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Evaluating growth and exploitation dynamics of *Thunnus albacares* for sustainable fisheries in fishery landed in Bali's Benoa Harbor

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Abstract. *Lelono TD, Bintoro G, Setyanto A, Sutjipto DO, Tumulyadi A, Adhihapsari W, Sari WK, Rihmi MK, Aliviyanti D, Isdianto A, Putri ADR. 2024. Evaluating growth and exploitation dynamics of* Thunnus albacares *for sustainable fisheries in fishery landed in Bali's Benoa Harbor. Biodiversitas 25: 2858-2869.* This study aims to analyze the population dynamics of *Thunnus albacares* (Bonnaterre, 1788), particularly focusing on factors such as length-weight relationships, length frequency distribution, first caught size, gonadal maturity size, growth rate, mortality rate, and exploitation rate. The analysis, conducted using FISAT II software with data from 2018 to February 2022, also includes evaluating fish utilization status. This evaluation involves estimating Allowable Biological Effort (ABE), Allowable Biological Catch (ABC), and Total Allowable Catch (TAC) based on yellowfin tuna (*T. albacares*) production data from 2012 to 2021 in Bali's Benoa Harbor. These parameters and analyses are crucial for maintaining the sustainability of catch utilization. This will be achieved using the Feedback Harvest Control Rules (FHCR) with a random sampling method. The length-weight relationship analysis yielded positive allometric growth (b>3), influenced by genetic, environmental, reproductive, and overexploitation factors. The initial catch size value (Lc50%) was determined to be 134.7 cmFL, while the gonadal maturity size (Lm) was estimated to be 103.3 cmFL. Therefore, it is paramount to refrain from fishing before reaching reproductive maturity to ensure the stock's survival. The asymptotic length (L∞) was estimated at 235.45 cmFL, t0 -2.91, with a growth rate (K) of 0.20. This indicates a relatively slow growth rate, which is important information for effective fisheries management. The exploitation rate (E) of 0.88 per year indicates overexploitation. Hence, the need for sustainable fishing practices should be noted in certain areas. Applying the FHCR model provides insights into stock estimation and sustainable management strategies that are of value in informing the development of more careful management practices.

Keywords: Dynamics fisheries, feedback harvest control rules, length-weight relationship, maximum sustainable fishing, recruitment

INTRODUCTION

Tuna is a valuable commodity in the fishing industry, with a global market value of at least US$42 billion in 2018 (Wiryawan et al. 2020). Tuna and similar species that migrate long distances have extensive feeding and spawning grounds, with Indonesia having the most significant tuna catch in the world (Pertiwi et al. 2017). However, the high demand for tuna has led to overfishing and declining stocks. *Thunnus albacares* (Bonnaterre, 1788), found in the Atlantic, Indian, and Pacific Oceans, is commercially important but classified as near-threatened due to intense fishing (Barth et al. 2017; Artetxe-Arrate et al. 2021). Various studies have explored aspects of yellowfin tuna biology, such as reproduction (Shi et al. 2022), habitat, and feeding behavior (Le-Alvarado et al. 2021), genome and demographic history (Barth et al. 2017), and histamine-related risks (Pais et al. 2022), global population genomics and the impact of size on female gonads (Pecoraro et al. 2018, 2020). However, a previous study reported the vulnerability of juvenile fish to purse seine fishing methods (Scutt Phillips et al. 2017). Further insight into the growth and associative behavior of *T. albacares* juvenile fish with other species (Dortel et al. 2015; Rodríguez-Madrigal et al. 2023).

Feedback Harvest Control Rules (FHCR) are essential for regulating fishing activities to ensure fish sustainability. FHCR maintains fish catch at levels that do not exceed the Maximum Sustainable Yield (MSY), balancing the trade-off between achieving MSY and maintaining ecosystem resilience (Harlyan et al. 2022). However, it is crucial to estimate Allowable Biological Catch (ABC), Allowable Biological Effort (ABE), and Total Allowable Catch (TAC) using the FHCR model by considering environmental factors in resource management (Pershing et al. 2015) and a framework for comparing management strategies (Punt et al. 2016). Several previous studies reported the effectiveness of FHCR feedback in managing multispecies fisheries with limited data, emphasizing advanced modeling techniques and adaptive management strategies (Kvamsdal et al. 2016; Harlyan et al. 2019, 2022).

The Von Bertalanffy Growth Function (VBGF) is commonly used to estimate growth parameters based on length-at-age data (Jefferson et al. 2022; Campbell et al. 2023). This model has been applied to various fish species, including yellowfin tuna (Bennetts et al. 2019; Pardee and Wiley 2022; Sheffer et al. 2022). Several studies demonstrated that the variations in the population structure and methylmercury levels among yellowfin tuna could impact their growth and development (Grewe et al. 2015; Nicklisch et al. 2017; Barbosa et al. 2022; Tseng et al. 2021). On the contrary, contradictory evidence regarding the population structure of yellowfin tuna was reported to affect their growth modeling due to early life stages caught near their spawning area (Pecoraro et al. 2018).

The VBGF model generates specific data such as asymptotic length ($L\infty$), growth coefficient (k), and theoretical age (t0) (da Cunha-Neto et al. 2022). It has been instrumental in evaluating long-term changes in fish growth rates and estimating growth parameters, longevity, and mortality rates across diverse fish species (Duan et al. 2022; Rodríguez-Madrigal et al. 2023; Schieber et al. 2023). The model's versatility has been demonstrated in different biological contexts, including age and size estimation for sea turtles and Pacific bluefin tuna (Avens et al. 2015; Sheffer et al. 2022). Although widely used, the VBGF may not always suit certain species, such as skate species (Joung et al. 2016). Long-term yellowfin tuna viability requires sustainable management that considers fishing pressure, population dynamics, environmental conditions, and conservation status. Therefore, the study aimed to evaluate *T. albacares* population dynamics, concentrating on length-weight relationships, length frequency distribution, first caught size, gonadal maturity size, growth rate, death rate, and exploitation rate.

MATERIALS AND METHODS

Study area

This study was conducted at Benoa Port, Denpasar, Bali (Figure 1). Benoa Port serves as a hub for tuna fishing vessels, with numerous fishing companies conducting loading, unloading, and processing activities directly at the port for export, primarily to European Union countries. The fishing vessels operating from Benoa Port cover fishing grounds in WPPNRI 573, WPPNRI 713, and the Indian Ocean (Figure 1). Tuna resources are distributed across Indonesian waters, from the western (Indian Ocean) to the eastern parts (The Banda Sea and North Irian Jaya). The yellowfin tuna was caught and landed at Benoa Harbor in the fishing grounds of Indonesian Fisheries Management Area 573, Indonesian Fisheries Management Area 713, and the Indian Ocean (Figure 1). The data of yellowfin tuna (*T. albacares*) length-weight was present from 2018 to February 2022. The yellowfin tuna (*T. albacares*) measurement and weighing were carried out when the ship unloaded the fish, and if the fish had been brought, the weighing was done in the shelter using a manual scale. The catch (kg) and fishing effort (fishing trips) data of yellowfin tuna (*T. albacares*) from 2012 to 2021 were obtained from logbooks at Benoa Harbor, Denpasar, Bali. The fishing gear used to catch tuna in WPP753 was vertical long lines.

Data analysis

Data analysis was conducted based on the type of data used. Biological data such as Fork Length (FL) (cm) and weight (kg) of yellowfin tuna (*T. albacares*) were calculated using regression analysis. This relationship is commonly expressed using an equation such as $BW=a\times SL^b$, where BW represents the fish's weight in grams, and SL is the standard length of the fish in centimeters. The logarithmic transformation of this equation yields $\log BW=a+(b\times\log SL)$, establishing a linear relationship between weight and length (Froese 1998; Garcia 2010; Lelono et al. 2021a; Lelono et al. 2023a).

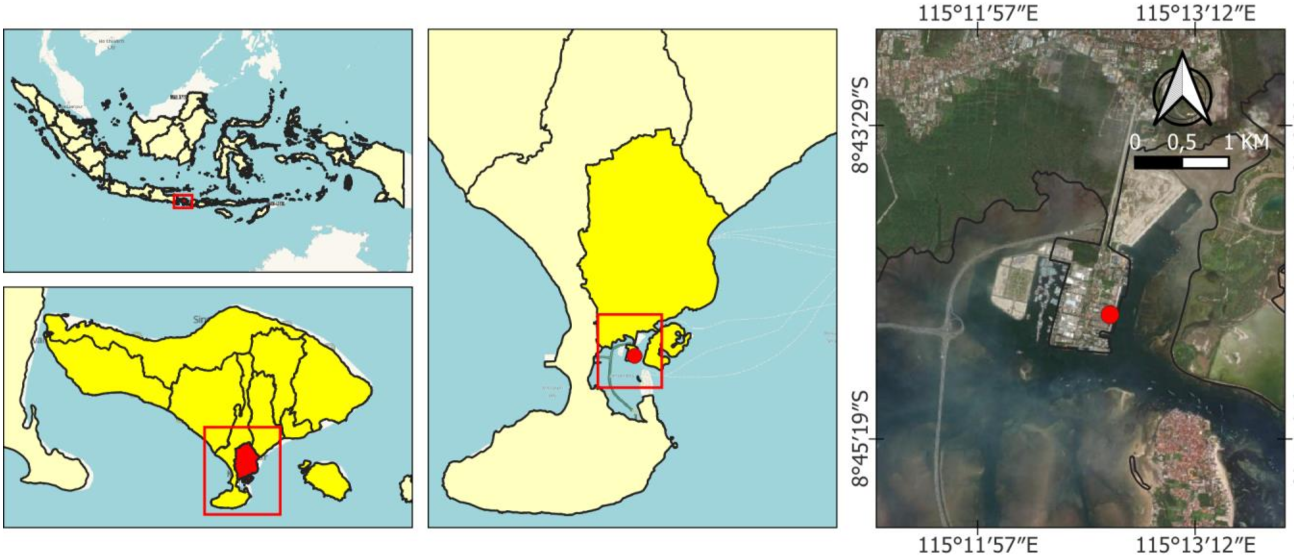

Figure 1. Map location at Benoa Port, Denpasar, Bali, Indonesia

$$W = aL^{b}$$

Where: W: Total weight (kg); L: Forked Length (cm); a: Linear regression intercept; b: Linear regression coefficient

The results of the conversion obtained the equation for the relationship between length and weight (Lw):

$$\ln W = \ln a + b \ln L$$

Growth parameters

The analysis of the estimated growth parameters can be calculated using the von Bertalanffy formula (Sparre and Venema 1985; Sparre 1998; Gayanilo Jr et al. 2005; Damora et al. 2021; Lelono et al. 2021b), as follows:

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

$$L_t = L_\infty \left[1 - e^{(-k(t-t0))}\right]$$

Where: L_t: length of the fish at age year t (cm); L_∞: possible maximum length of fish; t_0: theoretical age of fish at zero length; t: year; k: growth coefficient; e: natural number; e = 2.71.

The values of growth parameters, including L_∞ and k, were obtained using the electronic length-frequency analysis (ELEFAN) I method on FISAT II, while t_0 was calculated using the following equation (Pauly 1980; Sparre and Venema 1998; Gayanilo Jr et al. 2005)

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

Length at first capture (Lc)

Analysis of the length at first capture can be calculated based on the equation (Gayanilo Jr et al. 2005; Lelono et al. 2023b) as follows:

$$Fc\ (L) = \frac{n\ x\ dL}{S\ \sqrt{2\pi}}\ x\ e^{\left[\frac{(L-\acute{L})^2}{2s^2}\right]}$$

Where: Fc (L): frequency of fish included in the class length; dL: interval of each class length; π= 3.14; e = 2.72; n: number of samples in sampling; L: long class middle value; $\bar{L}$ = average length of one fish cohort; *s*: standard deviation of the average length.

Then, the equation is transformed into a linear form as follows:

$$\Delta\ Ln\ Fc\ (z) = a - b\ \left[L + (\tfrac{dL}{2})\right]$$

Where: $\Delta \text{Ln Fc } (z)$= the difference between length classes in ln; $L+(\frac{dL}{2})$ = upper limit of each length class; a and b: constants.

The value of Lc can then be calculated by comparing the intercept and slope values as follows:

$$Lc = -\frac{a}{b}$$

Mortality and exploitation rate

The mortality rate was divided into natural mortality (M) and fishing mortality (F). Natural mortality can be calculated using the equation (Pauly 1980)as follows:

$$\text{Ln } M = -0.0152 - 0.279 \times \ln L\infty + 0.6543 \times \ln K + 0.463 \times \ln T$$

Where: M: natural mortality; L∞: the asymptotic length of the von Bertalanffy growth equation; K: growth coefficient (month^{-1}); T: mean annual surface temperature (°C).

Meanwhile, fishing mortality (F) can be calculated using the following equation:

$$F = Z - M$$

The exploitation rate (E) is calculated by comparing the fishing mortality (F) to the total mortality rate (Z) as follows:

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

The asymptotic length (L∞) represents the maximum potential size a species can reach, while the growth velocity coefficient (K) indicates how fast a species approaches its asymptotic length. The t0 value indicates the hypothetical age at which the species would have zero length, thus providing insight into its early stages of growth (Li et al. 2023a). Fishing mortality and exploitation rates can be used to estimate the status of fisheries in certain waters. If E<0.5 or F<M, then underfishing; E=0.5 or F=M, then Maximum Sustainable Yield (MSY); E>0.5 or F>M, then overfishing. The recruitment pattern aims to separate the addition of certain species. This study calculated the recruitment pattern for 4 years and 2 months from 2018 to February 2022. The results of calculating the recruitment pattern were obtained using the FISAT II application program with the recruitment pattern sub-program. The program results display a histogram graph using the calculated k, L∞, and t0 values.

Data analysis in this study aimed to determine the estimated number of allowable catches (JTB) of yellowfin tuna (*T. albacares*) using two production methods: the Schaefer method (1954) and the feedback harvest control rule (FHCR). Both methods were applied to catch data to obtain the number of catches safe for biological use, and the results were compared to determine the appropriate management strategy for yellowfin tuna (*T. albacares*). To assess the abundance and utilization rate of yellowfin tuna (*T. albacares*), the Catch Per Unit Effort (CPUE) was calculated using the formula CPUE=Catch (C) / Effort (E), where Catch (C) is the total catch in kilograms and Effort (E) is the total effort in trips. The Schaefer production surplus model was used to estimate the Maximum Sustainable Yield (MSY). This model determines the optimum level of fishing effort without affecting stock production in the following year. The calculation of the Schaefer model involves linear regression analysis between the catch per unit of effort and the effort to catch, with the formula CPUE=a-bE, where a is the intercept, b is the slope, FMSY is the fishing effort that will produce sustainable yield in kilograms per trip, and CMSY is the sustainable catch in kilograms. Furthermore, the catch control rules were used to estimate the biologically safe number of catches for the following year (ABCy). This estimation was done using the formula ABCy= $\delta \times$ Cy-2 $\times \gamma$, where δ is the coefficient value for the stock level (1 for high and medium stock levels, 0.8 for low stock levels), Cy-2 is the total catch two years prior in kilograms, γ is the trend CPUE (2012-2021), k is the feedback factor, b is the slope CPUE, and I is the average CPUE. The determination of stock levels is based on the trend of catches per unit of effort from 2012 to 2021.

RESULTS AND DISCUSSION

The general condition of the research site

A combination of oceanographic parameters, fish behavior, environmental conditions, and fishing techniques influences the determination of tuna fishing grounds, emphasizing the importance of environmental parameters and their contribution to predicting tuna fishing grounds (Gao et al. 2016; Siregar et al. 2019). Therefore, these parameters play an important role in determining the presence and abundance of tuna species in a particular area. The distribution of tuna resources stretches across almost all Indonesian waters, from the western waters (Indian Ocean) to the eastern part of Indonesia (Banda Sea and North Irian Jaya) (Chodrijah and Nugraha 2013). Similarly, the tropical region in the northeast of the Indian Ocean historically has been a yellowfin tuna fishing ground (Setyadji and Hartaty 2022). Yellowfin tuna congregate near or slightly above the thermocline during the day, particularly in regions such as the Eastern Tropical Pacific (Scott et al. 2012). They are widely distributed throughout tropical and subtropical oceans globally, and the habitat and behavior of adult yellowfin tuna suggest that most of their vertical movements occur within a specific depth range (Wu et al. 2010; Weng et al. 2017). The productivity and conditions of yellowfin tuna fishing grounds are subject to the influence of several environmental factors, including ocean variations, the El Niño Southern Oscillation (ENSO), and the Indian Ocean Dipole (IOD). These factors can affect the distribution, abundance, and behavior of yellowfin tuna populations (Lan et al. 2011; Sambah et al. 2023); and the significance of environmental factors in determining fishing grounds (Teo and Block 2010; Wang et al. 2020). Remote sensing data, such as ocean color and temperature measurements, have been employed to map the potential habitat of tuna species in various ocean regions (Zainuddin et al. 2004; Lan et al. 2017).

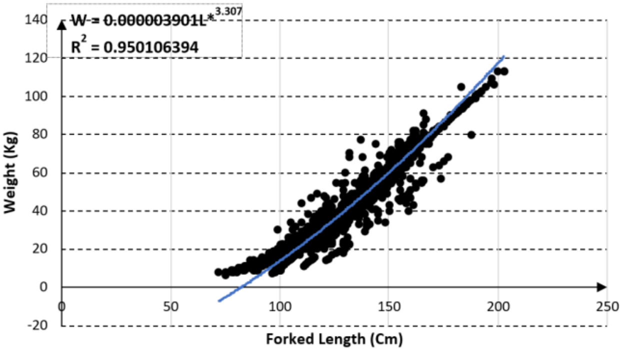

Figure 2. Length-weight relationship of *T. albacares* in 2018 - February 2022

Length-weight relationship

The results of the length-weight analysis with regression analysis used data from 16,527 fish. The research results at Benoa Port showed that the yellowfin tuna (*T. albacares*) fork length ranged from 86-190 cmFL. The smallest weight is 6 kg, and the highest is 149 kg. The length-weight relationship of yellowfin tuna (*T. albacares*) is explained using a scatter graph, which can be seen in Figure 2.

The regression analysis results for the length-weight relationship of yellowfin tuna are as follows: $W=0.000003901L^{*3.307}$. This indicates that the regression coefficient (b) value is greater than 3, implying a positive allometric growth pattern where weight increases faster than length (Verreycken et al. 2011; Luin et al. 2014; Abdullah and Zain 2019). The b value of 3 signifies ideal growth, b<3 indicates thin growth and b>3 suggests fat growth (Cella-Ribeiro et al. 2015; Famoofo and Abdul 2020; Falsone et al. 2022). The coefficient of determination (R^2) is 0.95, indicating that 95% of the variation in fish weight can be explained by the length of yellowfin tuna, with the remaining 5% attributed to other unknown factors. Some factors influence the allometric growth of fish, including genetic, environmental, and reproductive aspects, as well as the overexploitation of fish populations. Understanding length-weight relationships is critical in fisheries management, conservation efforts, and assessing fish populations' overall health and dynamics. The growth patterns of a species can vary between different populations of the same species or within the same population at different times of the year, depending on many factors, including food availability (Narvaez et al. 2016), water quality (Tumwesigye et al. 2022), and biological factors (Paujiah et al. 2023).

Furthermore, the growth patterns of a species can be influenced by sampling, which encompasses fishing grounds, fish communities, fish weights at each observation, the sampling period, and errors resulting from the actions of observers or laboratory equipment. In contrast, isometric growth patterns, positive and negative allometric, can be observed in the same species in different regions or environments. A previous study reported that *T. albacares* landed in OFP Bungus and NFP Palabuhanratu, Indonesia, exhibited negative allometric growth (Muqsit et al. 2022). Similarly, the *T. albacares* landed at the Labuhan Lombok Fishing Port in the Indian Ocean, south of Nusa Tenggara (FMA 573), Indonesia also exhibited a negative allometric growth (Damayanti et al. 2023). Consequently, many factors, including reproductive cycles, food availability, and habitat and environment, can influence fish growth (Li et al. 2023b).

Length at first capture

The calculation results showed that the first caught yellowfin tuna (*T. albacares*) length was 134.7 cmFL, placing it in the 134-135 cmFL length class. The study's Lc50% indicated that most yellowfin tuna were caught at this size. The previous study reported that the first gonad maturity size for yellowfin tuna is 100 cmFL (Ghofar et al. 2021; Gussasta et al. 2021). Therefore, the study's results, Lc>Lm, suggest that most yellowfin tuna have matured when caught.

The comparison of the length at first gonadal maturity (Lm) and length at first caught (Lc) in fish populations is of great importance to gain insight into the impact of fishing activities on the sustainability of fish stocks (Lappalainen et al. 2016; Suyasa et al. 2023). This information can then be used to inform fisheries management strategies due to the impact of fishing on fish populations. In the context of the analyzed results on yellowfin tuna, it was found that Lc was greater than Lm, indicating that most yellowfin tuna were caught after reaching maturity. This finding significantly affects fish populations and fisheries management (Pramulati et al. 2023). Therefore, it is essential to understand fish species' reproductive biology and maturity to achieve sustainable fisheries management. Studies have demonstrated that environmental variables, habitat quality, and population demographics significantly influence fish populations reproductive success and maturity (Leclercq et al. 2010; Piazza and La Peyre 2010). Fishing, the impact of fishing activities on fish populations must be considered. Fishing-induced evolution, changes in reproductive ecology, and fishing pressure can all affect fish species reproductive traits and population dynamics (Enberg et al. 2010; Rojo-Bartolome et al. 2016). Overfishing and harvesting fish before they reach reproductive maturity can lead to population declines and negatively impact the sustainability of fisheries (Enberg et al. 2010; Froese et al. 2016). Understanding the relationship between size at first maturity (Lm) and maximum size (L∞) is critical in fisheries biology. The Gill Oxygen Limitation Theory posits that the slowing of fish growth with age is related to energy expenditure for maturation, resulting in a relatively constant relationship between Lm and L∞ across fish species (Meyer and Schill 2021). This relationship provides valuable insights into fish populations' reproductive biology and life history strategies.

Growth rate

The growth rate of yellowfin tuna (*T. albacares*) was an asymptotic length value (L∞) of 235.45 cmFL with a growth velocity coefficient (K) of 0.20, indicating a relatively slow growth rate. The t0 value was found to be -2.91. The Von Bertalanffy result can be seen in Figure 3. Figure 4 illustrates the examination of the recovery rate over the year.

The asymptotic length (L∞) and growth rate coefficient (K) are crucial parameters in comprehending the growth patterns of fish species, assessing population dynamics, and elucidating the life history traits of fish species. These parameters provide valuable insights into fish populations growth patterns, age at maturity, and longevity.

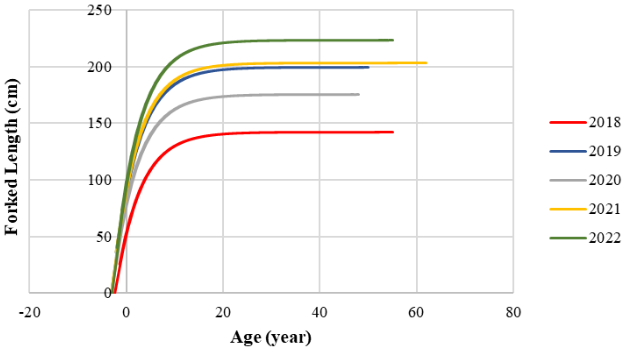

Figure 4. Annual growth rate of yellowtail tuna (*T. albacares*)

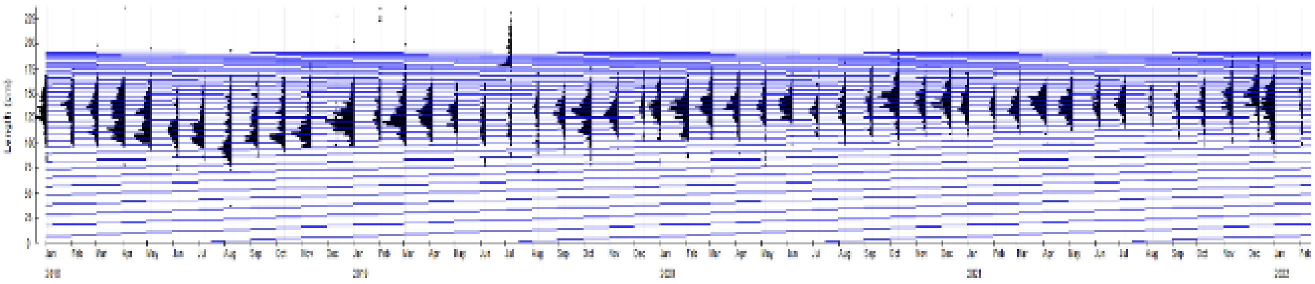

Figure 3. The von Bertalanffy growth of yellowfin tuna (*T. albacares*)

A comparison of these findings with those of other studies of different places reveals that growth parameters can vary significantly between tuna species. For instance, the von Bertalanffy growth equation for *T. albacares* in the Banda Sea, Indonesia, demonstrated a value of L∞ of 215 cm and a K of 0.31 yr^{-1} (Haruna et al. 2018). Similarly, studies in the coastal waters of Kenya reported that the asymptotic lengths of *T. albacares* were 195 cmFL and K was 0.43 $year^{-1}$ (Kimakwa et al. 2021). Another report suggested that L∞ value of *T. albacares* was 211.1 cmFL and K was 0.27^{-1} years in the Indian EEZ. Moreover, based on the von Bertalanffy equation, *T. albacares* demonstrated a fast growth (11.3 years to reach 201 cm) (Abdussamad et al. 2012). Moreover, another study in the Mediterranean Sea of Atlantic bluefin tuna (*Thunnus thynnus* (Linnaeus, 1758) reported that there is a significant slowdown after reaching maturity in the developmental phase because the K value of adult fish was lower than juvenile fish (Bello et al. 2021). However, ocean acidification due to CO_2 absorption by the ocean might threaten the larval of *T. albacares* because it has sub-lethal and lethal effects (Frommel et al. 2016). A decrease in mean asymptotic length was observed as temperature increased, indicating the impact of climate change on fish growth (Gilligan-Lunda et al. 2021). This highlights the necessity of considering external factors when interpreting fish population growth parameters. Analyzing growth parameters such as asymptotic length, growth coefficient, and t0 might provide valuable insights into the growth dynamics of fish species.

Mortality and exploitation rate

The natural mortality (M) calculated using the Pauly Empirical formula is 0.216 years-1, and the total mortality (Z) calculated using the exponential decay model is 1.743 years-1. The fishing mortality rate (F) is calculated as F= Z-M, resulting in a value of F=1.53 $years^{-1}$. Applying the equation E=F/Z, the fishing mortality rate (E) is calculated as 0.88 $year^{-1}$. Since F>M, it can be concluded that the fisheries in the waters of WPP 573 and the Indian Ocean High Sea are experiencing overfishing. According to Pauly (1980), if the exploitation rate (E)<0.5, it is underfishing; if (E)=0.5, it is optimum; but if (E)>0.5, it is overfishing. Therefore, it can be inferred that yellowfin tuna (*T. albacares*) in the waters of WPP 573 and the Indian Ocean High Sea has been over-exploited. Surprisingly, in the coastal waters of Kenya, the fishing mortality (2.0 $years^{-1}$) of *T. albacares* was higher than the natural mortality rates (0.59 $years^{-1}$) (Kimakwa et al. 2021). Also, in the Banda Sea, Indonesia demonstrated that the fishing mortality (0.98 $years^{-1}$) of *T. albacares* was higher than the natural mortality rates (0.49 $years^{-1}$) (Haruna et al. 2018)**.** The exploitation has led to the estimation that the exploitation rate of yellowfin tuna has exceeded the optimal exploitation rate (E=0.5), resulting in overexploitation (Ghofar et al. 2021). The high fishing mortality observed in yellowfin tuna populations in the Indian Ocean and WPP 573 highlights the urgent need to improve management strategies to ensure the sustainability of this globally important tuna resource. By considering factors such as natural mortality rates, environmental conditions, diet composition, and reproductive potential, fisheries management can be better informed to address the challenges of overexploitation and ensure the long-term viability of yellowfin tuna populations. Furthermore, implementing sustainable fishing practices, effective MSY-based management, habitat protection, and the recovery of threatened fish populations can assist in the reduction of overfishing and the maintenance of the sustainability of fishery resources. Overfishing pressure, a significant contributing factor, should be addressed by monitoring and limiting the amount of fishing gear (Glassic et al. 2020).

Other factors, such as the incidental capture of nontarget species during fishing operations, pose a significant threat to *T. albacares* populations. *T. albacares* is a globally important resource that is heavily exploited in fisheries around the world (Grewe et al. 2015). This species faces challenges in stock delineation due to population genomics (Pecoraro et al. 2018), and its foraging habitat and trophic position are influenced by factors such as intrinsic isotope tracers (Le-Alvarado et al. 2021). Bycatch, particularly in the Gulf of Mexico, is a concern, affecting not only yellowfin tuna but also other species (Agustian et al. 2021). In addition, the impact of environmental variables on the population structure of yellowfin tuna in various regions further complicates management efforts (Fu et al. 2023; Nóbrega et al. 2023; Vaihola and Kininmonth 2023; Wang et al. 2023). These factors collectively contribute to the complex dynamics surrounding the impact of bycatch on *T. albacares* populations. The lack of information on the status of fisheries exploitation can impede effective resource management (Wang et al. 2022). Therefore, it is essential to emphasize the need for accurate data collection and monitoring to understand fisheries exploitation status and take appropriate conservation measures. Implementing regulations regarding minimum size and optimal catch limits can prevent overfishing (Moreau and Matthias 2018). Furthermore, strict monitoring and prudent fishing regulations are also important, such as controlling the use of fishing nets (Ginzel et al. 2022). Implementing catch targets based on the Maximum Sustainable Yield (MSY) concept could assist in avoiding overfishing (Bach et al. 2022). Furthermore, research has identified straightforward management alterations' significance in reducing overfishing, particularly in long-lived species (Ben-Hasan et al. 2021).

Recruitment pattern

The recruitment pattern is used to determine the addition of a new individual to a population. The histogram chart (Figure 5) shows the recruitment pattern. It can be concluded that the stock of yellowfin tuna (*T. albacares*) in the waters of WPP 573, the High Seas, and the Indian Ocean experienced the highest recruitment in October with a value of 14.32 and the lowest recruitment in December with a value of 0.00. Recruitment represents a crucial factor in the dynamics of tuna populations, with October being the peak recruitment month, coinciding with the migration of many tuna populations to fishing grounds

(McBride et al. 2015). This concentration of tuna populations in October illustrates the significance of understanding recruitment patterns for effective fisheries management and conserving tuna populations in the Indian Ocean and the High Seas. Meanwhile, recruitment is influenced by several factors, including environmental conditions, genetic diversity, and fishing pressure, among others. This concentration of tuna populations in October highlights the significance of understanding recruitment patterns for effective fisheries management and conserving tuna populations in the Indian Ocean and high seas. The environmental variation in the presence of food can influence recruitment variability (Britten et al. 2016). Furthermore, there is an environmental relationship between turbid water conditions and low reef fish recruitment rates (Hess et al. 2015). A previous study reported how factors such as overfishing and productivity can affect the recruitment capacity of global fish stocks (Britten et al. 2016). Furthermore, Korman et al. (2021) investigated alterations in prey availability, turbidity, and competition, which can result in reduced somatic growth and population declines, consequently influencing subsequent recruitment. Farmer et al. (2015) demonstrated the impact of short winters on fish populations in temperate regions, illustrating the relationship between recruitment events and factors such as predator abundance and temperature. Research has demonstrated that alterations in the productivity of fish stocks during the early life stages can result in alterations in recruitment capacity (Green et al. 2015).

Schaefer model (1954)

The Schaefer model (1954) was analyzed using catch and effort data in units (times/trips) for yellowfin tuna landed at Benoa Port, fishing in areas WPP 573, High Seas (WPP713), and the Indian Ocean from 2012-2021. The analysis calculated the Catch Per Unit Effort (CPUE) value. Linear regression analysis was then applied using effort data as the independent variable (X) and catches per unit effort data as the dependent variable (Y). Figure 6.A shows that the curve of the Schaefer model (1954) produces an estimate of the maximum sustainable yield (Cmsy) of 2,104 kg. The allowable catch in Indonesia is 80% of the sustainable potential, so the Allowable Biological Catch (ABC) is 3,495,722.59 kg, and the Allowable Biological Effort (ABEy) is 718.69 trip times and utilization rate of 73% and classified in the moderately exploited category. Figure 6.B shows the regression analysis results in a negative slope; this means that an increase in the number of times at sea will cause a decrease in the catch of yellowfin tuna (*T. albacares*) by 0.63 kg per fishing time.

The relationship between spawning fish stock size and juvenile fish production (recruitment) has undergone significant global changes, indicating fundamental shifts in fish stock productivity (Harrison et al. 2020). It is evident that environmental factors, such as larval dispersal patterns, habitat degradation, and exposure to contaminants, can also influence fish recruitment.

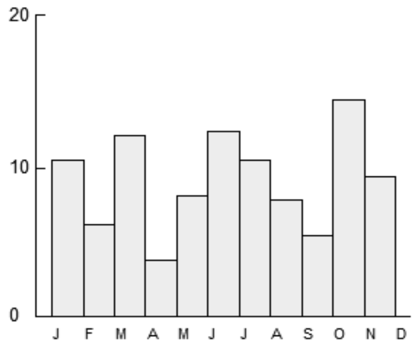

Figure 5. Recruitment pattern of *T. albacares*. The y-axis represents recruitment percentage (%). The x-axis represents the months in the following order: J: January; F: February; M: March; A: April; M: May; J: June; J: July; A: August; S: September; O: October; N: November; D: December

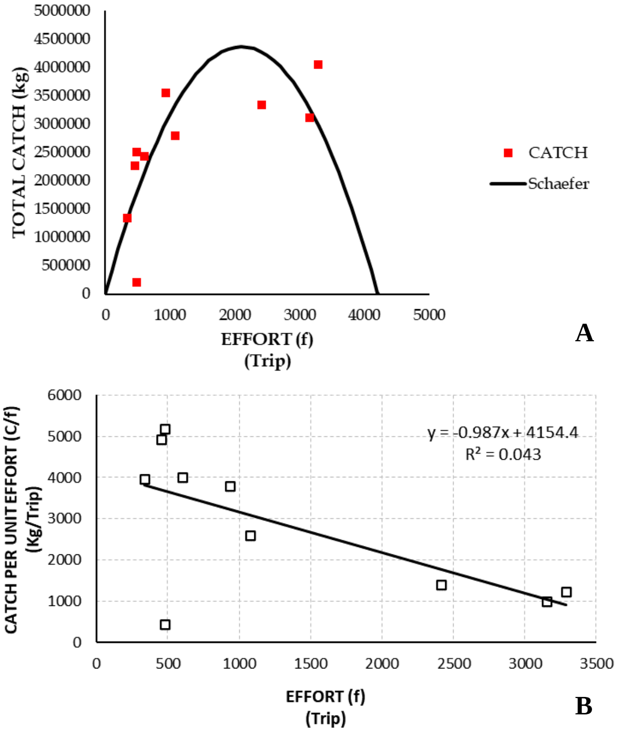

Figure 6. Calculation results of the Schaefer (1954) model: A) Model curve of yellowfin tuna production; B) Regression analysis results

The connectivity of larval fish populations plays a significant role in recruitment dynamics, affecting fish stocks' persistence and genetic diversity (Thorson 2020). Furthermore, habitat degradation has been demonstrated to negatively impact coral reef fishes' settlement behavior, potentially affecting their recruitment success (Besson et al. 2020). The interactions between climate variability, hydrology, and water temperature can significantly influence fish recruitment dynamics. Hydrological conditions and water temperature have been identified as key drivers of recruitment fluctuations in fish populations, thus emphasizing the importance of understanding abiotic factors for effective fisheries management (Trochta et al. 2020; Wang et al. 2023). Also, the Maximum Sustainable Yield (MSY) concept is important to gain an understanding of the ecosystem approach to maintaining a balance between maximizing yields and maintaining the health and resilience of the ecosystem. MSY is the sustainable catch level of a fish species without reducing the species ability to reproduce naturally in the future. Apart from that, fisheries management to achieve MSY can also help in maintaining ecosystem balance (Kempf et al. 2016; Fulton et al. 2022) .

Feedback harvest control rule

The HCR feedback model analysis was conducted to obtain the Allowable Biological Catch (ABC) and Allowable Biological Effort (ABE) values for the coming year. The data needed is the catch and effort of yellowfin tuna from 2012-2021. The calculation of the stock level (δ) obtained from the stock trend in the last 10 years shows that it is at the middle level, namely 1.0 because it is between the upper and lower limit lines (Figure 7). The catch of yellowfin tuna (*T. albacares*) in the two years before the estimated year (C_{2020}) was 207,794 kg. The regression coefficient (b) for the $CPUE_{2012-2021}$ trend is 1.0, and the trend average (I) $CPUE_{2012-2021}$ is 0.00092. The result is that the allowable catch (ABC2022) is 225,188.47 kg, and the fishing effort value (ABE2022) is 523.13 sea trips.

The application of the Feedback Harvest Control Rule (FHCR) model is a stock estimation concept that has evolved into a catch policy successfully implemented in Japanese fisheries. The FHCR catch strategy is used explicitly for fishery resources with complete species-specific information. The FHCR management strategy aims to estimate the number of catches for the following year. Before analyzing with FHCR, we need to know the growth rate (k) of yellowfin tuna (*T. albacares*), which is k=0.20, indicating a relatively slow growth of this fish. This study uses two catch strategies, namely applying the feedback HCR and the Schaefer 1954 production model, to estimate ABCy and ABEy. Based on the comparison table, the results show differences in the catch and fishing effort between the two analyzed methods. The ABC value in the HCR method is higher than in the Schaefer 1954 production model, while the ABE value in the Schaefer 1954 production model is higher than in the HCR method. The technical comparison of the fishing effort values used to produce biologically safe catches (YJTB2022 or ABC2022) shows a significant difference between the two fishing strategies. Overall, the feedback from the FHCR analysis results and the Schaefer 1954 production model provide similar biologically safe catch values to be utilized (JTB).

The FHCR calculations from 2012-2021 show a maximum value of 0.0023 and a minimum of 0.0002. The CPUE trend regression coefficient (b) is 1.0, and the average CPUE trend (I) is 0.00092, used to estimate ABC and ABE. Both species' stock level (δ) is 1.0 (middle) between the lower and upper stock boundaries. The stock level is known from the stock abundance index trend, i.e., the CPUE trend over 2012-2021. These calculations result in an ABC (2022) value of 225,180,779 kg and an ABE (2022) value of 523,414.1 trips. In the context of the excessive fisheries management issues often encountered in Indonesia, the Schaefer 1954 model approach has not addressed these issues. Both methods use a precautionary principle in estimating the allowable catch (JTB). However, managing single species with a high precautionary principle is insufficient to address the recovery of fish resources. Although calculations from both methods will yield a biologically safe catch value to be utilized (JTB), in reality, there are many cases of excessive fishing, so the process of fish resource recovery is not sufficient to stop the occurrence of overfishing (Ichinokawa et al. 2017; Harlyan et al. 2019, 2022). Fisheries biology analysis is conducted based on yellowfin tuna's length and weight variables from 2018 to February 2022. This analysis aims to investigate the growth rate, exploitation rate, and the level and status of utilization. Production analysis using the Schaefer 1954 surplus production method and FHCR are used to estimate the amount of catch and fishing effort allowed. The Schaefer 1954 surplus production method, the allowable catch (JTB) is 80% of the Maximum Sustainable Yield (MSY) value. Meanwhile, in the FHCR method, the ABC and ABE values are obtained from the CPUE trend of the last 3 years. The comparison of the level and status of yellowfin tuna utilization in WPP 573 and the Indian Ocean Outer Sea using fisheries biology analysis, and the Schaefer 1954 model is shown (Table 1).

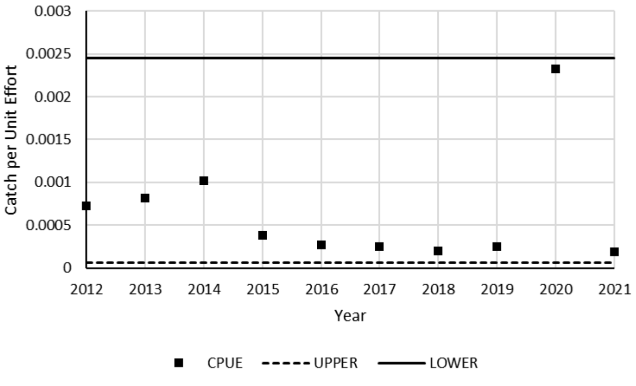

Figure 7. Level stock *T. albacares*. The y-axis represents catch per unit effort (CPUE) (kg/fishing trips)

Table 1. Comparison results of exploitation rates and the Schaefer 1954 Model, FHCR

Parameter	Exploitation rate (E)	Schaefer 1954	Feedback (HCR)
Utilization Rate	0.88	0.73	
Utilization Status	Overfishing	Moderately exploited	Moderately exploited
Y_{jtb}(2022) or ABC(2022		3,495,723 kg	225,188,47 kg
F_{jtb}(2022) or ABE(2022)		718.69 trips	523.13 trips

The results of the exploitation rate (E) analysis of yellowfin tuna indicate that the population is currently overfished, while the FHCR analysis shows that the population is facing moderate exploitation. This conflicting situation presents a significant challenge to the sustainable management of yellowfin tuna populations, as overfishing can lead to a decline in population size and reproductive success, ultimately jeopardizing the species' long-term survival (Eighani et al. 2021). In contrast, the negative impacts of overfishing can be caused by several factors, including changing ocean conditions, which can affect catch rates and population dynamics (Teo and Block 2010). The exploitation of yellowfin tuna populations is influenced by several factors, including fishing practices such as using Fish Aggregating Devices (FADs). These FADs can attract different sizes of tuna species, thus increasing fishing pressure on yellowfin tuna, which may contribute to the overfishing of yellowfin tuna (Dagorn et al. 2007; Cabral et al. 2014). Furthermore, the behavior of yellowfin tuna, including their movement and time spent around FADs, may influence their susceptibility to fishing activities (Weng et al. 2013; Yao et al. 2020; Govinden et al. 2021). Consequently, by identifying the biology of different tuna populations and assessing their reproductive success, targeted conservation measures can be implemented to ensure the sustainability of the species. This is exemplified by the findings of a study on the reproductive biology of yellowfin tuna, which can provide valuable insights into population dynamics and inform management strategies (Shi et al. 2022).

In conclusion, the study results underscore the need for a more unified approach to the exploitation and extent of exploitation of yellowfin tuna, highlighting the intricate nature of marine resource management. As a result, sustainable management practices must consider the interplay between fishing pressure, population dynamics, environmental factors, and conservation measures to ensure the long-term survival of yellowfin tuna populations. Applying the FHCR model, a robust tool offers valuable insights into stock estimation and sustainable management strategies for *T. albacares*.

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