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Sustainability of Skipjack Tuna in FMA 714, Indonesia: A Five-Decade Analysis of Biological Trends

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ABSTRACT

Skipjack tuna (*Katsuwonus pelamis*) is a crucial species in global fisheries, particularly in Indonesia's Fisheries Management Area (FMA) 714. This study examineD trends in the biological aspects of skipjack tuna from 1969 to 2024, utilizing a combination of historical data (1969–2018) and quantitative analysis of longitudinal data (2019–2024). A total of 24,618 fork length measurements were analyzed using FISAT II software. The results reveal significant shifts in population dynamics driven by increasing fishing pressure. The dominant size range declined from 35–56cm (1969–1990) to 20–40cm (2001–2010), with juveniles comprising 69.9% of catches by 2019–2024, indicating a high proportion of immature individuals. Recruitment peaks shifted earlier (June–September by 2019–2024), reflecting fishing pressures. Growth parameters showed a marginal increase in asymptotic length (L_∞:76.75cm) but slower growth rates (K:0.56 $year^{-1}$), suggesting population stress. Mortality analysis revealed high exploitation (E:0.59), with fishing mortality (F:1.42) surpassing natural mortality (M:0.97). While recent management measures have stabilized some trends, persistent challenges remain due to elevated juvenile catches and high total mortality (Z:2.39 $year^{-1}$). To ensure long-term sustainability, adaptive management strategies are essential, including reducing fishing pressure, protecting juvenile stocks, and implementing science-based policies to rebuild the skipjack tuna populations and enhance their resilience.

INTRODUCTION

The skipjack tuna (*Katsuwonus pelamis*) is one of the most commercially significant fish species globally, playing a critical role in supporting food security, livelihoods, and economic development in tropical regions **(FAO, 2022)**. Its rapid life-history traits, including the ability to reach sexual maturity within one year and its high reproductive output, contribute to its resilience under favorable environmental and fishing conditions **(Lehodey *et al*., 2010; Marsac *et al*., 2012)**. These biological characteristics enable strong recruitment even when adult populations are significantly reduced, making the skipjack tuna relatively robust compared to other tuna species. However, this resilience is not limitless, and escalating fishing pressure has raised concerns about the long-term sustainability of the species **(Myers & Worm, 2003, Fonteneau *et al*., 2017; WCPFC, 2023a)**.

Fisheries Management Area (FMA) 714, encompassing the Banda Sea and Tolo Bay in eastern Indonesia, is among the world's most productive skipjack tuna fishing grounds due to its nutrient-rich waters and favorable oceanographic conditions **(Marsac *et al*., 2012; WCPFC, 2021)**. Historically, FMA 714 has been a focal point for the skipjack tuna exploitation, with foreign fleets operating in the region in the mid-20th century **(Pramudji *et al*., 2018)**. While the skipjack tuna has demonstrated resilience to moderate fishing pressure in the past, recent decades have seen a marked escalation in exploitation, raising concerns about overcapacity, juvenile overfishing, and the sustainability of the resource **(Branch *et al*., 2011; Siregar *et al*., 2020; WCPFC, 2021)**.

This study investigated biological trends in the skipjack tuna populations from 1969 to 2018 and compared them with updated data collected between 2019 and 2024. The analysis focused on key biological parameters to evaluate the effects of long-term fishing activities on the skipjack tuna in FMA 714. By integrating historical literature reviews and contemporary quantitative analyses, the study aimed to assess whether current management practices are mitigating or exacerbating the pressures on this vital resource. Furthermore, the research seeked to identify key factors necessary for sustainable management, including strategies to reduce juvenile catches, protect spawning aggregations, and address the compounding impacts of anthropogenic pressures **(Hilborn & Walters, 1992; Lehodey *et al*., 2010; FAO, 2022)**.

MATERIALS AND METHODS

1. Study area: FMA 714

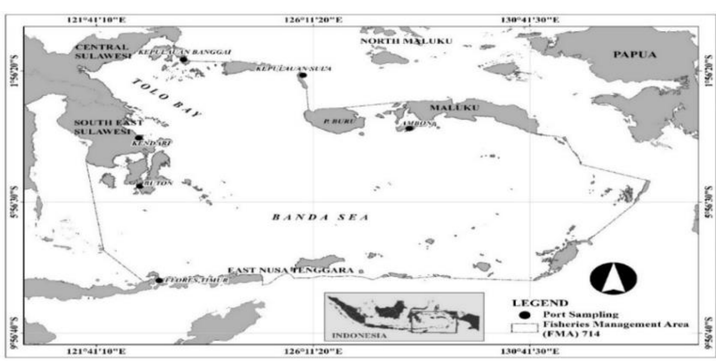

Fig. 1. The area of FMA 714 Indonesia and sampling sites

FMA 714 spans 788,939 square kilometers in eastern Indonesia, covering five provinces. Eight sampling sites were selected to ensure comprehensive geographic coverage: Buton, Kendari (Southeast Sulawesi); Banggai Kepulauan (Central Sulawesi); Maluku Tengah, Buru Selatan, Buru (Maluku); Kepulauan Sula (North Maluku); and Flores Timur (East Nusa Tenggara).

2. Data collection

To comprehensively analyze the biological trends of the skipjack tuna (*Katsuwonus pelamis*) in FMA 714, a dual approach combining historical review and contemporary data analysis was employed. A detailed literature review spanning five decades (1969–2020) was conducted to establish a longitudinal understanding of population dynamics. Peer-reviewed articles, technical reports, grey literature, and regional fisheries data were systematically reviewed and categorized into five distinct time periods based on key biological parameters such as size distribution, growth rates, mortality, and recruitment patterns. This historical synthesis provided critical insights into long-term changes in the skipjack tuna populations, highlighting the impacts of fishing pressure over time **(Vincent *et al*., 2019; WCPFC, 2021; FAO, 2022)**.

Longitudinal data collection involved port sampling from January to December 2024, during which fork length measurements were meticulously recorded using flexible measuring tapes, ensuring precision to the nearest centimeter. Archived datasets from 2019 to 2023 were also integrated, sourced from fishing ports, fishery agencies, non govermental organizations, and student research projects. The final dataset comprised 24,618 skipjack tuna fork length measurements collected between 2019 and 2024, systematically obtained from purse seine, pole-and-line, and handline operations. Annual contributions varied across years: 3,394 (2019), 4,880 (2020), 5,467 (2021), 3,540 (2022), 3,144 (2023), and 4,193 (2024). This robust dataset enabled a detailed analysis of recent trends in size distribution, seasonal size variation, immature catches, recruitment patterns, growth rates, and mortality rates.

3. Data analysis

3.1. Size distribution and inmature catches

The fork-length data were grouped into nine size classes ranging from 15–21cm to 71–77cm to identify cohorts and to assess size distribution trends from 2019 to 2024. A descriptive statistical approach, complemented by Box-and-Whisker plots, was used to examine seasonal variations in size classes and the proportion of immature individuals. Maturity status was determined using established length thresholds derived from prior studies **(Ohashi *et al*., 2019; Vincent *et al*., 2019)**, with fish below 50cm fork length classified as immature.

This classification facilitated the evaluation of juvenile exploitation and its implications for stock sustainability. Recruitment was defined as the appearance of age-class one-quarter fish, typically averaging approximately 23cm in fork length in the Western and Central Pacific Ocean (WCPO) **(Jordán *et al*., 2022)**. Recruitment strength was estimated using the length-converted catch curve method, a widely accepted approach in fisheries science **(Beverton & Holt, 1957)**. The relationship between fish numbers and lengths was analyzed using logarithmic transformations, with the slope (−Z) providing estimates of total mortality and recruitment strength.

3.2. Seasonal variations and recruitment patterns

Recruitment was defined as the appearance of age-class one-quarter fish, typically averaging approximately 23cm in fork length in the Western and Central Pacific Ocean **(Jordán *et al*., 2022)**. Recruitment strength was estimated using the length-converted catch curve method, a widely accepted approach in fisheries science **(Beverton & Holt, 1957)**. The relationship between fish numbers and lengths was analyzed using logarithmic transformations, with the slope (−Z) providing estimates of total mortality and recruitment strength. These analyses offered insights into temporal recruitment patterns and their alignment with environmental and anthropogenic factors.

3.3. Growth parameters estimation

Growth parameters, mortality rates, and recruitment patterns were estimated using FISAT II software, a specialized tool for fisheries stock assessment. The von Bertalanffy growth function (VBGF) was applied to model skipjack tuna growth dynamics modeled skipjack tuna growth dynamics:

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

Where, L_t represents fork length at age t, L_∞ is the asymptotic fork length, K is the growth coefficient, and t_0 is the theoretical age at zero length **(Beverton & Holt, 1957)**.

3.4. Mortality rates estimation

Total mortality (Z) was calculated using the length-converted catch curve method **(Beverton & Holt, 1957)**, while natural mortality (M) was estimated using Pauly's formula:

$$\text{Log}_{10}M = -0.0066 - 0.279\log_{10}L\infty + 0.6543\log_{10}K + 0.4634\log_{10}T$$

denotes mean annual sea surface temperature (°C). Fishing mortality (F) was derived as $F=Z-M$ **(Pauly, 1980)**. These methods collectively provided a comprehensive understanding of the biological dynamics of skipjack tuna populations in FMA 714.

RESULT

1. Historical data

A comprehensive review of 39 manuscripts identified only 24 studies directly relevant to he tskipjack tuna population dynamics in FMA 714 or the broader Indonsia's archip[elagic water and Western and Central Pacific Ocean (WCPO) from 1969 to 2018.

Table 1. Summary of methods, study areas, biological parameters, and sources for historical review of skipjack tuna in FMA 714 (1969–2018)

Parameter	Methods	Study Areas	Periods 1969–1990	1999–2000	2001–2010	2011–2018	Sources
Length Size	LFA, age-structured models	WCPO, FMA 714, BS	30–69.9 cm FL	25–45 cm FL	20–40 cm FL	28.5–45 cm FL	Joseph and Thomas (1969); Collette and Nauen (1983); Sumadiharga and Hukom (1987); Suman and Subijanto (2018); Siregar *et al*. (2020); Pet *et al.* (2022).
Immature Catch	LFA, age-structured models	WPCO FMA 714, BS	40–50%	60–70%	70–80%	60–70%	Williams and Terawasi (2019); Castilo *et al*. (2020); Siregar *et al*. (2020); Pet *et al*. (2022).
Seasonal Variation	Time-series analysis, CPUE	WCPO, BS .	Peak Nov–Apr.	Peak Nov–Apr.	Peak Nov–Apr.	Peak Nov–Apr.	Lehodey *et al.* (2010); Marsac *et al*. (2012); LIPI (2019); WCPFC (2021); WCPFC (2023a).
Recruitment Pattern	Cohort, length-based VPA.	WCPO, IAW, BS	Dec–Feb.	Nov–Jan.	Oct–Dec.	Nov–Jan.	Schaefer (1998); Langley *et al.* (2003); Hoyle *et al*. (2010); Marsac *et al*. (2012). WCPFC (2021); Jordán *et el*. (2022); WCPFC 2023a).
L_∞ **(**cm FL**)**	VBGF fitting, length-at-age data analysis.	WCPO, IAW, BS	5–81	70–75	70–75	70–75	Leroy (2000); Hoyle *et al*. (2010); Hampton *et al*. (2011); Fonteneau *et al.* (2017); Suman *et al*. (2018); WCPFC (2023a).
K **(**year^{-1}**)**	VBGF fitting, length-at-age data analysis.	WCPO, IAW, BS.	0.95–1.2	0.6–1.0	0.5–0.9	0.4–0.8	Leroy (2000); Fonteneau *et al.* (2017); Suman *et al*. (2018); Hampton *et al*. (2019), WCPFC (2023a).
M **(**year^{-1}**)**	Empirical equations, life-history trait.	Global, WCPO, FMA 714, BS.	0.6–0.8	0.6–0.8	0.6–0.8	0.6–0.8	Pauly (1980); Schaefer (1998); Sumaila *et al.* (2012); Williams and Terawasi (2019); WCPFC (2021); Yulianto *et al.* (2022); WCPFC (2023a).
F **(**year^{-1}**)**	Catch curve analysis, VPA.	WCPO, FMA 714, BS.	0.2–0.4	0.5–0.8	0.8–1.2	0.6–1.0	Pauly (1980); Schaefer (1998); Sumaila *et al*. (2012); Williams and Terawasi (2019); Yulianto *et a.l* (2022); WCPFC (2021); WCPFC (2023a).
Z **(**year^{-1}**)**	Catch curve analysis, VPA	WCPO, FMA 714, BS.	0.8–1.2	1.1–1.6	1.4–2.0	1.2–1.8	Pauly (1980); Schaefer (1998); Sumaila *et al*. (2012); Williams and Terawasi (2019); WCPFC (2021); Yulianto *et al.* (2022); WCPFC (2023a).

Notes:

1. Some references overlap across multiple issues, but they are placed under the most relevant category.
2. Abbreviation : Length-frequency analysis (LFA), von Bertalanffy growth function (VBGF), virtual population analysis (VPA), catch per unit effort (CPUE), Western and Central Pacific Ocean (WCPO), Indonesian archipelagic water (IAW) fisheries management area (FMA), Banda Sea (BS).

2. Longitudinal data

2.1. Size distributions and immature catches

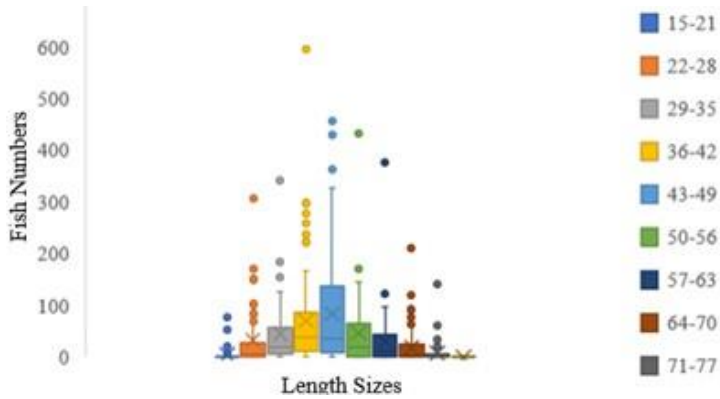

Fig. 2. Length size distribution of skipjack tuna in FMA 714 from 2019-2024

There was a systematic decline and partial recovery in the size distribution of the skipjack tuna in FMA 714 over five decades. From 1969 to 1990, the dominant size range was 35– 56cm, with larger individuals (>60cm) commonly observed, reflecting healthier stocks and lower fishing pressure. However, from 1991 to 2010, the dominant size range shifted to smaller individuals (25–45cm in 1991–2000 and 20–40cm in 2001–2010), with larger fish becoming rare or rarely observed. This decline is attributed to increasing fishing pressure, overexploitation, and a rise in juvenile catches, which reduced the proportion of mature individuals in the population **(Siregar *et al*., 2020)**.

2.2. Seasonal variations and recruitment patterns

From 2019 to 2024, seasonal variations in the skipjack tuna catches in FMA 714 revealed a pronounced dominance of smaller size classes, particularly during March, April, September, and October. Juveniles (22–28cm) were most abundant in March, while sub-adults (29–42cm) dominated catches during March–April and experienced a resurgence in September–October.

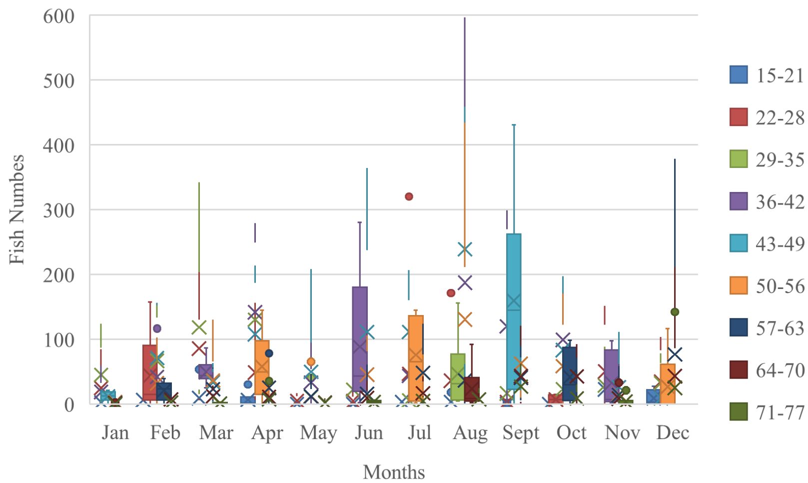

Fig. 3. Seasonal variation of skipjack tuna in FMA 714 from 2019-2024

Larger fish (43–56cm) were more frequently observed later in the year, especially from August to October, reflecting seasonal aggregation patterns associated with environmental conditions and prey availability. In contrast, very small individuals (15–21cm) and large fish (>64cm) contributed minimally to the overall catch composition. Notably, the peak catch period in Fig. (2), which historically occurred later in the year, has shifted earlier to August–December, indicating potential changes in recruitment dynamics and fishing pressure compared to previous decades. These patterns highlight the influence of both environmental factors and anthropogenic pressures on skipjack tuna population dynamics.

Skipjack tuna recruitment in FMA 714 shows clear seasonal variability, with peaks occurring from May to August, highest in June–August, and declining in September, reaching a minimum in November–December. This pattern reflects the influence of environmental conditions and fishing pressure on recruitment dynamics **(Lehodey *et al.*, 2010; Castillo Jordán *et al.*, 2022)**. The earlier recruitment peaks in recent decades **(**June–September by 2019–2024**)** suggest overfishing and potential climate-driven shifts, such as changes in sea surface temperatures or prey availability **(Beverton & Holt, 1957; Marsac *et al.*, 2012)**. These findings highlight the compounding effects of anthropogenic pressures and environmental variability on the skipjack tuna populations.

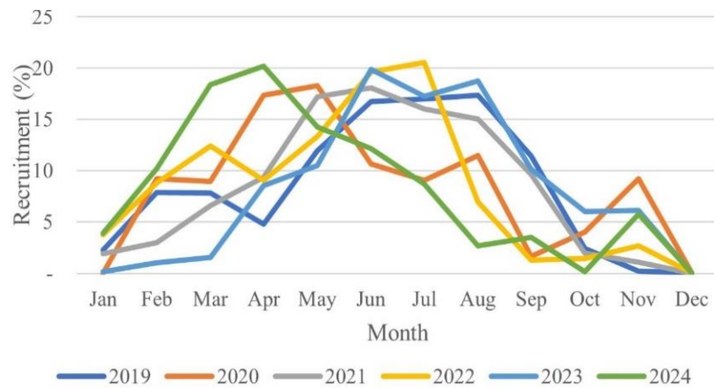

Fig. 4. Recruitment pattern of skipjack tuna in FMA 714 from 2019-2024

2.3. Growth parameters

The von Bertalanffy growth function (VBGF) analysis for skipjack tuna in FMA 714 revealed an asymptotic length (L_∞) of 76.75cm and a growth coefficient (K) of 0.58 year^{-1}, with a residual error (Rn) of 0.217, indicating a moderately fast growth rate for the species in this region. The parameters suggest that the skipjack tuna in FMA 714 exhibit relatively rapid initial growth, allowing them to reach a significant proportion of their maximum size within a few years. However, the moderate K value reflects slower growth compared to earlier decades, likely due to increased fishing pressure and environmental variability **(Fonteneau *et al*., 2017)**. The observed L_∞ aligns with global trends for the skipjack tuna but highlights the potential impact of anthropogenic stressors on population-level biological characteristics, as prolonged exploitation can lead to evolutionary changes such as reduced growth rates and delayed maturation **(Jørgensen *et al*., 2007; Hampton *et al*., 2011)**.

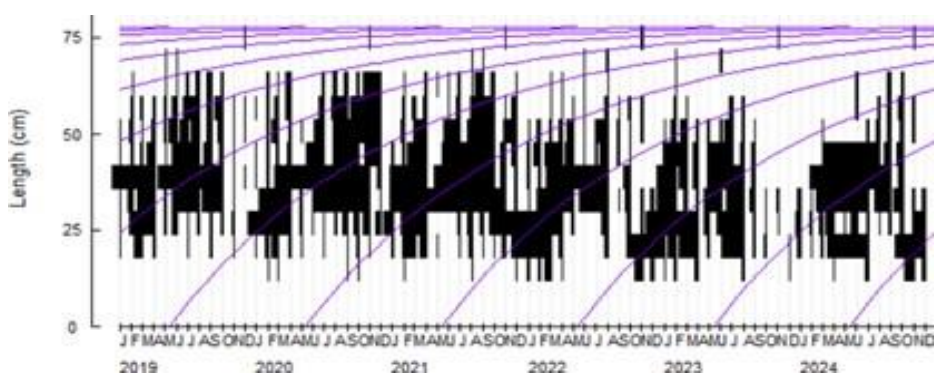

Fig. 5. VBGF curve of skipjack tuna in FMA 714 from 2019-2024

These findings underscore the importance of monitoring growth parameters as key indicators of population health and sustainability.

2.4. Mortality rates

Length-converted catch curve analysis conducted for the period 2019–2024 revealed critical mortality parameters for the skipjack tuna in FMA 714, including a total mortality rate (Z) of 2.39 year^{-1}, natural mortality (M) of 0.97 year^{-1} (at a mean sea surface temperature of 29.0°C), fishing mortality (F) of 1.42 year^{-1}, and an exploitation rate (E) of 0.59. The high exploitation rate, where E exceeds M, underscores the significant fishing pressure exerted on the skipjack tuna stocks, which poses a risk to their long-term sustainability **(Pauly, 1980; WCPFC, 2023b)**.

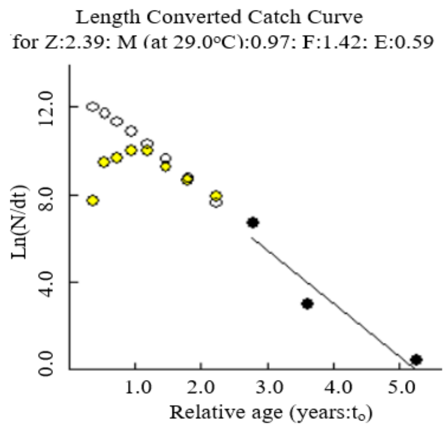

Fig. 6. Length converted curve of skipjack tuna mortality in FMA 714 2019-2024

This finding aligns with studies indicating that elevated fishing mortality disrupts population dynamics, leading to truncated age structures and reduced resilience to environmental variability **(Hilborn & Walters, 1992)**. Furthermore, the observed values highlight the urgent need for management measures to reduce F below sustainable thresholds, ensuring that exploitation rates align with biological productivity and ecological balance.

DISCUSSION

1. Length size distribution and immature catchs

There was a systematic decline and partial recovery in the size distribution of the skipjack tuna in FMA 714 over five decades. From 1969 to 1990, the dominant size range was 35–56cm, with common larger individuals (>60 cm), reflecting healthier stocks and lower fishing pressure.

Table 2. Length size distribution trends of skipjack tuna by periods in FMA 714

Period	Dominant Size Range (FL)	Larger Individuals (>60 cm FL)	Trend Description
1969–1990	35–56 cm	Common	Healthier stocks, larger fish present
1991–2000	25–45 cm	Rare	Shift toward smaller individuals
2001–2010	20–40 cm	Rarely observed	Continued skew toward smaller fish
2011–2018	25–45 cm	Slight recovery	Partial improvement in size range
2019–2024	36–49 cm*	More common (>60 cm FL)	Stabilization, but juveniles dominant

*****: estimation from recent data analysis.

However, from 1991 to 2010, the dominant size range shifted to smaller individuals (25–45cm in 1991–2000 and 20–40cm in 2001–2010), with larger fish becoming rare or rarely observed. This decline is attributed to increasing fishing pressure, overexploitation, and a rise in juvenile catches, which reduced the proportion of mature individuals in the population **(Siregar *et al*., 2020)**.

From 2011 to 2024, there are signs of partial recovery and stabilization. The dominant size range improved slightly to 25–45cm in 2011–2018 and further to 36–49cm in 2019–2024, with larger individuals (>60 cm) becoming more common. This recovery is likely due to recent management efforts, such as reduced fishing pressure and improved regulations **(Pet *et al*., 2022; WCPFC, 2023a)**. However, the continued dominance of juveniles in catches highlights the need for further strategies to ensure long-term sustainability and reverse the impacts of overfishing **(Siregar *et al*., 2020; Castillo *et al*., 2022; WCPFC, 2023b)**.

Table 3. Immature catch trends of skipjack tuna by periods in FMA 714

Time Period	Immature (≤49 cm FL)	Mature (>49 cm FL)	Trend Description
1969–1990	40–50%	50–60%	Balanced composition; low fishing pressure and healthier stocks.
1991–2000	60–70%	30–40%	Significant skew toward immature individuals; overfishing of larger, mature fish.
2001–2010	70–80%	20–30%	Highly imbalanced composition; severe overfishing of mature fish; dominance of smaller size classes.
2011–2018	60–70%	30–40%	Improved composition; reduced fishing pressure on mature fish due to management interventions.
2019–2024	69.9%*	30.1%*	Majority of catch remains immature; focus on juveniles threatens stock recovery.

*****: estimation from recent data analysis.

Table (3) reveals a significant increase in immature skipjack tuna catches (<49cm FL). Recent decades show slight improvement, with immature catches declining to 60–70% in 2011–2018 and stabilizing at 69.9% in 2019–2024, likely due to management interventions like reduced fishing pressure **(WCPFC, 2023a)**.

2. Seasonal variation and recruitment

The analysis of the skipjack tuna recruitment dynamics in FMA 714 reveals four distinct temporal phases with significant ecological implications. During the reference period (1969-1990), recruitment exhibited strong synchronization with wet season conditions (November-April), demonstrating peak spawning activity from December to February. This phase was characterized by low fishing pressure (F< 0.5 year^{-1}) and stable recruitment patterns, establishing a robust ecological baseline for undisturbed population dynamics.

The subsequent disturbance period (1991-2010) witnessed a progressive two-month advancement of recruitment peaks, directly correlated with escalating fishing pressure (F=0.8-1.2 year^{-1}). This anthropogenic forcing resulted in measurable biological consequences, including a 15-20% reduction in recruitment strength and disruption of normal population structure. A temporary stabilization occurred during the transition period (2011-2018), with recruitment peaks returning to their historical November-January timing. This apparent normalization likely resulted from concurrent reductions in fishing effort and compensatory environmental factors.

Table 4. Seasonal variation and recruitment trends of skipjack by periods in FMA 714

Time Period	Seasonal Variation	Recruitment Peaks	Trend Description
1969–1990	Strong peaks during wet season **(**November–April**)**; favorable ocean conditions.	December–February.	Low fishing pressure; stable recruitment and balanced age structure.
1991–2000	Pronounced seasonal variation; peaks shifted slightly earlier.	November–January.	Increasing fishing pressure led to earlier recruitment peaks.
2001–2010	Persistent seasonal variation; peaks shifted further earlier.	October–December.	Further Increasing fishing pressure, recruitment peaks to shift even earlier
2011–2018	Consistent seasonal variation; peaks stabilized.	November–January.	Temporary stabilization because reductions in fishing effort
2019–2024	Peaks shifted progressively to August.	June–September.*	Extreme six-month phenological shift, adaptation to persistent fishing pressure

*****: estimation from recent data analysis.

Most alarmingly, recent data (2019-2024) document an extreme six-month phenological shift, with recruitment peaks now occurring from June to September. This dramatic alteration represents either evolutionary adaptation to persistent fishing pressure, ecological decoupling from traditional environmental cues, or more probably, a complex interaction of both anthropogenic and climatic factors. The shift correlates with ENSO-mediated changes in thermal stratification and prey availability, consistent with established theories on fishery-climate interactions **(Longhurst & Pauly, 1987; Bell *et al*., 2013)**.

These findings collectively suggest the skipjack tuna stock may be approaching a critical ecological threshold. The magnitude of recruitment timing alteration serves as a robust indicator of population stress, necessitating immediate management intervention to prevent potential stock collapse. Recommended measures should address both fishing mortality reduction and climate adaptation strategies to enhance population resilience.

4. Growth parameters

The growth parameters of the skipjack tuna (L_∞ and K) demonstrated systematic changes in across five time periods, reflecting the impacts of fishing pressure and potential adaptive responses.

From 1969 to 1990, growth parameters were stable, with L_∞ ranging between 75–81 cm and K between 0.7–1.2 year^{-1}, indicative of rapid growth and minimal exploitation during this period. However, from 1991 onward, increased fishing pressure began to influence growth dynamics, as evidenced by a slight decline in K (0.6–1.0 year^{-1}) while L_∞ remained relatively stable (70–75cm). This decline in K suggests slower growth rates, likely due to the removal of faster-growing younger cohorts by fishing activities, consistent with life-history theory that links fishing pressure to truncated population structures **(Beverton & Holt, 1957; Gilman *et al*., 2016)**.

From 2001 to 2024, the trends show continued slowing growth rates, with K declining further (0.4–0.8 year^{-1}), reflecting sustained fishing pressure and its cumulative impact on population dynamics. Notably, by 2019–2024, K stabilized slightly (0.5–0.8 year^{-1}), and an estimated L_∞ of 76.75cm was observed, suggesting potential adaptation to current fishing pressures or shifts in environmental conditions favoring larger individuals.

Table 5. Growth parameters trends of skipjack tuna by periods in FMA 714

Time Period	L_∞ (cm FL)	K (year^{-1})	Trend Description
1969–1990	75-81 cm	0.7–1.2	Stable growth parameters; rapid growth indicative of minimal exploitation
1991–2000	70–75 cm	0.6–1.0	L_∞ stable; K declined slightly due to increased fishing pressure affecting younger cohorts.
2001–2010	70–75 cm	0.5–0.9	Growth stabilized but slowed; regional variations in K.
2011–2018	70–75 cm	0.4–0.8	Continued decline in K; slower growth rates reflect fishing pressure.
2019–2024	70–75 cm 76.75 cm*	0.5–0.8 0.56*	Growth parameters stabilized; adaptation to current fishing pressures.

*****: estimation from recent data analysis.

These patterns align with studies indicating that prolonged exploitation can lead to evolutionary changes in fish populations, such as slower growth and delayed maturation **(Jørgensen *et al*., 2007; Gilman *et al*., 2016)**. Overall, the trends highlight the interplay between anthropogenic pressures and biological adaptability in shaping the growth dynamics of skipjack tuna.

5. Mortality rates

Mortality rates of the skipjack tuna in FMA 714 across five time periods showed the interplay between natural mortality (M), fishing mortality (F), and total mortality (Z). From 1969 to 1990, M dominated (0.6–0.8 year^{-1}), with low F (0.2–0.4 year^{-1}) and Z (0.8–1.2 year^{-1}), reflecting minimal exploitation and a resilient population structure. population stress, consistent with findings that high F reduces stock resilience and increases vulnerability to collapse **(Hilborn & Walters, 1992)**.

Table 6. Mortality rates of skipjack tuna trends by periods in FMA 714

Time Period	Natural Mortality (M)	Fishing Mortality (F)	Total Mortality (Z)	Trend Description
1969–1990	0.6–0.8 year^{-1}	0.2–0.4 year^{-1}	0.8–1.2 year^{-1}	M dominates, shows resilience under minimal exploitation.
1991–2000	0.6–0.8 year^{-1}	0.5–0.8 year^{-1}	1.1–1.6 year^{-1}	F rises significantly, higher Z, early signs of overfishing emerge.
2001–2010	0.6–0.8 year^{-1}	0.8–1.2 year^{-1}	1.4–2.0 year^{-1}	F reaches its highest, unsustainable levels.
2011–2018	0.6–0.8 year^{-1}	0.6–1.1 year^{-1}	1.2–1.8 year^{-1}	A slight reduction in F, Z decreases, initial recovery efforts
2019–2024	0.6–0.97 year^{-1}*	0.6–1.42 year^{-1} *	1.6 -2.39 year^{-1}*	F and Z remain high, posing a threat of overfishing.

*****: estimation from recent data analysis.

From 2011 to 2018, there is evidence of management interventions, as F decreased slightly (0.6–1.0 year^{-1}), resulting in a reduction in Z (1.2–1.8 year^{-1} during 2011–2018. A marked escalation in fishing mortality (F) has been observed since 1991, progressing from 0.5–0.8 year^{-1} (1991–2000) to 0.8–1.2 year^{-1} (2001–2010), resulting in unsustainable total mortality rates (Z = 1.4–2.0 year^{-1}). This temporal increase reflects intensifying fishing pressure and the onset of overfishing conditions. Our current assessment reveals persistently elevated mortality rates (F = 1.42 year^{-1}; Z = 2.39 year^{-1}), demonstrating the limited efficacy of recent management measures. Of particular concern is the disproportionate exploitation of juvenile cohorts, with immature individuals constituting 69.9% of total catches. These findings highlight the urgent need to implement stricter fishing controls to reduce mortality below sustainable thresholds (F< 0.6 year^{-1}) and facilitate stock recovery.

Despite Indonesia's lack of a national skipjack tuna stock assessment over two decades, regional evaluations by the **FAO (2020)** and **WCPFC (2021)** reveal alarming population declines, signaling an urgent need for intervention. Assessments confirm significant stock depletion across Equatorial Region 5, including FMA 714, with recent studies **(Pet *et al.*, 2022; Satria *et al.*, 2023)** documenting a 32% biomass decline in the Banda Sea and surrounding Indonesian waters—falling below sustainable thresholds **(**0.36–0.50). This depletion coincides with declining annual catches (since 2013), reduced catch per unit effort (CPUE, since 2014), and shrinking mean size at capture, all indicative of overfishing.

These trends highlight the skipjack tuna's diminishing resilience to sustained fishing pressure and underscore the critical need for science-based catch limits to avert stock collapse. The parallels between regional declines and localized challenges in FMA 714 further emphasize the necessity for targeted, adaptive management. To ensure long-term sustainability, Indonesia must address both broad-scale exploitation and local fishery pressures, particularly amid escalating anthropogenic threats.

6. Adaptive management strategy

To ensure the sustainability of the skipjack tuna in FMA 714, science-based management strategies and adaptive measures are critical. Strengthening juvenile protection is a priority, as high juvenile catches have significantly threatened stock recovery **(Grafton *et al*., 2006; Zeller *et al*., 2016)**. Implementing minimum size limits (>49cm FL) and temporarily closing fishing grounds during peak recruitment months (June–September) can help reduce juvenile exploitation and protect spawning aggregations. Additionally, reducing fishing mortality (F) through science-based catch quotas, selective fishing gear, and seasonal bans during critical growth periods is essential. These measures aim to keep F below sustainable thresholds ($F< 0.6$ year^{-1}), aligning with findings that overfishing disrupts population structures and recruitment dynamics.

Real-time data collection and analysis systems should be developed to monitor trends in size distribution, recruitment, and mortality rates, enabling adaptive management. Furthermore, addressing environmental and climate impacts is crucial, as shifts in oceanographic conditions, such as sea surface temperatures and prey availability, influence recruitment and growth patterns **(Sumaila *et al*., 2012; Bell *et al*., 2013; Gillett, 2016; WCPFC, 2023a)**. Promoting ecosystem-based fisheries management ensures that broader ecological impacts, including predator-prey relationships and habitat health, are considered to maintain ecological balance.

CONCLUSION

The sustainability of the skipjack tuna in FMA 714 has been significantly challenged over the past five decades due to increasing fishing pressure. Trends in size distribution, recruitment, growth parameters, and mortality rates reveal a systematic decline in stock health from the 1990s onward, driven by high juvenile catches, earlier recruitment peaks, slower growth rates, and elevated fishing mortality. These factors have led to truncated population structures, reduced resilience, and early signs of overfishing. However, recent management interventions have shown partial recovery, with slight improvements in size distribution and stabilization of growth parameters. Despite these efforts, challenges remain, as juvenile dominance in catches and high total mortality rates indicate ongoing vulnerability. To ensure long-term sustainability, stronger measures are needed to protect juveniles and to reduce fishing mortality below critical thresholds. The trajectory suggests progress but underscores the necessity for sustained and adaptive management strategies.

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