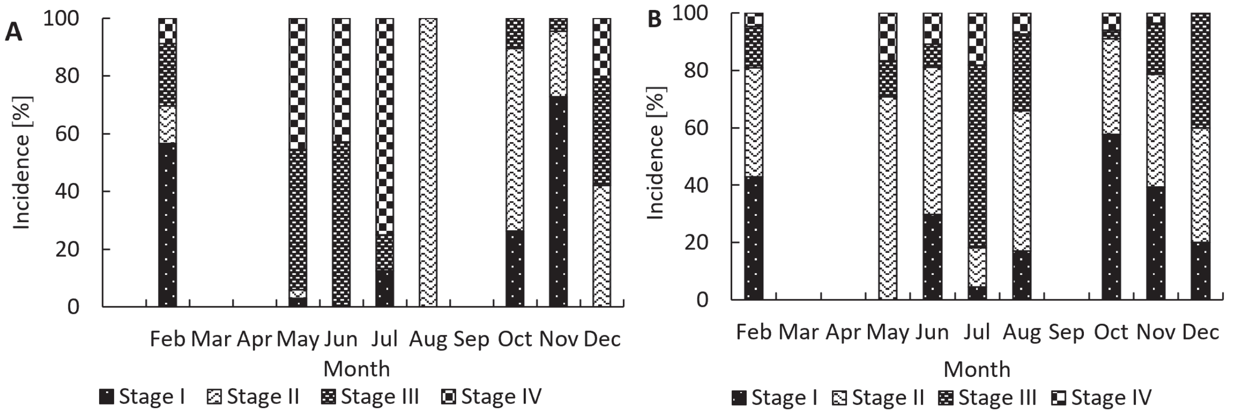

Figure 4. The incidence of gonadal maturity stages (GMS) of *Trichiurus lepturus* from the waters southern Java, Indonesia; (**A**) females and (**B**) males.

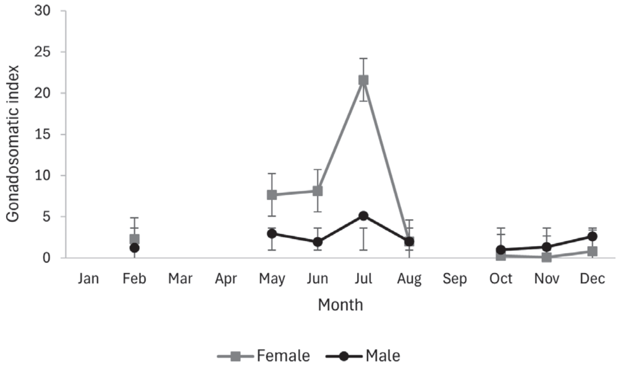

Figure 5. The gonadosomatic index (GSI) per month is for females (gray line) and males (black line) of *Trichiurus lepturus* from the waters southern Java, Indonesia.

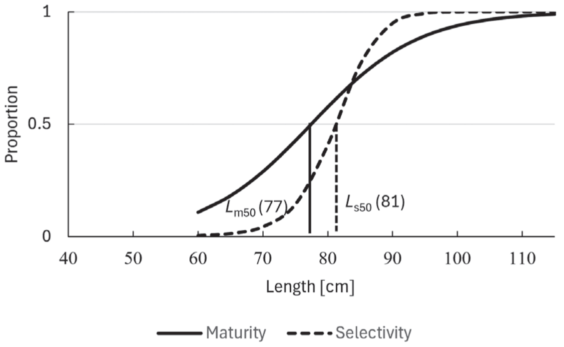

Figure 6. Length at 50% selectivity (L_{s50}), length at 50% maturity male (L_{m50} ♂) and female (L_{m50}♀) for *Trichiurus lepturus* from the waters southern Java, Indonesia.

The study also assessed the mortality rates, indicating that the natural mortality rate (M) was lower (0.44 year^{-1}) than the fishing mortality rate (F) (1.16 year^{-1}). The total mortality rate (Z) was 1.60 year^{-1} (Fig. 8). The exploitation rate (E) of *T. lepturus* was 0.72, higher than the optimum level ($E = 0.50$).

Yield per recruit (Y/R). The most significant yield per recruit ($Y/R_{\max}$ = 8068.37 g recruit^{-1}; $F_{\max}$ = 1.13 year^{-1}) was reached by *T. lepturus* when fishing mortality rose. It suggests that there may be some fishing pressure on *T. lepturus* in the waters off southern Java, as evidenced by the present fishing mortality (F_{cur} = 1.16 year^{-1}), marginally more significant than the reference point $F_{\max}$ (1.13 year^{-1}). The fishing mortality from the current condition (F_{cur}) must be slightly reduced by 2% to reach the ideal $F_{\max}$ level, based on the analysis of recruitment outcomes. The research also indicates that *T. lepturus* is being captured before it can contribute to the recruitment process, as its length at selectivity (L_{scur} = 81.0 cm) is less than the value that would result in the maximum yield recruit^{-1} (L_{smax} = 88.0 cm). Based on the existing length and selectivity, the yield per recruit is 8;.068 g recruit^{-1}, with a maximum of 8610 g recruit^{-1}. To obtain L_{smax}, an 8% improvement in the current selectivity (L_{scur}) is required (Fig. 9A, 9B).

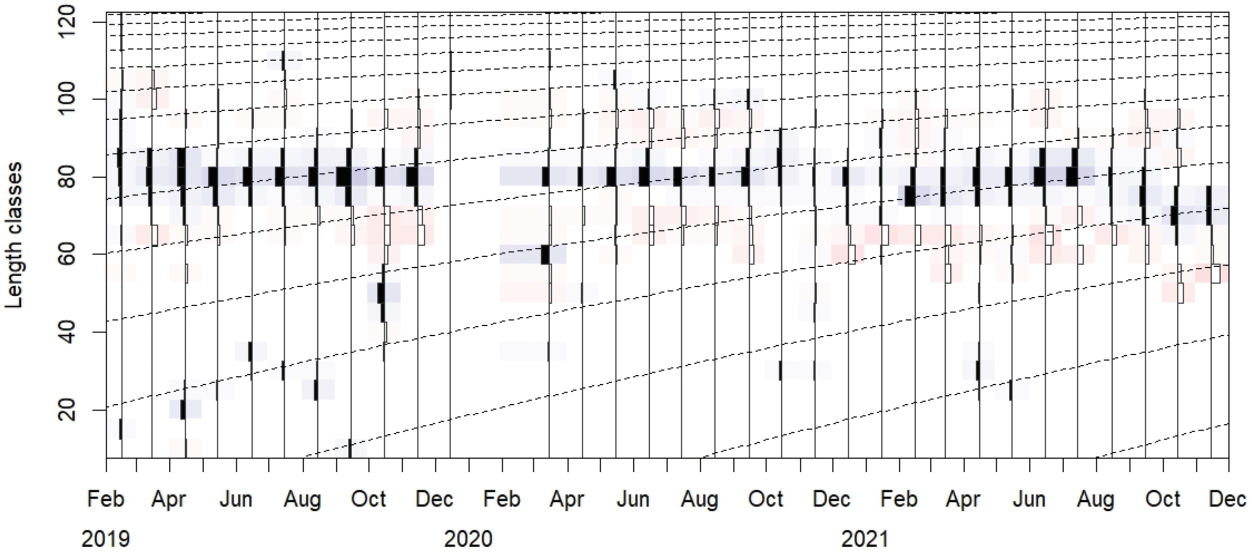

Figure 7. Plot von Bertalanffy Growth Function Curve of *Trichiurus lepturus* from the waters southern Java, Indonesia.

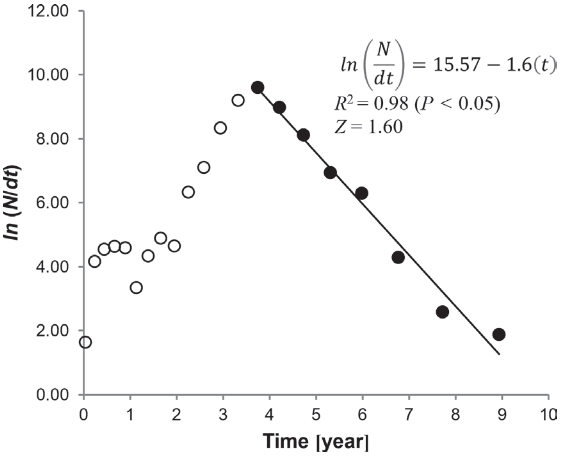

Figure 8. Length converted catch curve of *Trichiurus lepturus* from the waters southern Java, Indonesia; t = time.

Spawning potential ratio (SPR). The spawning potential ratio (SPR) of *T. lepturus* in the waters of southern Java waters is 26%, falling between the target reference point ($\mathrm{SPR}_{40\%}$) and the limit reference point ($\mathrm{SPR}_{20\%}$) (Fig. 10A, 10B). Although it suggests that the *T. lepturus* stock biomass in the wild is still in good shape, it is advisable to think twice before increasing fishing efforts. In south Java's seas, the present fishing mortality of *T. lepturus* (F_{cur} = 1.16 year^{-1}) is 48% greater than the fishing mortality that would provide 40% spawning potential ratio ($F_{40\%}$ = 0.60 year^{-1}). Based on the L_{s} value, the spawning potential ratio will reach 40% SPR with a 0.1% increase in selectivity length to 89 cm ($L_{\max}$) under the current fishing conditions.

Discussion

It is essential to comprehend the length–weight relationship to assess the state and well-being of fish populations (Abd Hamid et al. 2015; Yousuf et al. 2023). The measured length distribution of *Trichiurus lepturus* is represented by the mean length of 78.33 cm TL and a range of 7.0 to 135.0 cm TL. It suggests that hairtail fish in the southern Java waters can grow quite large. The distribution of lengths of this fish is more significant than research reported by Satria et al. (2007) in the same waters of 69.0–112.0 cm TL and 8.0–114.0 cm TL and reports from Abdussamad et al. (2006) from the east coast of India of 124 cm. It also exceeds reported lengths from the Arabian Sea coast of Oman (Al-Nahdi et al. 2009) in the range of 16.0–126.0 cm TL and from Ghanaian waters (Amador and Aggrey-Fynn 2020) in the range of 24.8–103.9 cm TL. The lengths found in this study are shorter than those found in southeast Australia, as reported by Clain et al. (2023a), where fish were found to attain lengths of up to 193.0 cm TL.

Differences in the length of *T. lepturus* in each region are hypothesized to be associated with variations in the intrinsic growth of the fish (Shih et al. 2011). The selectivity of fishing gear also plays a role, as the gear used in this study, such as longlines and bottom-set longlines, is generally more selective in capturing larger hairtail fish compared to trawls (Al-Nahdi et al. 2009; Amador and Aggrey-Fynn 2020; Clain et al. 2023a). Additionally, the physiological behavior of fish concerning water depth may contribute to these differences, where fish found in deeper waters (500–1000 m) tend to have smaller sizes than those inhabiting waters at depths of 250–500 m (Liu and Cheng 2023).

Trichiurus lepturus has a weight distribution of 130–807 g, averaging 241 g. *Trichiurus lepturus* in the Indian Ocean off the coast of southern Java waters has a positive allometric development trend, meaning that weight increases more quickly than length increases. According to Pastorino et al. (2020), fish with a higher weight at a specific length have better health conditions. This finding aligns with De la Cruz-Torres et al. (2014) results in Mexico and Al-Nahdi et al. (2009) in

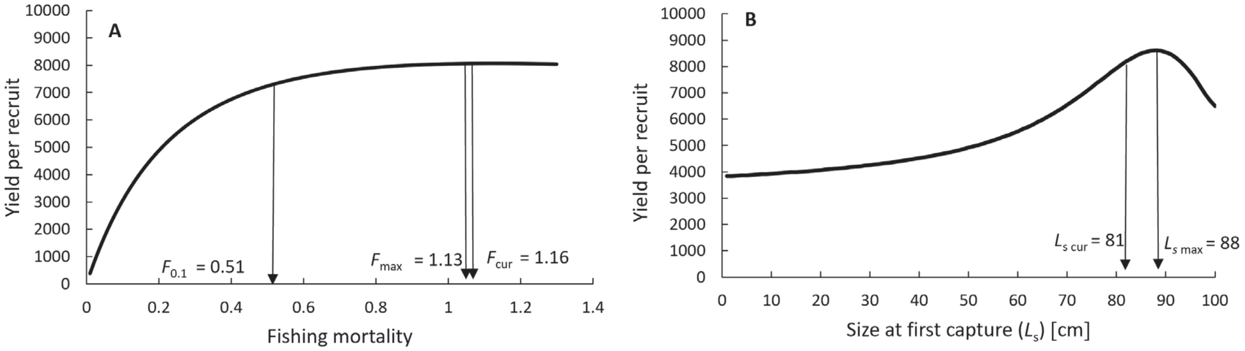

Figure 9. The fishing mortality (F_{max}) (**A**) and the size at first capture (L_{smax}) (**B**) for *Trichiurus lepturus* from the waters southern Java, Indonesia.

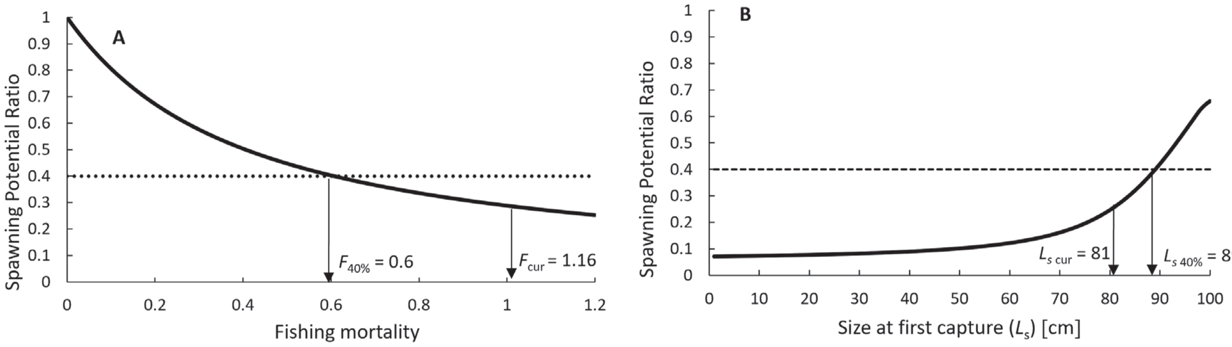

Figure 10. The biological reference point of $F_{40\%}$ (**A**) and $L_{s40\%}$ (**B**) for *Trichiurus lepturus* from the waters southern Java, Indonesia.

Oman, confirming a positive allometric growth pattern. Furthermore, the length–weight connection between male and female fish does not differ noticeably; seasonal variations are noted. In contrast, Ghosh et al. (2014) found that the growth pattern of *T. lepturus* in the northern Bay of Bengal is allometric, while that of the northern Arabian Sea is isometric. The differences in the length–weight relationship of hairtail fish across various aquatic regions suggest potential variations influenced by seasonal changes, environmental factors such as temperature and habitat type, gonad maturity stage, food availability, competition for resources, and fish behavior and physiology (Al Nahdi et al. 2016; Amador and Aggrey-Fynn 2020; Pastorino et al. 2020).

In this study, overall, the sex ratio of *T. lepturus* in the southern Java waters is imbalanced (1.31:1.0), with males being more dominant than females (Table 1). It differs from other regions such as the waters of Australia Clain et al. (2023a), the Arabian Sea Al-Nahdi et al. (2009), and the northern Bay of Bengal (Ghosh et al. 2014), and southwestern coast of India (Rajesh et al. 2015), where females tend to dominate. Based on monthly observations, February, March, November, and December are dominated by females, while males dominate June, July, August, and October. The differences in sex ratios among different areas and times could be attributed to various factors, including environmental conditions, fishing pressure, and reproductive dynamics of the species. It is believed that variations in fishing, including male and female migration patterns to and from fishing regions and the type of fishing gear employed, account for the sex ratio in various locations and periods (De la Cruz-Torres et al. 2014; Ghosh et al. 2014).

The highest monthly percentage of GMS value for both males and females *T. lepturus* happened in July (Fig. 4). The highest GSI value for males and females, *T. lepturus* occurred in July (Fig. 5). The GMS and GSI values show that the spawning season in the southern Java waters occurs from July to August. The spawning season in this study is different from the other research in several regions, such as in Ghanaian waters where it occurs in March–June (Amador and Aggrey-Fynn 2020); in the Arabian Sea where it occurs in May–June (Al-Nahdi et al. 2009); in Mexico during January–March (De la Cruz-Torres et al. 2014); in the northern Arabian Sea and north Bay of Bengal in December–March (Ghosh et al. 2014); in southern Brazil in spring to summer (Martins and Haimovici 2000) and in southeastern Australia in March–September (Clain et al. 2023a). Differences in spawning periods between regions can be caused by several factors, including seasonal variations, geographic location, fishing pressure, and environmental factors (Ghosh et al. 2014). Understanding the spawning season is part of the fish reproduction strategy (Vieira et al. 2016). To maintain sustainability, one of the efforts to manage *T. lepturus* resources in the southern waters of Java, Indonesia, is by reducing fishing activities during the peak of the spawning season (close season), namely in July–August.

The mean estimated length of *T. lepturus* at first caught (L_{s50}) from handline and bottom longline gear was 81.25 cm. The results of this study are greater than those reported by Amador and Aggrey-Fynn (2020) in the Ghanaian waters. The mean length of *T. lepturus* first caught with shrimp trawl was 47.11 cm. It suggests that L_{s50} values of *T. lepturus* with handline and bottom longline gear are more selective at larger fish sizes than L_{s50} from shrimp trawls. Ghosh et al. (2014) and De la Cruz-Torres et al. (2014) added that large *T. lepturus* size (>80 cm) is dominantly caught by handline while small size (<25 cm) is dominantly caught by trawl. Thus, one of the actions to manage *T. lepturus* resources to remain sustainable in the southern waters of Java, Indonesia, is to use handline and bottom longline fishing gear that is more selective and environmentally friendly. Sun et al. (2020) stated that fish selectivity can evolve life history. The exploitation of *T. lepturus* with shrimp trawls in the long term will affect the biological properties of fish populations, including a reduction in average body length. Tirtadanu et al. (2023) added that the management strategy to prevent fish population reduction is to prioritize larger fishing sizes.

The estimated mean length at first maturity females of *T. lepturus* in this study (L_{m50} = 77.0 cm) was more significant than the results of studies on southern Brazil at 63.0 and 69.0 cm (Martins and Haimovici 2000); northern Arabian Sea, and north Bay of Bengal at 52.9 and 61.2 cm (Ghosh et al. 2014); northwest coast of India by 75.0 cm (Khan 2006); Persian Gulf and Oman Sea by 70.9 cm (Taghavimotlagh et al. 2021b); southwest coast of India by 55.4 cm (Rajesh et al. 2015); Ghanaian waters by 70.5 and 71.1 cm (Amador and Aggrey-Fynn 2020) and in the waters of the Sunda Strait, Indonesia by 71.85 cm (Kurnia et al. 2022), but it is smaller than the L_{m50} of *T. lepturus* in the Arabian Sea coast of Oman at 79.0 cm (Al-Nahdi et al. 2009) and southeastern Australia at 108 and 109 cm (Clain et al. 2023a). Variations in the L_{m50} values of *T. lepturus* in some areas are assumed to be associated with variations in environmental conditions, such as lower mean annual temperatures and temperature cycles in tropical and subtropical regions, food availability, and overfishing (Martins and Haimovici 2000; Al-Nahdi et al. 2009; Taghavimotlagh et al. 2021b).

Trichiurus lepturus subjected to intensive fishing exploitation generally has lower L_{m50} values (Clain et al. 2023a). Shin et al. (2023) added that differences in the average length at first gonadal maturity of *T. lepturus* in each region were due to differences in the analytical methods used in determining adult fish and growth rates. The L_{s50} value of this fish is greater than the L_{m50} value. This value indicates that when *T. lepturus* was caught with the handline and bottom longline, the species was already gonadally mature and had the opportunity to reproduce well and carry out the recruitment process. This condition is excellent for sustainable largehead hairtail fishing (Reis and Ateş, 2020). The L_{m50} value of 77.0 cm can be used to determine the minimum legal size of *T. lepturus*.

Table 2 presents the *T. lepturus* growth and mortality parameters from different research conducted in various parts of the world. The asymptotic length for *T. lepturus* in southern Java waters of Indonesia is the same as from the northern Arabian Sea (Ghosh et al. 2014) but longer than that found in Bombay, northwest and east coast of India, north Bay of Bengal, Persian Gulf and Oman Sea (Abdussamad et al. 2006; Khan 2006; Al-Nahdi et al. 2009; Ghosh et al. 2014; Khadem et al. 2021; Taghavimotlagh et al. 2021b). It is connected to upwelling, which raises the water's surface and brings nutrients from the bottom to the surface, providing an abundance of food for *T. lepturus* in southern Java and promoting fish growth (Wen et al. 2023). While the asymptotic length of *T. lepturus* in Karnataka (India) waters, Chinese waters, northern waters of the Oman Sea, Ghanaian waters, and southeastern Brazil (Rajesh et al. 2015; Liang and Pauly 2017; da Costa et al. 2018; Amador and Aggrey-Fynn 2020; Taghavimotlagh et al. 2021a) have a more extended size, even *T. lepturus* fish in southeastern Australian waters show different populations where L_∞ reaches 186 cm (Clain et al. 2023a).

Table 2. Growth, mortality, and exploitation rate parameters of *Trichiurus lepturus* collected from Indonesia and other locations.

L_∞ [cm]	K [year^{-1}]	t_0 [year]	M [year^{-1}]	F [year^{-1}]	Z [year^{-1}]	E	N	Area	Source
127.3	0.68	–0.943	0.93	2.37	3.30	0.72	1021	NW coast of India	Khan 2006
129.0	0.46	–0.690	—	—	—	—	10 742	Arabian Sea coast of Oman	Al-Nahdi et al. 2009
131.6	0.15	–0.074	0.34	0.18	0.52	0.35	3089	Northern Arabian Sea	Ghosh et al. 2014
114.4	0.28	–0.056	0.54	0.81	1.34	0.60	3146	Northern Bay of Bengal	
134.0	0.82	–0.171	0.91	2.41	3.32	0.73	5750	Karnataka, India	Rajesh et al. 2015
152.4	0.38	—	0.54	1.45	1.99	0.73	—	Chinese waters	Liang and Pauly 2017
145.3	0.64	–0.100	0.77	0.19	0.96	0.20	345	Southeastern Brazil	da Costa et al. 2018
121.5	0.29	–0.320	0.53	0.63	1.16	0.54	3321	Persian Gulf and Oman Sea	Taghavimotlagh et al. 2021b
176.0	0.50	—	0.67	3.52	4.37	0.85	—	Northern Oman Sea	Taghavimotlagh et al. 2021a
119.35	0.30	–0.300	0.53	0.63	1.16	0.54	1826	Persian Gulf	Khadem et al. 2021
133.66	0.46	–0.660	0.66	2.03	2.69	0.75	1677	Ghanaian waters	Amador and Aggrey-Fynn 2020
128.2	0.72	–0.003	0.98	3.34	4.32	0.77	—	East coast of India	Abdussamad et al. 2006
186.1	0.12	–0.799	—	—	—	—	417	SE Australia	Clain et al. 2023b
198.6	0.18	–1.127	—	—	—	—	34	Southern East China Sea	Shih et al. 2011
131.67	0.22	–0.509	0.44	1.16	1.60	0.72	19 587	Southern Java, Indonesia	This study

L_∞ = asymptotic length, K = growth coefficient, t_0 = theoretical age at zero length, M = natural mortality, F = fishing mortality, Z = total mortality, E = exploitation rate, N = number of specimens studied.

According to Sparre and Venema (1998), growth rate (*K*) is a parameter of von Bertalanffy's growth function that determines how quickly the fish reaches its asymptotic length. The value of *K* is equal to 1 year^{-1}, indicating a fast growth rate; *K* is equal to 0.5 year^{-1}, indicating a medium growth rate; and *K* is equal to 0.2 year^{-1}, indicating a slow growth rate. The growth coefficient of *T. lepturus* varies in several global regions, ranging from 0.12 to 0.82 year^{-1} (Table 2). The fish in this study and several research results such as in southeastern Australia, the northern Arabian Sea and the north Bay of Bengal, the Persian Gulf and Oman Sea, Chinese water, and southern east China Sea have slow growth rates, so they take a very long time to attain their asymptotic length. In comparison, other waters have a moderate growth rate. Variations in *T. lepturus* growth parameters, including asymptotic length (L_∞) and growth rate (*K*) in some areas are caused by biological aspects such as gonad maturity and genetic factors, fishing gear used, seasons and fishing grounds, food availability, predation, competition for food, size composition and methods used in estimating population parameter values (Taghavimotlagh et al. 2021a; Santos et al. 2022; Goodrich and Clark 2023).

The fish samples for this study were obtained from handline fishing gear and bottom gillnet, which are more selective when targeting larger fish. Larger fish samples may be difficult to get in over-exploitation fisheries, which will annul growth parameters. Ghosh et al. (2014) added that variations in environmental conditions, such as temperature, can affect differences in growth parameters. Temperatures in southeastern Australia (Clain et al. 2023b) and in the southern East China Sea (Shih et al. 2011) are more extraordinary than in south Java waters, Indonesia, and other tropical waters. As a result, the asymptotic length is longer than in the seas of south Java, Indonesia. Fish with a low growth coefficient generally live longer (Pauly 1980). Based on the examination of the length frequency, the maximum age (t_{max}) of *T. lepturus* is believed to be 14 years old. It differs significantly from the 15-year-old East China Sea fish t_{max} (Shih et al. 2011).

The most important life history parameter of fisheries stock assessment is the natural mortality rate. In addition to growth parameters, the natural mortality rate value of *T. lepturus* in some global regions also varies between 0.34 and 1.05 year^{-1}. The natural mortality rate in this study was more significant than in the waters of the northern Arabian Sea but smaller than in Bombay waters, Karnataka; India, northwest coast of India, east coast of India, Arabian Sea coast of Oman, northern Bay of Bengal, Chinese water, southeastern Brazil, Persian Gulf, Ghanaian water, southeast Australia and southern East China Sea (Table 2). Natural mortality rates in some regions are due to disease, cannibalism, spawning stress, old age, food supply, sex, and predator density (Santos et al. 2022). The natural mortality rate (*M*) is related to the value of growth rate (*K*) and longevity of fish. The value *K* of *T. lepturus* from this study is slow growth, so the *M* value is also low at 0.44 year^{-1}. The *M*/*K* ratio of *T. lepturus* in southern Java waters is 2.0. According to Beverton and Holt (1957), this value is still within the average threshold of 1.5–2.5. The mortality rate due to fishing in this study ($F = 1.16$ year^{-1}) was higher than the natural mortality rate ($M = 0.44$ year^{-1}). It indicates that the fish in this study have experienced high fishing pressure. Sparre and Venema (1998) state that a high mortality rate due to fishing combined with a low natural mortality rate indicates overfishing conditions.

Gulland (1971) expresses that fisheries are healthy and optimally exploited if natural mortality and fishing mortality are balanced ($M = F$) and if the exploitation rate (*E*) = 0.5. The exploitation rate (*E*) value for *T. lepturus* from this study is 0.72, which means that fishing activities cause 72% of this fish mortality in southern Java waters, and the *E* value is higher than the optimal exploitation value of 0.5. However, when observed from the biological aspect, the exploitation rate of *T. lepturus* in this study is still quite good because of the value of $L_{s50} > L_{m50}$, which means that the average fish caught has experienced gonad maturity or at least has experienced recruitment once a year. In addition, the growth rate of *T. lepturus* is relatively slow ($K = 0.2$ year^{-1}). Fish with a low growth rate coefficient will take longer to reach their maximum length. The slower the fish reaches its maximum size, the slower it reaches the size of adult gonads (mature gonads) and spawning, so the recruitment of *T. lepturus* will be disrupted due to high exploitation rates (Sparre and Venema 1998).

The current state of *the* largehead hairtail fishery, as determined by an examination of yield per recruit in the southern Java waters, is in a growth overfishing condition, meaning that in the current fishing conditions, *T. lepturus* have been captured before they can grow to contribute more optimally in biomass. This situation is demonstrated by the fact that the current length at first capture ($L_{ccur} = 81$ cm) is currently shorter than the length at first capture, which generate the maximum yield per recruit ($L_{smax} = 88$ cm). Modification of the hook and bait type can also be used to increase selectivity. Hirose et al. (2017) found that using sizeable artificial bait can increase the size of fish caught for hairtail fish. Apart from the size of the catch, reducing fishing efforts at the optimal point will also be more profitable, whereas high fishing operations will increase costs. Watari et al. (2017) also reported the impact of overfishing on the hairtail fishery in Japan, which led to a decrease in catch and recommended a reduction in fishing efforts. Based on the current fishing mortality (F_{cur}=1.16 year^{-1}) that exceeds the reference point of fishing mortality that would provide maximum yield per recruit F_{max} (1.13 year^{-1}) and the reference point of fishing mortality that would provide the slope of 10% from the initial value of yield per recruit $F_{0.1}$ (0.51 year^{-1}), a reduction in effort can also be used as an option to maintain the sustainability of the stock and economic aspects of the fishery in the southern Java waters.

Recruitment overfishing conditions have also been found based on the current SPR indicator ($SPR_{cur} = 26\%$), which is smaller than the optimal reference of 40% SPR.

This condition indicates that the spawning stock biomass of *T. lepturus* in the southern Java waters is too low, which can hinder population recovery through reproduction. Overfishing recruitment conditions have also occurred in several fisheries commodities in Indonesia, causing economic losses due to decreased catches of fishers, including lobster fisheries in Gunungkidul and shark fisheries in Arafura (Nurdin et al., 2023; Tirtadanu et al., 2023). In nature, a rise in spawning stock biomass can be attributed to a decrease in effort and an increase in selectivity. A 40% SPR reference is ideal, requiring a 48 percentage-point reduction from the current attempt. Several studies have also provided management options for overfished *T. lepturus* fisheries, including closing season mechanisms, total allowable catch, and enlarging selectivity (Ye and Rosenberg 1991; Ji et al. 2019). The government needs to develop effective regulations to reduce the fishing effort of *T. lepturus* in southern Java waters for stock sustainability, economic aspects, and food sources. The participation of fishers, traders, and various parties in fisheries management is also critical for the effective implementation of the policy.

Conclusion

This study provides comprehensive insights into the stock assessment and reproductive biology of large hairtail, *Trichiurus lepturus*, off south Java, Indonesia. The results showed that *T. lepturus* showed a positive allometric growth pattern, with a slightly biased sex ratio of females. The prolonged spawning period, as evidenced by the stage of gonad maturity and gonadosomatic index, indicates that the species can adapt to the region's upwelling solid conditions. The estimated length at first gonadal maturity (L_{m50}) of males and females of 77.0 cm and 84.5 cm, respectively, highlights the importance of implementing size-based catch limits to protect spawning stocks. The growth parameters derived from the von Bertalanffy model and the high mortality and fishing mortality rates suggest that current fishing efforts may exceed the maximum sustained yield rate. It is further supported by a low spawning potential ratio (SPR) of 26%, which indicates an alarming level of stock exploitation. Immediate implementation of appropriate fisheries management measures is crucial to ensure the long-term sustainability of the *T. lepturus* fishery in the southern Java waters. It should include regulating fishing efforts by 48%, implementing size-based catch limits, and establishing temporary fishing closures during the main spawning period (July–August). Such measures will help maintain the productivity and ecological balance of the *T. lepturus* population, protecting this economically vital resource and essential nutrients for local and global markets.

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