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Assessment of Fishing Pressure on the Ole Fish Population in the Customary Area of Tomia–Wakatobi National Park Using the FISAT II Approach

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ABSTRACT

The *ikan ole* population in Tomia Island's customary fishing grounds is subject to high exploitation from intensive fishing pressure. This study applied the FiSAT II framework to assess stock status by analyzing growth, mortality, recruitment, yield-per-recruit (Y/R) and biomass-per-recruit (B/R) using the Knife-Edge Selection method. Length-frequency data were collected from artisanal fishers between January and March 2023 and were analyzed to estimate von Bertalanffy growth parameters ($L\infty$ and K), mortality rates (Z, M, F), exploitation rate (E), recruitment patterns, and cohort structure through the modal progression analysis. The estimated growth parameters were $L\infty$ = 12.39 cm and K = 1.20 year^{-1}, assuming $t_0 = 0$. Total mortality (Z) was 6.36 year^{-1}, with natural mortality M = 2.57 year^{-1} and fishing mortality F = 3.79 year^{-1}, yielding an exploitation rate E ≈ 0.60. Recruitment occurred year-round, with a pronounced peak in June–July that accounted for about 41% of annual recruitment. Cohort analysis indicated that mid-sized individuals (9–10.5cm) at the start of the year progressed into older cohorts (10.8– 11.6cm) by March, while individuals under 9cm were rarely observed, suggesting intense fishing pressure on juveniles. Y/R and B/R analysis showed that E_{50} ≈ 0.28, at which biomass declined to 50% of its unexploited level with Y/R ≈ 0.045, and Emax ≈ 0.42, which maximized Y/R (≈ 0.060) but reduced biomass to 28% of the original level. The current exploitation rate (E ≈ 0.60) exceeds both thresholds, indicating overfishing. Although growth and recruitment remain stable, high juvenile capture rates and excessive exploitation threaten long-term stock sustainability. Management action is urgently required, including the establishment of a minimum catch size of at least 9.5– 10cm, an increase in mesh size to at least 9mm to reduce juvenile capture, the implementation of a seasonal closure from May to July to protect peak recruitment, and the reduction of fishing effort to align E with sustainable levels. Regular length-frequency monitoring is essential to evaluate the effectiveness of these management measures and to prevent further overfishing of ikan ole stocks in Tomia's customary fishing grounds.

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INTRODUCTION

Fisheries resources play a strategic role in global food security. Beyond serving as a vital source of animal protein, the fisheries sector provides income and livelihoods for millions of people, particularly in developing countries. According to the **FAO (2022)**, capture fisheries and aquaculture make a significant contribution to global nutrition, with per capita fish consumption reaching 20kg in 2014. More than 3 billion people rely on fish as their primary source of animal protein, accounting for approximately 17% of daily intake. This underscores the critical role of fisheries in meeting global nutritional needs while presenting ongoing challenges for sustainability and marine ecosystem health.

As a maritime nation, Indonesia holds an important position in global fisheries production. However, high fishing pressure, if not properly managed, poses serious risks to both ecosystems and economic stability. The FAO reports that over 35% of global fish stocks are overexploited, with an estimated economic loss of USD 298.9 billion between 1950 and 2010 **(Ding *et al.*, 2017)**. Although global production continues to rise—driven largely by aquaculture, which reached 223.2 million tonnes in 2022 (a 4.4% increase from 2020) **(FAO, 2024)**—sustainability challenges remain. A key constraint is the sector's dependence on marine-based high-protein feeds, which limit environmentally sustainable aquaculture expansion **(Serra *et al.*, 2024)**.

At the national level, the Indonesian Ministry of Marine Affairs and Fisheries has prioritized sustainable fisheries as part of its strategic agenda, especially during the 2014–2019 period. Community-based and data-driven management initiatives have been introduced, particularly in small-scale fisheries **(Adhuri *et al.*, 2016)**. On Tomia Island in Wakatobi Regency, the harvesting of ikan ole has long provided livelihoods for indigenous communities. However, increased fishing activity without scientific monitoring has raised concerns over stock depletion and habitat degradation **(Isman *et al.*, 2025)**. This reflects broader challenges in small-scale fisheries across Indonesia, where limited biological data and the absence of stock assessments hinder effective management **(Ismail, 2020; Stacey *et al.*, 2021)**.

Overfishing of small-bodied species such as the ikan ole often results in a declining Spawning Potential Ratio (SPR), signaling reduced reproductive capacity of the population **(Prince *et al.*, 2020)**. In data-limited contexts, tools such as FiSAT II offer practical solutions. Developed by FAO and ICLARM, FiSAT II analyzes growth parameters, natural and fishing mortality, and exploitation rates using length-frequency and length-weight data **(FAO, 2006)**. Its utility has been demonstrated in Bangladesh **(Amin *et al.*, 2002)**, the Persian Gulf **(Hashemi *et al.*, 2012)**, Ghana **(Abobi & Ekau, 2013)**, and Nigeria **(Uneke, 2018)**, showing its capacity to generate critical stock data in resource-poor fisheries.

This study evaluates the impact of fishing activities on the stock status of ikan ole in the indigenous fishing grounds of Tomia, within Wakatobi National Park. By estimating growth, mortality, and exploitation parameters through FiSAT II, the research aimed to determine whether the stock is overfished, optimally utilized, or underexploited. The findings would provide a scientific basis for adaptive and sustainable management, contributing not only to the conservation of local fish resources but also to the strengthening of data-driven, community-based fisheries governance in Indonesia's customary coastal regions.

MATERIALS AND METHODS

1. Study area and period

This study was conducted in the coastal waters of Tomia Island, Wakatobi Regency, which represent one of the primary habitats of ikan ole (Fig. 1). The site was selected due to the high intensity of fishing activity and its critical role in sustaining local livelihoods **(UNDP, 2012)**. Data collection was carried out over a four-month period to capture different seasonal conditions and to ensure comprehensive representation. Biological sampling was conducted from January to March 2023, coinciding with the peak fishing season and enabling an accurate assessment of stock conditions under high exploitation pressure. Tomia Island was chosen for its combined ecological and economic importance, making it a representative location for investigating the population dynamics of ikan ole and providing insights for sustainable fisheries management.

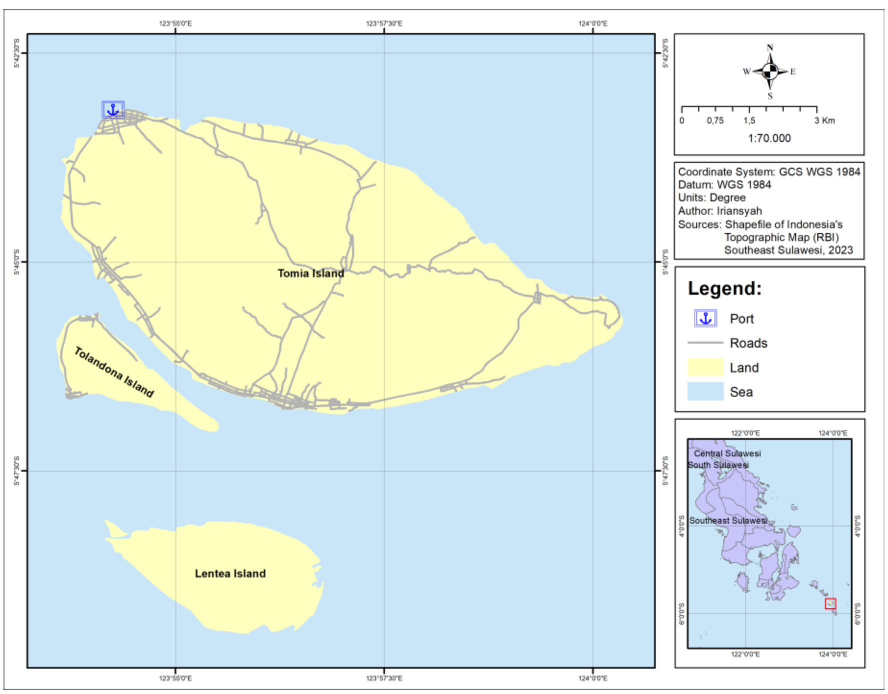

Fig. 1. Map of the research location

2. Materials and tools

This study utilized a range of tools and materials essential for data collection, processing, and analysis of ikan ole stock. Equipment was selected to ensure accurate biological measurements and geospatial documentation, while materials supported the preservation and handling of samples. A digital scale was used to measure body and gonad weights, while a fish meter was employed to record total and standard lengths of fish specimens. To evaluate fishing gear characteristics, a roll meter (ruler) measured mesh sizes and a caliper determined net twine diameter, aiding in gear selectivity analysis. A GPS device was used to record the geographic coordinates of fishing sites, and DSLR cameras documented fish specimens, gear, and field conditions. FiSAT II software served as the primary analytical tool to estimate growth parameters, mortality, recruitment, and exploitation rates. Ole fish specimens constituted the main biological material, used for length, weight, and gonad analysis. Plastic sampling bags were employed to preserve and transport gonad samples prior to laboratory analysis.

3. Types and sources of data

The study incorporated both primary and secondary data. Primary data consisted of direct biological measurements of ole fish obtained from artisanal catches using standardized instruments. Secondary data included relevant literature and previous reports on ole fish stock dynamics, growth patterns, and exploitation rates in the study area. Together, these datasets provided the foundation for analyzing both the biological aspects of reproduction and the technical aspects of fishing practices targeting ole fish around Tomia Island.

4. Data collection methods

A combination of fish sampling, semi-structured interviews, and field observations was employed. Ole fish specimens were sampled from artisanal catches across multiple fishing locations, and their total lengths were measured to generate length-frequency distributions. Semi-structured interviews with local fishers provided contextual information on seasonal fishing patterns and gear types. Field observations complemented these efforts by documenting ecosystem conditions and spatial distributions of ole fish within the study area.

5. Data analysis

Data analysis was conducted using FiSAT II (FAO-ICLARM Stock Assessment Tools II), a software suite developed for fish stock assessment. The analytical workflow included several steps aimed at evaluating the population dynamics and exploitation status of ole fish in Tomia waters.

5.1 Growth parameter estimation

Growth was modeled using the von Bertalanffy Growth Function (VBGF) implemented in FiSAT II. The model estimates three key parameters: the theoretical asymptotic length (L_∞), the growth coefficient (K), and the hypothetical age at zero length (t_0). L_∞ represents the maximum theoretical size attainable under optimal conditions, estimated from length-frequency data. K describes the rate at which fish approach L_∞, with higher values indicating faster growth. t_0 represents the hypothetical age at which fish length would be zero, serving as a baseline for growth trajectory modeling. It is used in the standard VBGF equation, where L_t is the length at age t, as follows:

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

Estimation was conducted using the ELEFAN I (Electronic Length Frequency Analysis) method within FiSAT II, which fits growth curves to length-frequency data. The quality of fit was evaluated using the Score Function.

5.2 Mortality and exploitation rate estimation

Mortality analysis aimed to quantify the extent of natural and fishing-induced mortality and to assess exploitation pressure on the population. Total mortality (Z) was estimated using the Linearized Catch Curve method in FiSAT II, which involves regression analysis of the logarithmic cumulative catch against fish length. The negative slope of the regression line corresponds to Z. Natural mortality (M) was calculated using Pauly's empirical formula, which incorporates water temperature and previously estimated growth parameters ($L\infty$ and K). Fishing mortality (F) was derived by subtracting natural mortality from total mortality by the equation F = Z-M. The Exploitation ratio (E) was calculated using the equation E = F/Z. This ratio indicates the proportion of total mortality attributable to fishing. A value of E ≈ 0.5 is generally considered the threshold for sustainable exploitation. Values exceeding 0.5 suggest overexploitation, while values below indicate underutilization.

6. Recruitment pattern analysis

This analysis was conducted to determine the timing and frequency of new individuals entering the fishable stock, which is crucial for assessing population replenishment and long-term sustainability. Monthly recruitment patterns were estimated using length-frequency data processed through FiSAT II, incorporating previously derived growth parameters ($L\infty$ and K) from the VBGF, which indicated that recruitment occurs throughout the year, with distinct peaks observed during specific months.

a. Cohort analysis using modal progression analysis

Cohort analysis was conducted to characterize the population structure of ikan ole based on distinct age or size classes. Length-frequency data were analyzed using the modal progression analysis in FiSAT II, employing the Bhattacharya method to separate overlapping size distributions into identifiable cohorts. Each modal component represented a group of individuals with similar size and presumed age. These cohorts were then fitted to the VBGF to estimate their age structure. This analysis provided critical insights into population dynamics, including growth stages, recruitment timing, and the presence or absence of younger cohorts. Such information is essential for identifying optimal harvesting periods and for minimizing the exploitation of juvenile individuals to ensure sustainable stock management.

b. Yield-per-recruit (Y/R) and biomass-per-recruit (B/R) analysis

This analysis aimed to evaluate the sustainability of current exploitation levels by assessing their effects on yield and biomass per recruit. Using FiSAT II and the Knife-Edge Selection model, the analysis incorporated essential biological and fishery parameters, including the growth parameters ($L\infty$, K, t_0), natural mortality (M), fishing mortality (F), and exploitation rate (E). Key reference points were calculated to guide interpretation: E-max, the exploitation rate that maximizes yield per recruit (Y/R); E-10, the rate at which Y/R declines by 10% from its maximum; and E_{50}, the rate at which biomass per recruit (B/R) falls to 50% of the unfished stock level.

Graphs were produced to visualize the relationship between the exploitation rate (E) and the corresponding Y/R and B/R values. These outputs provided a scientific basis for determining biologically optimal exploitation levels that sustain productivity while avoiding overfishing. The integration of growth, mortality, recruitment, cohort structure, and yield analyses within FiSAT II enabled a comprehensive evaluation of the stock dynamics of ikan ole. This methodological approach supports data-driven, sustainable fisheries management, particularly suited for small-scale, data-limited contexts such as the artisanal fisheries in Wakatobi.

RESULTS

1. Growth of ole fish based on the von Bertalanffy model

The length-frequency data of ole fish used in this analysis are presented in Table (1), which displays the distribution of fish lengths across three sampling periods: January, February, and March 2023. These data were used to estimate growth parameters based on the VBGF. Growth estimation was conducted using the ELEFAN I method implemented in the FiSAT II software, with the results illustrated in Fig. (2). The visualization highlights the relationship between the growth constant (K), the growth performance index (ϕ), and the model's goodness-of-fit score.

Table 1. Length-frequency data of Ole fish

Fish length (cm)	January 2023	February 2023	March 2023
8.5	0	1	0
8.8	2	3	2
9.1	5	12	4
9.4	20	37	19
9.7	41	65	31
10.0	49	101	64
10.3	33	84	42
10.6	30	63	23
10.9	11	23	9
11.2	9	10	2
11.5	0	1	3
11.8	0	0	1

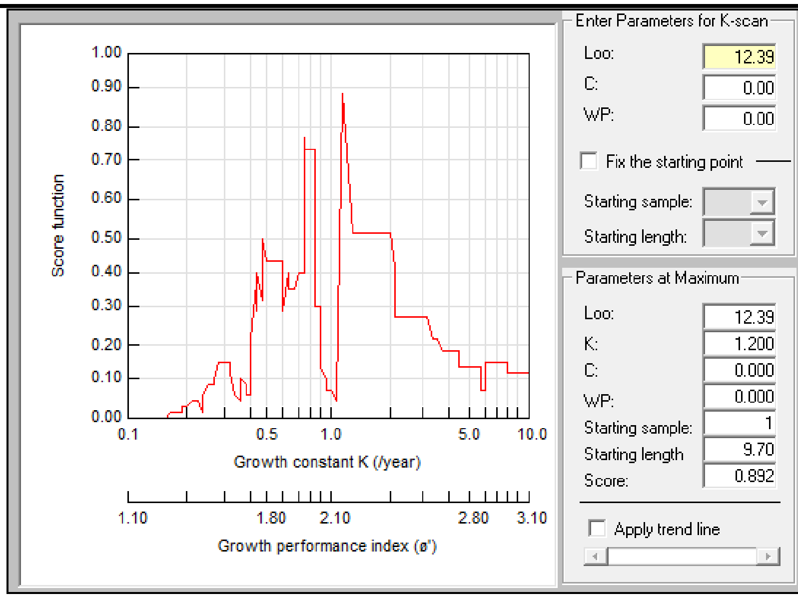

Fig. 2. Non-parametric assessment of the fit of the VBGF using ELEFAN I in FiSAT II

After estimation, the length distribution was analyzed based on the sampling periods to understand the population structure of ole fish during the study. The results served as the basis for estimating the parameters L∞, K, and t_0 using the VBGF model. These parameters are essential for understanding the growth dynamics of the fish, particularly in identifying the potential maximum body size and the growth rate of the population in its natural habitat. Assuming $t_0 = 0$, the analysis indicated a good fit between the VBGF model and the field data, as evidenced by the high Score Function value (Table 2).

Table 2. Growth parameters estimation of Ole fish

Parameter	Value	Explanation
L∞	12.39 cm	Theoretical maximum length achievable by ole fish under optimal conditions.
K	1.2 / year	The growth rate of ole fish approaching the maximum length (L∞).
t_0	0 (assumed)	Theoretical initial age when fish length equals zero.
Starting length	9.70 cm	Initial length estimated on the growth curve.
Score function	0.892	The goodness of fit of the von Bertalanffy model to fish length-frequency data.

2. Mortality rate and exploitation ratio of ole fish

This analysis aims to assess the mortality rates of ole fish resulting from both natural causes and fishing activities, serving as a basis for evaluating the level of exploitation pressure on the population. Estimates of total mortality (Z) and natural mortality (M), derived using the FiSAT II software, are presented in Figs. (3, 4), as well as in Table (3).

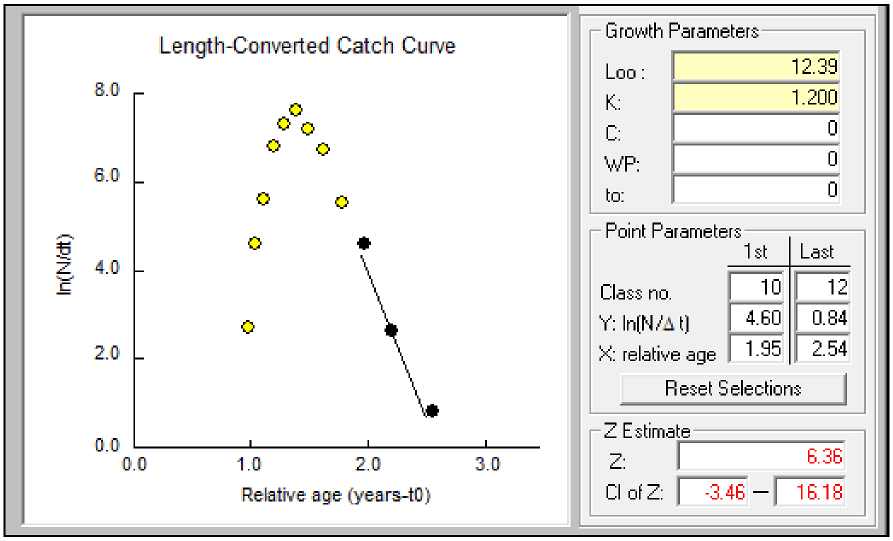

Fig. 3. Length-converted catch curve analysis

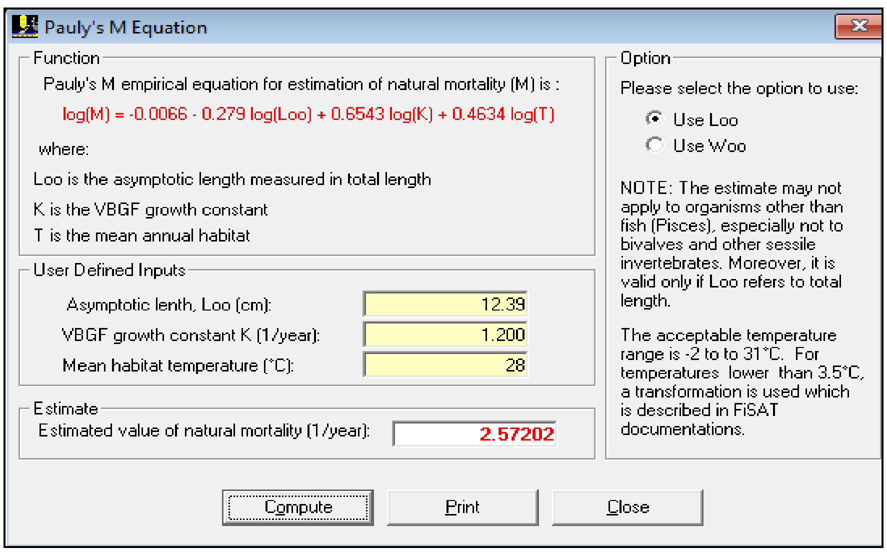

Fig. 4. Estimation of natural mortality using *Pauly's Empirical Equation*

The results indicate that the total mortality rate (Z) of ole fish is estimated at 6.36 year^{-1}. This value encompasses all causes of mortality, including both natural factors and fishing-induced deaths. The confidence interval for Z, ranging from -3.46 to 16.18, reflects substantial variability in the estimate, which is likely influenced by the quality of input data and the sensitivity of the model parameters. In contrast, the natural mortality rate (M) was estimated at 2.57 year^{-1}. This value represents the proportion of the population that dies from natural causes such as predation, disease, and environmental stressors, independent of fishing pressure. The exploitation rate (E) was calculated at 0.60, indicating that approximately 60% of the total mortality is attributable to fishing activities. This level of exploitation exceeds the commonly accepted threshold for sustainable harvesting ($E \approx 0.5$), suggesting that the ole fish population is subject to heavy fishing pressure. These findings highlight the urgent need for improved fisheries management strategies aimed at ensuring the long-term sustainability of the stock.

Table 3. Mortality and pressure of fish exploitation

Parameter	Value	Explanation
Total mortality (Z)	6.36 $year^{-1}$	The total mortality rate of the ole fish population is due to fishing and natural causes.
Natural mortality (M)	2.57 $year^{-1}$	Mortality rate is caused by natural factors such as predation and environmental conditions.
Mortality caused by fishing activities (F)	3.79 $year^{-1}$	Mortality rate due to fishing activities.
Exploitation ratio (E)	0.60	The proportion of fishing mortality to total mortality.

3. Monthly recruitment distribution of ole fish

The percentage distribution of ole fish recruitment throughout the year is detailed in Table (4) and illustrated in Fig. (5). The data reveal that new individuals consistently enter the population each month, except for December, during which no recruitment was observed.

Table 4. Annual percentage distribution of ole fish recruitment

Month	**Recruitment percentage (%)**
Month -1	1.330
Month -2	2.970
Month -3	6.360
Month -4	10.73
Month -5	16.05
Month -6	21.50
Month -7	19.56
Month -8	13.24
Month -9	6.480
Month -10	1.290
Month -11	0.490
Month -12	0

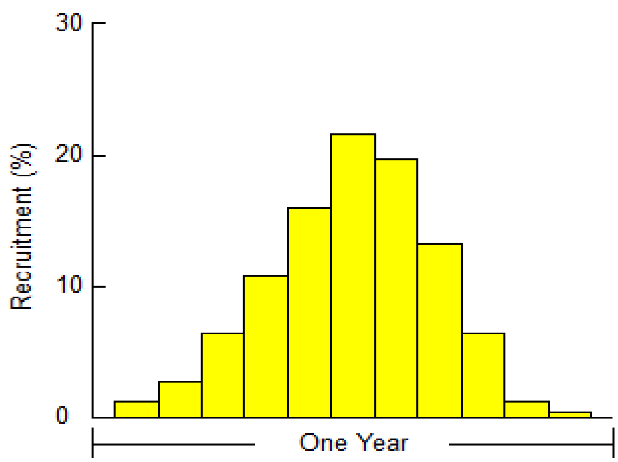

Fig. 5. Annual recruitment pattern of ole fish

The lowest recruitment percentage was recorded in January at 1.33%, followed by a gradual increase at 2.97% in February and 6.36% in March. A more pronounced rise occurred in April (10.73%) and May (16.05%), culminating in a peak recruitment of 21.50% in June. In July, the recruitment percentage declined slightly to 19.56%, yet it remained relatively high. Following this peak, recruitment steadily decreased to 13.24% in August, 6.48% in September, 1.29% in October, and 0.49% in November. Recruitment reached its absolute minimum of 0% in December, indicating almost no new individuals entered the population during this period. Fig. (5) illustrates this pattern, showing recruitment beginning at low levels (approximately 1–2%) at the start of the year, gradually rising to a peak of around 21–22% mid-year (June), and then steadily declining toward near zero by year-end.

4. Cohort grouping of Ole fish based on modal progression analysis

Cohort grouping was employed as a method to identify groups of Ole fish individuals based on similarities in body length and relative age. This approach is essential in population dynamics studies as it enables researchers to map the age structure of a population and to assess its growth patterns over time. In this study, cohort analysis was conducted on three sample groups derived from length-frequency data collected across three distinct sampling periods, as illustrated in Figs. (6, 7, and 8).

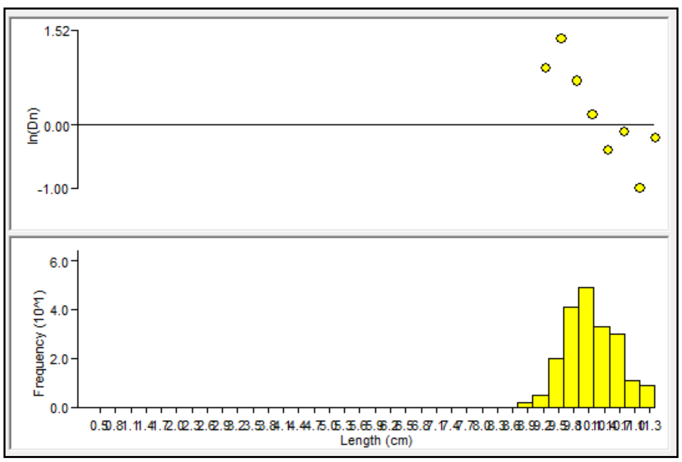

Fig. 6. Length-frequency and cumulative Log Catch (ln D) on January 26, 2023

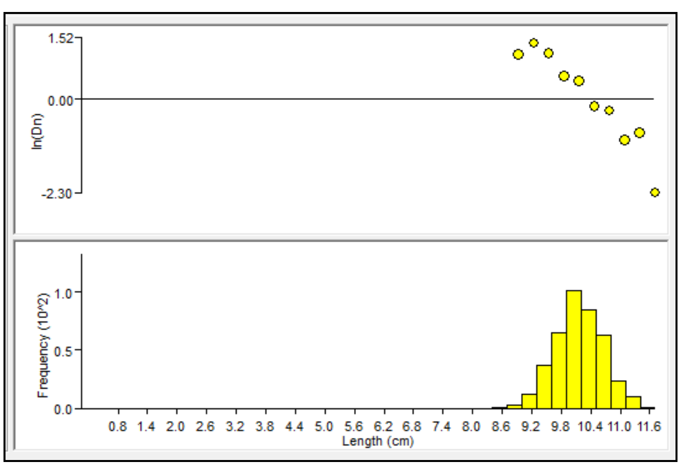

Fig. 7. Length-frequency and cumulative Log Catch (ln D) on February 27, 2023

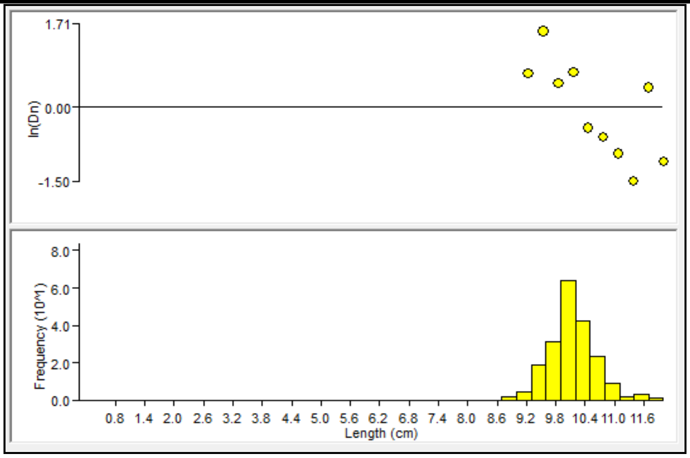

Fig. 8. Length-frequency and cumulative Log Catch (ln D) on March 22, 2023

Through this analysis, valuable insights were gained regarding the population structure of ole fish, particularly in identifying the dominant age cohorts during each sampling period and estimating the recruitment rate of new individuals into the population. These findings are crucial for understanding population dynamics and the sustainable utilization of fishery resources. Moreover, they provide a scientific basis for developing fisheries management strategies grounded in biological and ecological data.

5. Y/R and B/R evaluation for the ole fish population

Y/R and B/R analyses were conducted to evaluate the impact of the exploitation rate (E) on catch yield and the remaining biomass in the ole fish population. The study utilized previously estimated parameters, including the theoretical maximum length ($L\infty$), growth coefficient (K), hypothetical age at zero length (t_0), natural mortality (M), fishing mortality (F), and the ratio of length at first capture to maximum length ($Lc/L\infty$). The results illustrate the relationship between exploitation rate (E) and both relative yield (Y/R) and relative biomass (B/R), as shown in Fig. (9) and Table (5). These outputs were employed to determine the maximum exploitation rate (E-max), which corresponds to the highest yield per recruit, along with precautionary exploitation reference points such as E-10 and E-50. These reference points serve as critical thresholds to guide sustainable fisheries management. The following figures present the detailed results of this analysis.

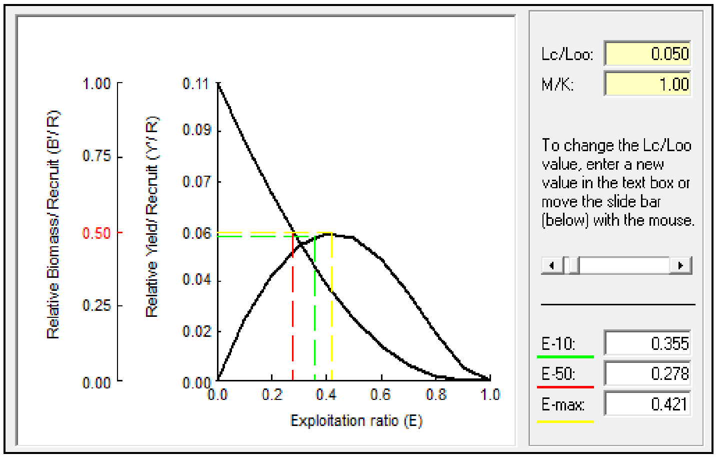

Fig. 9. Y/R and B/R of Ole fish

Fig. (9) presents two key curves illustrating the relationship between exploitation rate (E), yield per recruit (Y/R), and biomass per recruit (B/R) for ole fish. The B/R curve, plotted on the left axis, represents the proportion of remaining biomass relative to an unfished population, while the Y/R curve, plotted on the right axis, shows the yield per recruit under different exploitation scenarios. The analysis reveals several important reference points. At an exploitation rate of E = 0.278 (indicated by the yellow dashed line), the biomass is reduced to 50% of its original, unexploited level. At this point, the Y/R reaches approximately 0.045. As fishing pressure increases to E = 0.355 (red dashed line), the yield per recruit rises slightly to around 0.05, but the rate of increase begins to slow down, indicating diminishing returns. Meanwhile, biomass continues to decline, dropping to about 35% of the unfished state. The peak yield is reached at E = 0.421 (green dashed line), where Y/R is maximized at roughly 0.06. However, this comes at a significant ecological cost, as the relative biomass falls sharply to just 28% of the original level.

Overall, the figure highlights a classic trade-off between harvest and stock sustainability. At low exploitation levels (E near 0), biomass remains high, close to 100%, but the yield is minimal. As exploitation intensifies, yield increases up to a certain point, but biomass declines steadily. Beyond E = 0.355, gains in yield become marginal while biomass loss accelerates. Although the maximum yield occurs at E = 0.421, this point represents a biologically risky threshold due to the substantial depletion of the stock, underscoring the need for precautionary management measures.

Table 5. Y/R and B/R based on exploitation ratio (E)

E	Y/R	B/R
0.01	0.022	0.805
0.20	0.039	0.626
0.30	0.050	0.466
0.40	0.054	0.327
0.50	0.053	0.211
0.60	0.045	0.120

0.70	0.032	0.055
0.80	0.018	0.018
0.90	0.005	0.002
0.99	0.000	0.000

Table (5) demonstrates a clear trend in how exploitation rate (E) affects both yield per recruit (Y/R) and biomass per recruit (B/R) in the ole fish population. As E increases from 0.01 to 0.30, Y/R also rises, reaching a peak of approximately 0.05 at E = 0.30. Beyond this point, Y/R gradually declines, eventually approaching zero at an exploitation rate of 0.99. In contrast, B/R exhibits a continuous exponential decline as E increases. At a low exploitation level of E = 0.01, the relative biomass is still high at 0.805. However, it drops to 0.466 by E = 0.30, and then declines more sharply, falling to 0.327 at E = 0.40 and to 0.211 at E = 0.50. The decline continues steadily, reaching near-zero levels as E approaches 0.99. These results indicate that catch efficiency (Y/R) reaches its maximum at moderate levels of exploitation, while the standing biomass (B/R) consistently diminishes with increasing fishing pressure. This pattern highlights the trade-off between maximizing yield and preserving biomass, reinforcing the importance of setting exploitation rates that balance productivity with sustainability.

DISCUSSION

1. Growth analysis of ole fish based on the VBGF model

The length-frequency data collected between January and March 2023 showed that most individuals caught were within the 9.4– 10.3cm size range, with the 10.0cm length class being the most dominant. Specifically, 49 individuals were recorded in this class in January, increasing significantly to 101 in February, before declining to 64 in March. This pattern suggests a relatively uniform and consistent cohort growth over the study period. Only a few individuals exceeded 11cm in length, indicating a limited size increase over the three months. The estimated asymptotic length ($L\infty$) was 12.39cm, with a growth coefficient (K) of 1.20 year^{-1}, indicating a rapid growth rate. The starting length for the adjusted growth curve was 9.70cm, aligned with field observations. The assumed t_0 value of zero provided a practical fit, though it should be interpreted cautiously, especially when data on smaller size classes are limited.

This concern aligns with findings from **Droll *et al.* (2025)**, who emphasized the sensitivity of growth models to t_0, particularly in datasets with limited juvenile representation. The resulting growth curve achieved a high goodness-of-fit score of 0.892, close to the maximum possible, suggesting that the model accurately represents the length-frequency distribution. The high K value also indicates that ole fish exhibit traits typical of r-strategists: rapid growth, early maturity, and a short life cycle. Such life-history strategies are commonly observed in species subjected to intense selection pressures and highly variable environmental conditions.

Growth analysis of ole fish using the VBGF revealed a strong alignment between the observed length-frequency distributions and the theoretical growth curve, indicating that the model accurately represents the growth dynamics of the population. Parameters estimated via the ELEFAN I routine in the FiSAT II software yielded robust values for the asymptotic length ($L\infty$), growth coefficient (K), and growth performance index (ϕ), all of which reflect a fast-growing species with considerable size potential. The model assumed an initial condition of $t_0 = 0$, a standard simplification in length-based growth modeling, which was justified by the high Score Function value obtained, underscoring the reliability and goodness of fit of the estimated growth parameters.

These results underscore the utility of the VBGF in capturing key aspects of the growth trajectory of ole fish in the Tomia waters during the study period. Such growth information is critical for informing stock assessment models and for devising biologically sound management measures. The combination of a relatively high K value ($K = 1.20$ year^{-1}) and moderate $L\infty$ ($\approx$12.4 cm) suggests that the species grows rapidly, which, while ecologically advantageous, also renders it more susceptible to overfishing if recruitment is not consistently strong. However, from a fisheries management perspective, the high growth coefficient signals a biological trait that, while advantageous in terms of rapid biomass accumulation, also implies increased vulnerability to overexploitation if recruitment becomes inconsistent **(Santos *et al.*, 2022)**. This is a common trend observed in short-lived, fast-growing pelagic fish, as documented in comparable studies on *Sardinella longiceps* in Indian and Pakistani coastal waters **(Nadeem *et al.*, 2017; Ahirwal *et al.*, 2022)**.

From a fisheries management perspective, species with such life-history traits require proactive regulation. It is therefore recommended that a minimum legal capture size of 9cm be implemented, which would allow individuals to attain sexual maturity before being harvested, thus contributing to the reproductive pool. Furthermore, seasonal closures, particularly during peak recruitment and growth periods (e.g., May–July as identified in related analyses), would align fishing efforts with the biological cycles of the species and reduce juvenile mortality. Adopting these measures would not only protect vulnerable cohorts but also help maintain the long-term productivity and ecological resilience of the ole fish stock in Tomia.

2. Mortality and exploitation rate analysis of ole fish

The mortality and exploitation analysis of the ole fish population indicates that the species is currently experiencing high fishing pressure. The estimated total mortality (Z) was 6.36 year^{-1}, reflecting a substantial rate of population loss due to both natural causes and fishing activities. The natural mortality (M), calculated using Pauly's empirical formula based on $L\infty = 12.39$ cm, a growth coefficient (K) of 1.20 year^{-1}, and an average environmental temperature of 28 °C, was 2.57 year^{-1}. Consequently, fishing mortality (F), derived as the difference between Z and M, was 3.79 year^{-1}. This results in an exploitation rate ($E = F/Z$) of 0.60, suggesting that 60% of total mortality is attributable to fishing. An exploitation rate above the commonly accepted biological threshold of 0.5 indicates that the ole fish population is subject to overexploitation **(Teocharis *et al.*, 2025)**. This finding underscores the urgent need for more sustainable fisheries management strategies to prevent further depletion and to ensure long-term stock viability. Although the point estimate for Z is high, the confidence interval is broad (CI Z = –3.46 to 16.18), indicating considerable uncertainty in the estimate. This variation stems from the sensitivity of mortality models to input data variability and the selection of reference points on length-frequency curves, warranting cautious interpretation.

The current size structure of the catch also reflects the effects of high fishing pressure **(Fauconnet *et al.*, 2015)**. Length-frequency data from January to March 2023 show that most captured individuals were between 9.4– 10.3cm in length, with very few exceeding 11cm. Based on the VBGF curve with L∞ = 12.39cm, ole fish approach their asymptotic size at around 2–3 years of age. However, the dominance of sub-11cm individuals suggests that the effective mesh size in use is capturing fish smaller than 9cm, resulting in the premature harvest of juveniles before they can contribute to population replenishment. This is a clear indication of growth overfishing, where individuals are harvested before reaching their optimal size for yield. To mitigate this, a crucial first step would be to raise the minimum capture size to at least 9.5cm. This would allow a greater proportion of individuals to reach sexual maturity and to complete more of their growth before being subject to fishing. Supporting evidence from March 2023 length-frequency distributions shows a strong dominance of small individuals in the catch, with very few specimens above 11cm. This size skew indicates a significant loss of reproductive potential in the population and reinforces the need for regulatory adjustments.

A similar situation was observed in *Selaroides leptolepis* populations in Tomini Bay, where **Pasisingi *et al*. (2021)** reported a fishing mortality (F) of 2.45 year^{-1} and an exploitation rate (E) of 0.80 for males, well above sustainable limits. One of the primary drivers of this overfishing was the use of nets with excessively small mesh sizes, which failed to allow juvenile fish to escape. Both *S. leptolepis* and Ole fish exhibit comparable consequences: a population size structure dominated by immature individuals and a scarcity of adults essential for reproduction. To address this issue, increasing the minimum mesh size to 9– 10mm is recommended. This adjustment would enable juvenile fish under 9cm to escape and reach the proposed legal size threshold. These technical interventions should be formalized through local fishing regulations or community-based agreements, such as village bylaws, and implemented through fishers' groups to ensure compliance and ownership **(Sululu *et al.*, 2025)**.

Such gear-based management approaches have proven effective elsewhere. For example, a study by **Amir *et al.* (2013)** on Katsuwonus pelamis in the Flores Sea demonstrated that the introduction of size limits and periodic mortality assessments successfully reduced the exploitation rate from excessive levels to below the sustainable threshold of 0.5. Their findings emphasize that technical regulations, particularly regarding gear selectivity and legal capture size, can significantly alleviate fishing pressure and contribute to stock recovery when combined with effective monitoring and community participation. This experience provides a valuable precedent for managing the ole fish in Tomia waters. By targeting fishing mortality (F) through technically feasible and socially acceptable interventions, fisheries managers can promote both ecological sustainability and socio-economic resilience. A healthy fish stock not only supports stable catch volumes but also secures long-term livelihood opportunities for coastal communities **(Napitupulu *et al.*, 2022)**. Achieving this balance requires the integration of science-based policy, active fisher engagement, and adaptive, data-informed governance.

3. Annual recruitment pattern of ole fish

The annual recruitment pattern of ole fish, as illustrated in Table (4) and Fig. (5), indicates a clear seasonal concentration of new individuals entering the population between May and July. This period corresponds to the peak of reproductive activity and the transition from larval to juvenile stages. Recruitment was notably low at the beginning of the year, with only 1.33% recorded in January, gradually increasing to 2.97% in February and to 6.36% in March. A more pronounced increase occurred in April (10.73%), followed by a sharp peak in May (16.05%) and the highest level observed in June (21.50%). Recruitment then declined slightly in July (19.56%) before dropping steeply through the remainder of the year, reaching nearly zero by December. This pattern suggests that larval settlement and juvenile recruitment into the main population occur most intensively during the fifth to seventh months of the year. Such a trend is consistent with seasonal spawning behaviors typical of small pelagic fish, where environmental factors such as water temperature, ocean currents, and plankton availability drive reproductive success and larval survival **(Lima *et al.*, 2022)**.

After July, recruitment declined significantly, falling to 13.24% in August and continuing to decrease through September (6.48%), October (1.29%), and November (0.49%). No recruitment was detected in December, indicating a biological dormancy period during which no individuals reached detectable size classes. This phenomenon could be attributed to decreased larval densities due to predation pressure, larval drift or migration, or unfavorable environmental changes such as reduced temperatures, altered currents, or limited food availability. A comparable pattern was observed in Cichlidae fish populations in Ghana, where **Kwarfo-Apegyah and Ofori-Danson (2010)** reported peak recruitment aligning with the rainy season when environmental conditions are most conducive to larval survival. The steady increase in recruitment between March and May strengthens the hypothesis that spawning and larval dispersal in ole fish occurs during early to mid-year. In June, when oceanographic conditions such as temperature, current flow, and primary productivity are optimal, nearly one-third of the annual cohort enters the population. A slight decline in July likely reflects the continued recruitment of late-spawned larvae from May. However, the sharper drop thereafter suggests that many individuals either grew beyond the juvenile detection range or were lost to natural mortality.

Ecologically, the May–July recruitment peak is likely driven by seasonal environmental triggers such as warmer seawater, increased nutrient influx due to seasonal currents, and abundant plankton availability. Consequently, regular monitoring of sea surface temperature and salinity is crucial for forecasting recruitment patterns **(Darmanin *et al.*, 2025)**. If climate variability shifts environmental conditions, the recruitment window may also shift. Therefore, any proposed closed-season policy should remain flexible and adapt to ecological changes to ensure effective timing and relevance.

This recruitment trend should be interpreted in conjunction with mortality and growth parameters. The previously estimated total mortality (Z) was 6.36 $year^{-1}$, with natural mortality (M) at 2.57 $year^{-1}$ and fishing mortality (F) at 3.79 $year^{-1}$, implying that approximately 60% of total mortality results from fishing pressure. The elevated F value suggests that a large portion of juveniles are harvested before reaching reproductive maturity. Temporarily suspending fishing activities during peak recruitment months could significantly reduce F, thereby increasing juvenile survival and supporting a more balanced population structure over time **(Richardson *et al.*, 2024)**.

From a fisheries management perspective, implementing a biologically informed closed season during the peak recruitment period could contribute to stock recovery **(Kasim *et al.*, 2024)**. However, such interventions must also consider socio-economic implications. Temporary fishing bans may reduce fishers' income during closure months. Therefore, local governments and fisheries authorities should provide compensatory support, such as fuel subsidies, alternative gear for non-targeted species, aquaculture training, or involvement in seaweed farming and value-added fish processing, to maintain livelihoods during closures. Offering these incentives can increase community compliance and promote long-term conservation efforts. Critically, it should be noted that Table 4 reflects recruitment dynamics over a single year. To validate these findings, ideally over at least three consecutive years, multi-year monitoring is essential to confirm temporal consistency. If peak recruitment consistently occurs within the same seasonal window, temporal regulations (e.g., closed seasons or mesh size restrictions) can be implemented with greater confidence. Conversely, if peak recruitment shifts to months such as August or September due to environmental variability, adaptive management will be necessary. Long-term monitoring can also provide early warnings about the impacts of climate change, pollution, or anthropogenic disturbances on the life cycle **(Baptist *et al.*, 2014)**.

4. Cohort analysis of ole fish using the modal progression in FiSAT II

Cohort analysis of ole fish, conducted using the modal progression method in the FiSAT II software, reveals a clear temporal shift in length-frequency distributions over a three-month sampling period (January to March 2023). These shifts provide insight into growth patterns, recruitment gaps, and the influence of fishing pressure on population structure. The first sample, collected on January 26, 2023, showed a dominant frequency peak within the 9.0–10.5 cm length range (Fig. 6), indicating that the majority of individuals caught during this period belonged to a mid-sized cohort. A small number of larger individuals nearing 11 cm were also present, suggesting the early presence of an older cohort. Notably, very few fish below 9cm were detected, implying that juvenile cohorts were either rare or had already grown beyond this threshold. This could also be attributed to early capture or natural mortality before they reached a detectable size.

By February 27, 2023 (Fig. 7), the length-frequency distribution had shifted, with the modal length advancing to the 10.2– 10.8cm range. This reflects a one-month growth progression of the cohort previously centered around 9– 10.5cm. Older cohorts (11–11.6 cm) began to appear more distinctly, although still in relatively low numbers, indicating that some individuals had entered the pre-asymptotic growth phase. Meanwhile, the abundance of fish smaller than 9cm remained negligible, suggesting limited recruitment or early loss of juvenile individuals, either due to natural predation or fishing. The third sample, taken on March 22, 2023 (Fig. 8), exhibited a dominance of older individuals in the 10.8– 11.6cm range. The number of mid-sized fish (9.5– 10.2cm) had declined markedly, confirming that the majority of the early-year cohort had grown beyond 10cm. However, individuals below 9cm remained virtually undetected. This consistent absence of smaller size classes across all three months suggests that early-stage recruits were not entering the fishable stock in detectable numbers during this period. Overall, the progression of modal lengths from January to March illustrates two critical patterns. The mid-sized cohort observed in January showed a clear trajectory of growth, transitioning into the older cohort class by March. The persistent absence of juvenile fish under 9 cm indicates a gap in recruitment input. This gap is likely driven by a combination of natural mortality (e.g., predation, disease) and fishing mortality before individuals reach 9cm—the lower limit of effective detection in sampling.

These findings have direct implications for fisheries management strategies. The scarcity of juveniles in samples suggests that fishing gear used in the field may selectively retain fish above a certain size threshold, likely filtering out juveniles smaller than 9 cm. Given the growth rate estimated using the von Bertalanffy Growth Function ($K = 1.20$ year^{-1}), this implies that most captured fish are at least 8–9 months old. To improve juvenile survival and ensure sustainable recruitment, gear regulations should aim to increase mesh size to allow fish under 9cm to escape. If the current mesh size captures individuals as small as 8– 9cm, a gradual adjustment to 9– 10mm mesh is recommended to provide juveniles sufficient time to grow into the more productive size classes. The observed cohort transition from mid-sized to older individuals over the three months suggests relatively fast growth under moderate fishing pressure. However, despite the growth from January to March, few fish approached the asymptotic length ($L\infty = 12.39$ cm). This limited representation of larger fish reflects the influence of high fishing mortality ($F \approx 3.79$ year^{-1}), which, when combined with total mortality (Z) of 6.36 year^{-1} and natural mortality (M) of 2.57 year^{-1}, shows that a substantial portion of the population is removed by fishing before reaching maximum size. Therefore, raising the minimum legal catch size to at least 10cm would likely increase the survival of middle-sized cohorts, enhancing reproductive output per recruit and overall stock resilience.

Third, the absence of juvenile cohorts (<9 cm) in the January–March period highlights the need for intensified recruitment monitoring. Previous monthly recruitment analyses suggest that peak recruitment occurs around June–July. However, recruits only become detectable once they reach ~9 cm, which typically occurs toward the end of the rainy season. To capture earlier stages of recruitment, sampling should begin earlier in the year, between February and April, and employ gear capable of detecting smaller individuals, such as fine-mesh plankton nets or micro-traps. This would help clarify whether low recruitment during this period is a sampling artifact or a real biological constraint. In conclusion, the cohort analysis provides a valuable framework for understanding growth dynamics, recruitment bottlenecks, and the influence of fishing on Ole fish populations. Addressing these issues through adaptive management, such as adjusting mesh sizes, implementing seasonal closures, and enhancing recruitment monitoring, will be essential for maintaining the sustainability of the stock in Tomia waters.

The modal progression analysis across three consecutive samples confirms a distinct growth trajectory in the ole fish population from mid-sized cohorts to older cohorts over a relatively short period. However, the persistent absence of newly recruited individuals below 9 cm in all samples highlights a concerning gap in juvenile input. This pattern underscores the urgent need for management strategies that promote early growth and survival prior to harvest. Three key management recommendations emerge from these findings:

a. **Increase the mesh size of fishing nets:** Adopting nets with larger mesh sizes, preferably 9–10 mm or more, would allow fish smaller than 9cm to escape and continue growing. The juvenile phase is critical for fish to reach reproductive maturity. Studies in tropical fisheries across Africa and Asia have demonstrated that modifying gear selectivity in this manner significantly improves juvenile survival and leads to healthier population size structures **(Peifeng, 2013)**. Such modifications can reduce growth overfishing and help replenish depleted stocks over time.
b. **Establish a minimum legal catch size above 10 cm:** Given the asymptotic length ($L\infty$) of ole fish is approximately 12.4cm and the growth rate is relatively high ($K = 1.2\ year^{-1}$), setting a minimum legal catch size above 10cm would allow mid-sized individuals to complete most of their growth before being captured. This measure aligns with recommendations from **Gayanilo *et al.* (2005)**, who showed that in heavily exploited fisheries, increasing the size at first capture effectively raises the average age and size of landed fish, reducing exploitation pressure and enhancing reproductive potential per recruit.
c. **Expand sampling efforts to capture early recruitment:** Since juveniles under 9cm were not significantly detected from January to March, it is recommended that future sampling begins earlier, between February and April, to capture initial recruitment events. Sampling tools must also be adapted to better detect smaller individuals, such as through the use of fine-mesh plankton nets or micro-gear. This is crucial to avoid underreporting early recruitment, a common issue in tropical small-scale fisheries due to gear selectivity bias, as highlighted by **Moreau and Sricharoendham (1999)**. Accurate detection of early recruits is essential for tracking cohort entry into the population and for evaluating recruitment strength.

Together, these three strategies form a biologically sound and empirically supported foundation for sustainable ole fishery management. Implementing them would improve the proportion of mature individuals in the stock and strengthen recruitment potential in future seasons. These approaches have already shown success in similar tropical fisheries facing analogous challenges. In conclusion, data from the three sampling periods between January and March demonstrate that mid-sized cohorts (9– 10.5cm) grew rapidly into older cohorts (> 10.8cm). However, no clear evidence of recruitment input from smaller cohorts (< 9cm) was detected. This gap likely results from either the failure of juveniles to reach detectable sizes or their premature removal due to early fishing. Similar dynamics have been widely documented in tropical fisheries literature. For example, a study on *Trachurus mediterraneus* in the Black Sea found that modal progression effectively revealed inter-cohort growth and recruitment gaps, often caused by fishing gear selectivity against smaller individuals **(Yankova, 2013)**. In the case of Ole fish, similar gear-based constraints likely exist, making gear specification adjustments an urgent management priority.

5. Analysis of the efficiency of ole fish exploitation using Y/R and B/R

The Y/R and B/R analysis for ole fish, as illustrated in Fig. (9), provides valuable insights into how changes in exploitation rate (E) affect the relative catch yield and the residual biomass in the fishery. Under the assumptions of a constant length-at-first-capture ratio ($Lc/L\infty$) of 0.05 and M/K ratio of 1.00, the B/R curve begins near 1 when E approaches zero. This suggests that, in the absence of fishing pressure, the biomass remains close to its unfished level. However, at these low levels of exploitation, the Y/R curve remains close to zero, indicating that while biomass is high, the catch yield per recruit is minimal due to low fishing intensity. As the exploitation rate increases to E = 0.20, Y/R rises to approximately 0.039, while B/R declines to 0.626. This reflects the initial phase of increasing fishing productivity, accompanied by a gradual reduction in biomass. At E = 0.30, Y/R peaks around 0.050, while B/R drops further to 0.466, indicating a near-optimal point in terms of catch yield, albeit with more than half the original biomass already extracted. The E_{50} reference point, where B/R is reduced to 50% of its unfished level, is observed at E ≈ 0.278, with a corresponding Y/R of approximately 0.045. This marks a biologically significant threshold, as it indicates that half of the potential biomass has been lost even though yield continues to increase.

Beyond E = 0.30, the marginal gains in Y/R begin to diminish. For instance, increasing E to 0.355 raises Y/R to 0.054, while B/R plummets to 0.327. The steep loss of biomass compared to the modest gain in yield highlights diminishing returns and increasing ecological risk. The maximum yield per recruit (E-max) is reached at E = 0.421, yielding a peak Y/R of 0.060 but leaving only 28% of the original biomass (B/R = 0.280). Although E-max technically represents the point of maximum catch per recruit, it also signifies critically low biomass, raising serious concerns about stock sustainability **(Ministry for Primary Industrie, 2017)**. These patterns are reinforced numerically in Table (5) showing that at E = 0.01, Y/R is merely 0.022 while B/R remains high at 0.805. As E increases to 0.20, Y/R grows to 0.039, and B/R declines to 0.626. At E = 0.30, Y/R reaches 0.050 with B/R at 0.466. However, between E = 0.30 and E = 0.35, the incremental increase in Y/R (from 0.050 to 0.054) is marginal, while B/R drops sharply (from 0.466 to 0.327), confirming that the biologically optimal exploitation threshold lies near E-50. Beyond this threshold, further increases in fishing pressure lead to disproportionately large biomass losses relative to yield gains.

Numerous studies have emphasized the importance of managing fisheries based on Y/R and B/R indicators, particularly when overfishing is evident. For example, research on *Parailia pellucida* in Nigeria showed that even with E below E-max (0.31 vs. 0.70 threshold), monitoring was essential to prevent long-term stock degradation **(Uneke *et al.*, 2011)**. In the case of ole fish, the current exploitation rate (E ≈ 0.60) exceeds E-50 (≈0.28), suggesting that the stock has long been under excessive fishing pressure. While the current Y/R may appear optimal, the remaining B/R at just 28% signals a severe loss of spawning biomass and a heightened risk of population collapse. Comparable findings have been reported for *Anguilla japonica* in Taiwan, where F values exceeding $F_{0.1}$ and F_{50} indicated serious threats to recruitment sustainability **(Lin *et al.*, 2010)**. Similarly, in *Penaeus indicus* populations in Oman, regulating fishing seasons and catch size led to substantial improvements in both Y/R and B/R **(Siddeek *et al.*, 1996)**. These examples align with the FAO's precautionary principle, which recommends maintaining E below E_{50} to preserve ecological resilience and to ensure long-term socio-economic viability **(Garcia, 2007)**.

In practical terms, this analysis strongly supports maintaining exploitation rates at or below E_{50}, estimated at approximately 0.28 for ole fish. The current fishing mortality (F) is 3.79 year^{-1}, and when combined with the natural mortality (M) of 2.57 year^{-1}, the total mortality (Z) reaches 6.36 year^{-1}. This results in a historical exploitation rate of $E = F/Z \approx 0.60$, more than double the biologically safe threshold. To ensure the sustainability of the ole fish stock, immediate management interventions are necessary, including reducing F by implementing stricter fishing regulations, adjusting fishing gear to increase selectivity and allow juvenile escape, establishing closed seasons during peak recruitment months (May–July), and enforcing minimum catch size limits to ensure that individuals have the chance to reproduce before being harvested. In conclusion, while higher exploitation rates may initially appear economically beneficial, the long-term ecological cost is unsustainable. Maintaining exploitation below E_{50} offers the best compromise between maximizing yield and ensuring the persistence of the ole fishery.

To reduce the exploitation rate (E) toward the biologically safer level of approximately 0.28, several management interventions can be implemented, including:

a. **Increasing the minimum catch size:** The minimum legal catch size should be raised slightly above the current length-at-first-capture (Lc), for example, to 9.5–10 cm. This measure delays harvest until individuals approach their asymptotic length ($L\infty$), allowing each recruit to contribute greater biomass before capture. Consequently, the weight per recruit increases, and the number of premature removals from the population declines.
b. **Reducing fishing effort:** Regulating the number of fishing days or limiting the number of active vessels can effectively reduce fishing mortality (F), thereby decreasing the exploitation rate (E). A reduction in effort allows the stock to grow

larger before harvest, increasing its reproductive potential and long-term productivity.

c. **Implementing closed seasons:** Introducing seasonal closures during key recruitment and early growth phases, particularly from May to July, allows recruits to reach the minimum catch size before the next fishing cycle. This timing aligns with observed peaks in larval transition to juvenile stages and ensures higher survivorship among new cohorts.
d. **Adjusting mesh size regulations:** Replacing nets of 8mm mesh sizes with larger meshes (9–10 mm) enables individuals smaller than 9cm to escape capture. This reduces juvenile mortality and increases the likelihood that these fish reach reproductive maturity. Selective gear modifications have proven effective in similar tropical small-scale fisheries.

From an economic standpoint, although fishers may need to wait longer to harvest marketable-sized fish, the increased weight per individual enhances catch value, productivity, and operational efficiency. In the long run, fewer trips may be needed to achieve comparable or even higher yields due to the healthier state of the stock. The Y/R and B/R analysis confirms that management strategies, focused solely on maximizing yield per recruit, particularly near E-max (≈0.421), pose substantial ecological risks. The biologically safer exploitation level lies around E-50 (≈0.28), where approximately 50% of the original biomass remains in the ecosystem. Maintaining E at or below this level ensures greater sustainability of the ole population. Moreover, fishers will benefit from a more stable and predictable fishery with higher long-term economic returns, as healthy stocks tend to support more consistent and valuable catches.

CONCLUSION

The ole fish population in Tomia waters exhibits rapid growth ($L\infty \approx 12.4$ cm; $K = 1.20$ year^{-1}), yet high fishing mortality ($F \approx 3.79$ year^{-1}) has led to an exploitation rate ($E \approx 0.60$) that significantly exceeds the sustainable threshold (≈ 0.28), indicating a clear case of overfishing. Most individuals are captured before reaching reproductive maturity, as evidenced by the dominance of fish in the 9– 11cm size range and the scarcity of individuals below 9cm. Peak recruitment occurs between May and July; however, continuous fishing during this period hinders effective stock replenishment. To restore population balance and ensure long-term sustainability, the following management measures are recommended: 1) Increase the minimum catch size to 9.5–10 cm (with mesh sizes ≥ 9 mm); 2) Implement a closed season from May to July, coinciding with peak recruitment; 3) Reduce fishing effort to bring the exploitation rate closer to the safe biological limit of 0.28. These actions, supported by routine length-frequency monitoring, are essential for protecting juvenile cohorts and maintaining the viability of the ole fish stock over time.

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