INTEGRATED STOCK ASSESSMENT OF GREY MULLET (*MUGIL CEPHALUS*) IN THE CROSS RIVER ESTUARY, NIGERIA

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Abstract
The grey mullet (Mugil cephalus) supports vital artisanal fisheries in West African estuaries, but sustainable management is hindered by limited quantitative stock data. This study aimed to assess growth, mortality, recruitment, and fishing pressure on M. cephalus in Nigeria's Cross River Estuary using length-frequency data collected monthly over two years (2023–2024). Von Bertalanffy growth parameters estimated an asymptotic length of 36.75 cm and a growth coefficient of 0.95 year^{-1}. Total mortality was 4.10 year^{-1}, with natural mortality at 1.66 year^{-1}, yielding a fishing mortality of 2.44 year^{-1} and an exploitation rate of 0.60, exceeding sustainable limits. Recruitment analysis revealed year-round recruitment with a distinct peak in May. Gillnet selectivity was low, allowing capture of juveniles and adults. Virtual population analysis confirmed fishing mortality well above natural mortality across size classes, with exploitation rates surpassing biological reference points (E10 = 0.355, Emax = 0.421). The evidence indicates growth overfishing and emphasizes urgent management interventions such as gear modification and seasonal closures. These results provide crucial insights for sustaining tropical estuarine mullet fisheries.
***Keywords**: Mugil cephalus*, population dynamics, exploitation rate, recruitment, fisheries management

Introduction

The grey mullet (*Mugil cephalus*) is a widely distributed fish species that supports important artisanal fisheries across tropical and subtropical estuarine systems worldwide. In West Africa and particularly Nigeria, the Cross River Estuary population constitutes a key resource for local communities, providing food security and livelihoods (Ifon, 2024). Despite its ecological and economic importance, little quantitative information exists regarding the stock status, growth dynamics, and fishing pressure on this species in the region, a knowledge gap that undermines sustainable fisheries management.

Previous studies on *Mugil cephalus* have employed classical biological and fishery assessment methods, including growth parameter estimation using the von Bertalanffy Growth Function (VBGF), mortality and exploitation rate calculations through length-based models, and recruitment pattern analysis (Pauly, 1984; Beverton & Holt, 1957). Mortality rates have traditionally been estimated from length-converted catch curves guiding assessments of overfishing risk (Pauly, 1983). However, conventional approaches tend to rely on assumptions such as steady-state populations, constant recruitment, and equal vulnerability of fish to sampling gear, which may not hold in dynamic estuarine environments. Furthermore, the separation of recruitment patterns often lacks advanced statistical rigor, frequently depending on simple decomposition rather than formalized stochastic modeling. Recruitment variability and its drivers remain underexplored in tropical estuarine fisheries (Thorson *et al*., 2015).

Virtual Population Analysis (VPA) techniques provide an alternative, computationally intensive approach that reconstructs population dynamics by cohort through time, integrating catch data and mortality estimates to better understand fishing impacts stratified by size or age classes (Hilborn & Walters, 1992). These methods, complemented by per recruit analyses, allow the calculation of reference exploitation rates such as E_{10}, E_{50}, and E_{max} that inform sustainable yield thresholds. Recent advances advocate for augmenting such stock assessment models with hierarchical and Bayesian frameworks that can incorporate environmental variability, observation error, and prior biological knowledge to improve parameter estimation and predictive capacity (Thorson *et al*., 2015).

In this study, we apply an integrated modeling approach combining classical growth and mortality estimation with modern computational techniques including length-structured VPA and recruitment pattern modeling via Gaussian decomposition using the NORMSEP algorithm. We explicitly formulate the mathematical underpinnings of these models and employ rigorous statistical inference to assess the stock status of *M. cephalus* in the Cross River Estuary. By doing so, we aim to address current gaps in understanding population dynamics in this understudied system, providing robust quantitative insights of direct relevance to fisheries management. Our methodological framework is chosen for its ability to relax some restrictive assumptions of earlier methods and to leverage all available length-frequency data for improved assessment accuracy. This approach contributes to fisheries science by demonstrating how combining established biological models with enhanced computational methodologies advances stock assessment fidelity in tropical estuarine contexts, thereby supporting more sustainable exploitation and conservation of grey mullet populations.

Materials and Methods

Study Area

This study was conducted in the Cross River Estuary, located in southeastern Nigeria, extending approximately from latitude 4°30'N to 5°45'N and longitude 8°15'E to 8°30'E (Fig. 1). The estuary opens into the Atlantic Ocean and is characterized by complex hydrological influences from the freshwater inflows of the Cross River combined with tidal exchanges from the Gulf of Guinea. Sampling took place at five representative locations (Ayadehe, Itu, Adiabo, Nsidung, and the estuary mouth) chosen to capture the full ecological and salinity gradient spanning from freshwater-dominated upstream zones through brackish mid-estuary sections to saline downstream regions. This spatial coverage ensured a thorough representation of the grey mullet population inhabiting diverse habitats within the estuary (Ifon *et al*., 2025; Asuquo & Ifon, 2024).

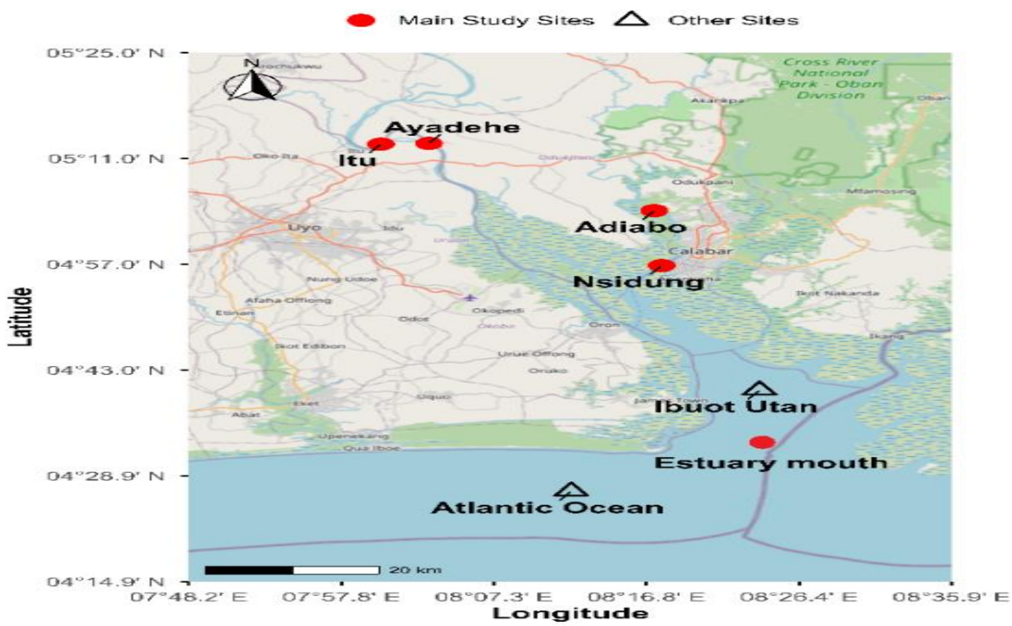

Figure 1. Map of Cross River estuary showing study sites

Fish Sampling and Data Collection

Monthly fish sampling was carried out from January 2023 through December 2024. Specimens of Mugil cephalus were collected from artisanal gillnet fisheries operating within the study sites, employing gillnets with stretched mesh sizes ranging from 25 mm to 60 mm, consistent with local fishing gear standards (Ifon, 2021). Fish were identified morphologically using the FAO field identification guides (Fischer *et al*., 1981). For each individual, total length (TL) and standard length (SL) were measured to the nearest 0.1 cm with calibrated ichthyometers, and body weight was recorded to the nearest 0.1 g using digital scales. In total, 2,146 specimens were measured, providing a substantial dataset for length-frequency analyses.

The length-frequency data were grouped into 1 cm size classes for subsequent analysis. Monthly data matrices were compiled in spreadsheet format and subjected to quality screening to exclude extreme outliers that could bias growth and mortality estimates. These datasets were then uploaded into the FiSAT II software package (FAO-ICLARM Stock Assessment Tools, version 1.2.2) for robust length-based stock assessment procedures (Gayanilo *et al*., 2005).

Growth Estimation

The von Bertalanffy Growth Function (VBGF) was used to model length-at-age according to the equation:

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

where L_t is the length at age t, L_∞ is the asymptotic length, K the growth rate coefficient, and t_0 the hypothetical age at zero length (von Bertalanffy, 1938). Growth parameters L_∞ and K were estimated using the ELEFAN I routine within FiSAT II, which applies a non-parametric scoring method on length-frequency data (Pauly & David, 1981). The quality of the fitted growth curve was visually inspected by overlaying it on monthly length-frequency histograms to ensure concordance between observed and predicted size distributions. Additionally, the growth performance index ϕ', calculated as

$$\phi' = \log_{10} K + 2\log_{10} L_\infty$$

was derived to enable comparative growth assessment relative to other mullet populations (Pauly & Munro, 1984).

Mortality Estimation

Total mortality rate (Z) was estimated by the length-converted catch curve method, which involves regressing the natural logarithm of fish abundance for descending size classes against relative age (Beverton & Holt, 1957). The length-frequency data were converted to relative ages using the estimated growth parameters. Natural mortality (M) was calculated through Pauly's empirical formula, which relates growth parameters and mean annual water temperature (T) as:

$$\log_{10} M = -0.0066 - 0.279\log_{10} L_\infty + 0.6543\log_{10} K + 0.4634\log_{10} T$$

where T is in degrees Celsius (Pauly, 1980). Fishing mortality (F) was then derived as $F = Z - M$, and the exploitation rate (E) was computed as the ratio $E = F/Z$. Confidence intervals for mortality parameters were generated within FiSAT II to assess precision.

Recruitment Pattern Analysis

Recruitment patterns were investigated using the NORMSEP routine in FiSAT II, which decomposes length-frequency data into multiple Gaussian components. This method facilitates the identification of seasonal recruitment pulses by fitting normal distributions to length cohorts, reconstructing recruitment timing and intensity throughout the sampling period (Ameh *et al.*, 2023). Recruitment curves were plotted monthly to visualize seasonal variability.

Gear selectivity estimation

The probability of capture at different lengths was estimated using the logistic selection ogive approach in FiSAT II, yielding lengths at 25%, 50%, and 75% capture probabilities (L_{25}, L_{50}, and L_{75}, respectively). Gillnet selectivity parameters were further analyzed by plotting the natural logarithm of catch ratios against fish mid-lengths, following Holt's method (1963). Selection parameters including lower and upper selection limits and mesh-related slopes were derived to characterize gear selectivity and assess the extent to which fishing gears targeted juvenile versus adult fish.

Virtual Population Analysis and Reference Points

Length-structured virtual population analysis (VPA) was conducted to estimate fishing mortality at length and assess the fishing pressure on specific size classes. VPA reconstructs cohort abundances backward through time using catch and mortality data, allowing detailed insights into exploitation impacts across the population size spectrum (Hilborn & Walters, 1992). Per recruit analyses assuming knife-edge selection were performed to calculate catch and biomass per recruit functions, generating biological reference points such as E_{10}, E_{50}, and E_{max} that signify exploitation thresholds for sustainable harvesting (Beverton & Holt, 1966). These analyses inform on how current fishing mortality compares to optimal management benchmarks, guiding recommendations for sustainable exploitation.

Ethical Considerations

All fish samples were ethically collected from commercial artisanal catches, without sacrificing live specimens for experimental purposes. Handling and processing adhered to international ethical standards, consistent with the FAO Code of Conduct for Responsible Fisheries (1995).

Results

Length-Frequency Distributions and Growth

The monthly length-frequency distributions of *Mugil cephalus* caught in the Cross River Estuary revealed a wide size range spanning from 8 cm to 35 cm across all months (Fig. 2). Modal lengths predominantly fell between 15 and 25 cm, reflecting the dominant age classes within the exploited population. Continuous recruitment was evident with cohorts present throughout the year, although modal size classes varied seasonally, indicating overlapping generations. The von Bertalanffy Growth Function (VBGF) fitted to the length-frequency data yielded an asymptotic length (L_∞) of 36.75 cm and a high growth coefficient (K) of 0.95 year^{-1}, indicating relatively fast growth in this population (Table 1). The growth performance index $\phi' = 3.11$ is consistent with fast-growing tropical estuarine fish populations.

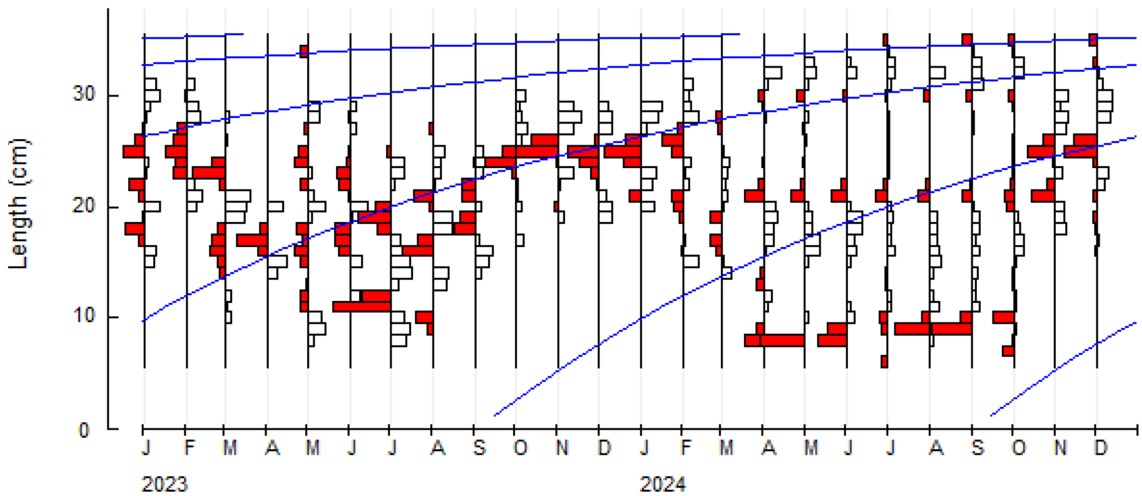

Figure 2. Grey mullet growth function and Length-frequency plot

Table 1. Estimated growth parameters of *Mugil cephalus* in the Cross River Estuary

Parameter	Estimate	Method & Notes
Asymptotic length L_∞ (cm)	36.75	Non-parametric scoring, VBGF fit
Growth coefficient K (year^{-1})	0.95	Indicates fast growth
Hypothetical age t_0 (year)	-0.12	Estimated from fit
Growth performance index ϕ'	3.11	$\log_{10} K + 2\log_{10} L_\infty$

Mortality and Exploitation Rates

Total mortality (Z) estimated through the length-converted catch curve method was 4.10 year with a 95% confidence interval from 3.17 to 5.04 (Table 2). Natural mortality (M) calculated using Pauly's empirical temperature-based formula was 1.66 year^{-1}, implying fishing mortality

$(F = Z - M)$ of 2.44 year^{-1}. The resulting exploitation rate (E) of 0.60 exceeds common biological reference points (e.g., $E_{max} = 0.42$), indicating growth overfishing and substantial fishing pressure on the stock.

Table 2. Mortality and exploitation rate estimates for *Mugil cephalus* in the Cross River Estuary

Parameter	Estimate	95% Confidence Interval	Method & notes
Total mortality rate Z (year^{-1})	4.10	3.17 – 5.04	Length-converted catch curve
Natural mortality M (year^{-1})	1.66	—	Pauly's temperature-based empirical formula
Fishing mortality (year^{-1})	2.44	—	Derived from difference
Exploitation rate	0.60	—	Indicates growth overfishing

Recruitment Patterns

Recruitment analysis using Gaussian mixture decomposition revealed continuous recruitment throughout the year with a pronounced major pulse in May (Fig. 3). This seasonal peak suggests temporal spawning or juvenile influx linked to environmental cues such as freshwater inflow or plankton availability. The protracted recruitment pattern is characteristic of tropical estuarine fish populations and supports sustained stock replenishment, albeit under considerable exploitation pressure.

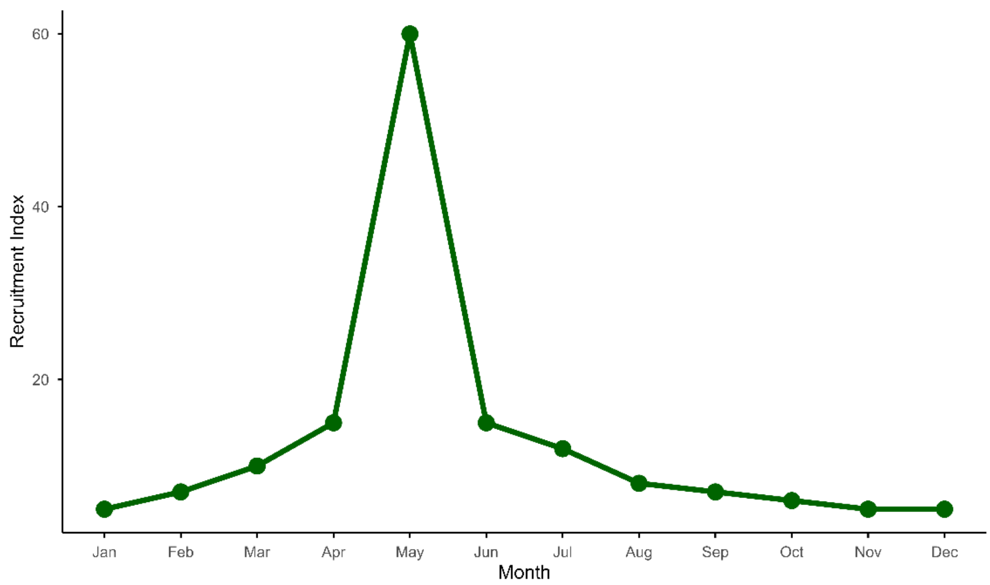

Figure 3. Monthly recruitment pattern of *Mugil cephalus* in the Cross River Estuary

Gear selectivity

Gillnet selectivity analysis demonstrated a logistic capture probability curve with lengths at 25%, 50%, and 75% capture probabilities estimated at 17.62 cm, 19.26 cm, and 20.91 cm, respectively (Table 3). The gear exhibited broad selection limits, effectively capturing both juvenile and mature fish, which likely contributes to elevated fishing mortality across multiple size classes. Mesh-related selectivity slopes further confirmed limited size discrimination by the nets (Fig. 4).

Table 3. Probability of capture and selectivity parameters of gillnet gear used in the *Mugil cephalus* fishery.

Parameter	Estimate (cm)	Method & Notes
Length at 25% probability of capture L_{25}	17.62	Logistic selection ogive
Length at 50% probability of capture L_{50}	19.26	Median effective selection length
Length at 75% probability of capture L_{75}	20.91	
Lower selection limit L_A	5.31	Gillnet selection curve parameter
Upper selection limit L_B	30.98	
Mesh-related slope m_A	6.00	Defines selection curve steepness
Mesh-related slope m_B	35.00	

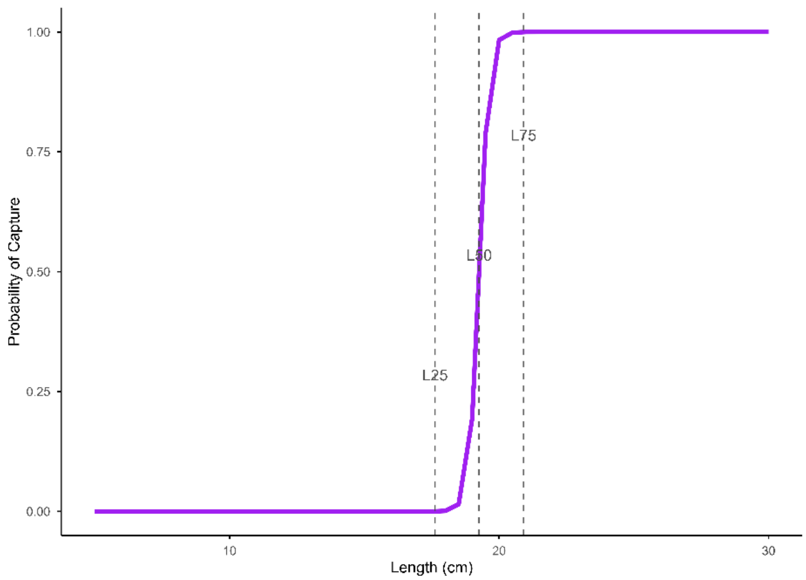

Figure 4. Gillnet gear selectivity logistic ogive curve for *Mugil cephalus* from the Cross River Estuary

Virtual population analysis and reference points

Length-structured Virtual Population Analysis (VPA) estimated fishing mortality at length (F_t) peaking at 7.5 year^{-1} for intermediate size classes, substantially exceeding natural mortality. Per recruit analyses under knife-edge selection assumptions indicated biological reference points for exploitation rates as $E_{10} = 0.355$, $E_{50} = 0.278$, and $E_{max} = 0.421$ (Table 4). The current exploitation rate of 0.60 surpasses all reference points, suggesting that the stock is subjected to unsustainable fishing pressure (Table 5). Relative yield per recruit (Y/R) and biomass per recruit (B/R) declined with increasing exploitation, further corroborating the necessity for management interventions to reduce fishing mortality (Fig. 5).

Table 4. Virtual Population Analysis (VPA) for sustainable exploitation of *Mugil cephalus*.

Parameter	Estimate	Method & Notes
Fishing mortality at length F_t	7.5 (year^{-1})	Length-structured VPA; indicates high fishing pressure
Natural mortality M (year^{-1})	1.66	Baseline from Pauly's formula
Exploitation rate at 10% yield E_{10}	0.355	Knife-edge selection model
Exploitation rate at 50% yield E_{50}	0.278	Knife-edge selection model
Exploitation rate at maximum yield E_{max}	0.421	Target reference for sustainable fishing
Relative biomass per recruit B_R	0.000 – 0.892	Range across exploitation rates
Relative yield per recruit Y_R	0.000 – 0.104	Range across exploitation rates

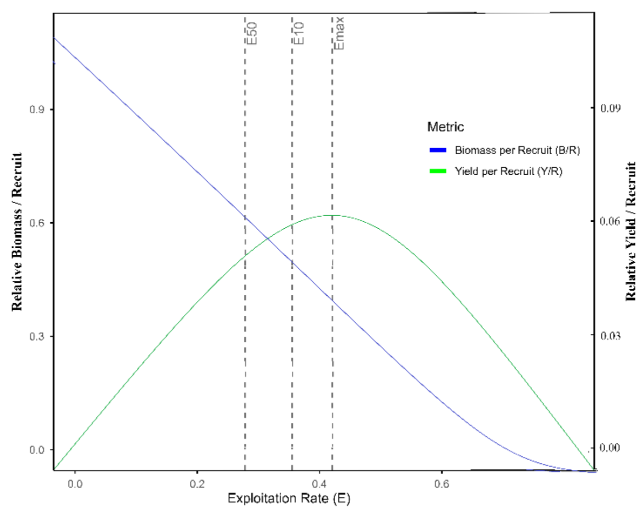

Figure 5. Per recruit analysis of *Mugil cephalus* from the Cross River Estuary

Discussion

This study provides a comprehensive assessment of the population dynamics and exploitation status of *Mugil cephalus* in the Cross River Estuary, Nigeria, using length-frequency data and advanced length-based stock assessment models. The estimated high growth coefficient (K=0.95 year^{-1}) and moderate asymptotic length ($L_\infty = 36.75$ cm) indicate that the grey mullet population exhibits rapid growth traits typical of tropical estuarine fish species, consistent with findings from other West African estuaries (Auma, 2024; Soyinka, 2015). These fast growth parameters are essential for maintaining population productivity in dynamic and often stressed tropical environments. Similar growth patterns have been reported in Kilifi Creek, Kenya (Auma, 2024), and Lagos Lagoon, Nigeria (Lawson & Jimoh, 2010), supporting the notion that tropical mullet populations compensate for environmental variability with accelerated growth rates.

The exploitation rate ($E = 0.60$) derived here exceeds biological sustainability benchmarks commonly reported for *M. cephalus* and other mullet species (Beverton & Holt, 1966; Pauly, 1980), indicating the stock is currently overfished. This exploitation rate is concordant with earlier studies on mullet populations in the Senegal River estuary, where similar concerns about growth overfishing were raised (Sarr *et al*., 2013). The total mortality rate (Z=4.10 $year^{-1}$) and fishing mortality component (F=2.44 $year^{-1}$) further corroborate high fishing pressure, aligning with regional reports of elevated fishing impacts in artisanal fisheries that often catch juveniles and adults indiscriminately (Bendjedid *et al*., 2022). Recruitment analysis in this study identified a major juvenile influx in May superimposed on continuous year-round recruitment, reflecting a protracted but seasonally peaked reproductive strategy. This pattern aligns with earlier observations in tropical estuarine mullet stocks, where environmental windows such as seasonal freshwater discharge and plankton blooms promote pulses of juvenile recruitment (Isangedighi *et al*., 2009; Soyinka, 2015). The continuity of recruitment throughout the year indicates the stock's reproductive resilience, though it may be undermined by excessive fishing mortality especially when gear selectivity is poor.

Analysis of gear selectivity demonstrated that gillnets currently in use capture a broad size range, including juveniles, underscoring its non-selectivity. This finding is supported by Holt's (1963) selectivity framework and matches reports from other tropical estuarine fisheries where mesh sizes are inadequate to protect immature individuals (Bendjedid *et al*., 2022). The capture of subadult fish before they contribute fully to reproduction exacerbates stock depletion risks and challenges sustainable management. Similar gear selectivity concerns have been documented in Nigerian fisheries (Ifon, 2021), emphasizing the urgent need for regulation. Virtual Population Analysis results show fishing mortality rates throughout vulnerable size classes greatly exceed natural mortality, an alarming insight that echoes trends seen in other artisanal tropical stocks (Hilborn & Walters, 1992). The per recruit analysis reveals that current fishing pressures surpass optimal reference points ($E_{max} = 0.421$), indicating growth overfishing. This corroborates evidence from other mullet fisheries globally where exploitation beyond biological reference points leads to diminished biomass and yields (Reis & Ate, 2020; Silva *et al*., 2017).

Conclusion

This study provides the first detailed length-based stock assessment of *Mugil cephalus* in the Cross River Estuary, revealing a fast-growing but heavily exploited population. The exploitation rate of 0.60 surpasses biological reference points, indicating growth overfishing exacerbated by non-selective gillnet gears that capture juveniles. Recruitment is continuous with a major pulse in May, highlighting critical periods for protection. Virtual population analysis emphasizes the urgent need to reduce fishing mortality to sustainable levels. Implementing mesh size regulations and seasonal closures during peak recruitment would likely restore biomass and improve yield. These findings offer essential guidance for adaptive, ecosystem-based fisheries management in tropical estuarine systems, supporting both conservation and artisanal livelihoods.

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