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Assessment of Maximum Sustainable Yield (MSY) for Octopus Fisheries in Torosiaje Village, Indonesia

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ABSTRACT

This study estimated the maximum sustainable yield (MSY) of octopus (*Octopus* spp.) in Torosiaje Village, Indonesia, to inform the sustainable management of small-scale fisheries. Primary data on catch and effort from 2021 to 2024 were collected through interviews, questionnaires, and fisher records, with local ecological knowledge (LEK) integrated to complement stock assessments. Using the Schaefer surplus production model, the MSY was estimated at 129,908 kg/year, with an optimum fishing effort (Emsy) of 172.74 standard fishermen. These results offer a biological benchmark for regulating harvest limits and fishing pressure. However, implementing MSY-based strategies entails socio-economic trade-offs that may impact fisher livelihoods. Co-management, participatory monitoring, and the integration of LEK are critical for ensuring compliance and equity. Minimum Landing Size (MLS) regulations should be supported by socio-economic measures to foster acceptance. Overall, this study highlighted the need for a holistic, community-based governance framework that balances ecological sustainability with the socio-economic resilience of small-scale fishing communities.

INTRODUCTION

Octopus (*Octopus* spp.) is a vital fishery resource for many coastal communities across Southeast Asia, particularly in Indonesia. In Torosiaje Village, Pohuwato Regency, octopus serves as a primary commodity for artisanal fishers, especially within the Bajo community. Increasing global and regional demand has intensified harvesting pressure, particularly due to the frequent capture of immature individuals before reaching reproductive maturity **(Domínguez-Contreras *et al*., 2018; Markaida *et al*., 2019; Willer *et al*., 2023)**.

The small-scale nature of these fisheries presents unique management challenges, especially for communities such as the Bajo, whose livelihoods, food security, and cultural identity are closely tied to marine resources **(Teh & Pauly, 2018; Erokhin *et al*., 2021)**. Small-scale fisheries (SSF) play a critical role in socio-economic development, contributing to employment, poverty reduction, and nutritional security **(Willer *et al*., 2023)**. Therefore, sustainable management strategies must address both ecological sustainability and economic viability.

However, despite ecological and economic significance of octopus fisheries, stock assessment data for eastern Indonesia, particularly in Torosiaje, remain largely unavailable. Scientific literature rarely addresses octopus population dynamics in this region, and few studies apply surplus production models to small-scale fisheries. This knowledge gap limits effective management and hampers policy formulation in data-poor artisanal fisheries. This study also supports global and national fisheries sustainability targets. At the international level, it aligns with Sustainable Development Goal (SDG) 14.4, which promotes the restoration of fish stocks through effective regulation. Additionally, it reflects the FAO Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries (SSF Guidelines), which emphasize inclusive, knowledge-based governance. At the national level, this research contributes to Indonesia's efforts under the Ministry of Marine Affairs and Fisheries (MMAF), including regulation No. 18/2021 on non-quota fisheries utilization, which advocates for MSY-based planning in small-scale fisheries.

Applying the maximum sustainable yield (MSY) concept in artisanal octopus fisheries introduces complex trade-offs. While MSY aims to maintain long-term stock productivity, its implementation may lead to short-term income losses due to restrictions on catch size or effort. These trade-offs must be mitigated through inclusive policies that strengthen fishers' economic resilience.

Co-management approaches have emerged as effective tools for enhancing governance and regulatory compliance. These strategies promote community ownership by engaging local fishers in decision-making and enforcement processes. For example, participatory monitoring in Madagascar's lobster fisheries resulted in a 435% increase in CPUE following the reopening of no-take zones **(Long, 2017)**. Similarly, periodic closures in Madagascar's octopus fisheries significantly improved CPUE, demonstrating the benefits of community-based conservation **(Oliver *et al*., 2015)**.

Minimum Landing Size (MLS) regulations are also critical in ensuring octopuses reach reproductive maturity before harvest. Although MLS policies can enhance recruitment and long-term income **(Nomura *et al*., 2022)**, their effectiveness depends on socio-economic conditions and perceived fairness. Regulations regarded as unjust often face low compliance **(Wallace *et al*., 2015)**.

Given the multidimensional socio-economic context of SSF including poverty, market barriers, and high dependency on marine resources management interventions must prioritize both equity and inclusivity. Inadequate enforcement and limited community participation can erode trust and undermine compliance **(Fauconnet *et al*., 2019)**. A holistic management framework is thus required, integrating biological assessments with social justice and economic support mechanisms.

The Schaefer model was selected due to its simplicity, low data requirements, and widespread application in small-scale, data-limited fisheries. While other models like Fox may account for asymptotic biomass curves, Schaefer remains robust and interpretable for fisheries like Torosiaje's, where comprehensive time-series data are not available. Accordingly, this study aimed to estimate the MSY of octopus in Torosiaje Village using the Schaefer surplus production model. The findings are intended to provide a scientific foundation for community-inclusive and ecologically sustainable fisheries policies. This study contributes to the growing body of small-scale fisheries research by providing the first empirical MSY assessment for octopus stocks in Torosiaje Village, a data-limited and previously undocumented region in eastern Indonesia. Beyond estimating MSY using the Schaefer surplus production model, this study uniquely integrates local ecological knowledge (LEK) to enrich stock assessments and contextualize management strategies. The use of multi-year primary data (2021–2024), combined with a focus on community-based co-management and socio-economic trade-offs, provides a novel framework for adapting classical biomass models to participatory and socially responsive fisheries governance.

MATERIALS AND METHODS

1. Research location

This study was conducted in Torosiaje Village, Popayato District, Pohuwato Regency, Gorontalo Province, an artisanal fishing community that relies heavily on octopus (*Octopus* spp.) as a primary fishery resource. The area is characterized by small-scale, subsistence-based fishing activities predominantly carried out by the Bajo community. Fig. (1) presents the geographic location of the study area, illustrating the village's coastal position along Tomini Bay and its proximity to productive octopus fishing grounds. This spatial context provides ecological justification for site selection and helps explain local fishing patterns and octopus abundance.

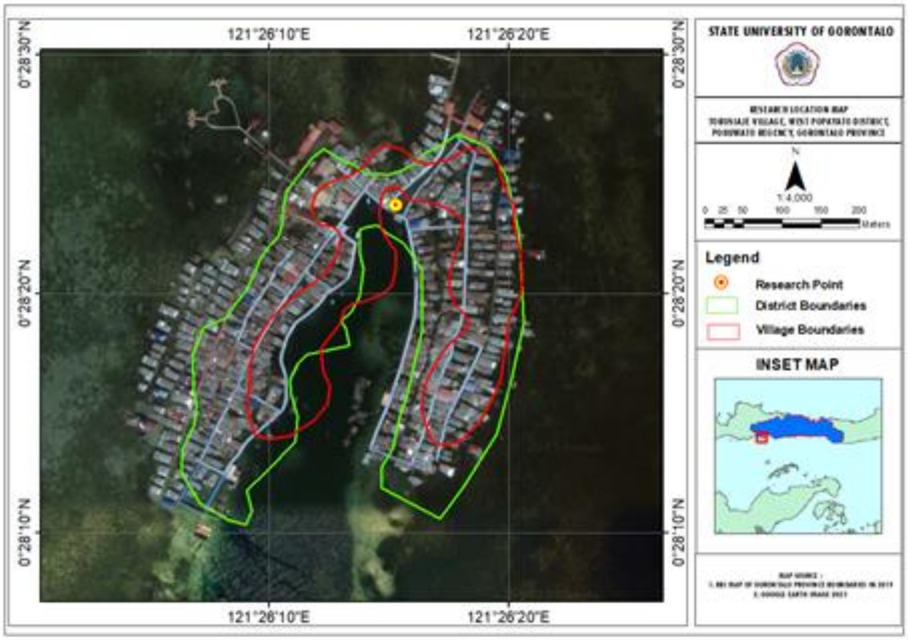

Fig. 1. Map showing the geographical location of Torosiaje Village along Tomini Bay, Gorontalo Province, Indonesia

Torosiaje was purposively selected based on its socio-economic dependence on octopus fisheries and the observed increase in fishing effort in recent years, making it a representative site for assessing sustainable management strategies in Eastern Indonesia.

2. Data collection

A mixed-methods approach was employed, combining quantitative data with qualitative insights. Fishing effort was defined as the number of “standard fishers”, which refers to active full-time fishers using handline or spear with similar gear characteristics and fishing hours (typically 5–7 hours/day, 4–5 days/week). This definition was derived from local fishing norms and verified through field observation and LEK interviews. Primary data on catch and effort were obtained directly from fisher-maintained logbooks, structured interviews, and field enumerator records from 2021 to 2024. Primary data on catch (in kilograms) and fishing effort (measured as the number of standard fishermen) were collected for the period 2021–2024 **(JAPESDA, 2025)**. These data were obtained through structured questionnaires, semi-structured interviews, and fishing logbooks maintained by local fishers.

A total of 40 stakeholders including fishers, community leaders, fisheries officers, and NGO representatives were selected using purposive sampling, based on their relevance and experience in octopus fisheries management. Secondary data were sourced from regional fisheries agencies and relevant scientific literature. Secondary data included prior CPUE records, octopus market landing reports, and gear-use statistics from the Gorontalo Fisheries Office. Adjustments were made to standardize CPUE by accounting for gear type, trip duration, and seasonal changes using correction factors derived from expert interviews and previous studies **(Jaziri *et al*., 2015; Aljafary *et al*., 2019)**. Particular attention was paid to standardizing Catch Per Unit Effort (CPUE) values to improve comparability across data sources. Potential confounding variables such as gear type, fisher behavior, and seasonal variability were controlled for during data harmonization **(Jaziri *et al*., 2015; Aljafary *et al*., 2019; Araújo *et al*., 2021)**. The multi-year dataset captures both interannual and seasonal fluctuations in stock abundance, accounting for natural recruitment cycles and fishing pressure **(Quetglas *et al*., 2015)**.

To enrich the dataset, local ecological knowledge (LEK) was incorporated through community consultations. Fishers provided insights into habitat preferences, seasonal abundance, and gear efficiency. These observations were triangulated with CPUE trends to enhance interpretive accuracy and promote community engagement in the research process **(Basurto *et al*., 2017; Avendaño *et al*., 2022)**. LEK data were collected through in-depth interviews with octopus fishing group leaders, active members, experienced fishers, and the Japesda Team. These interviews focused on habitat distribution, seasonal abundance, gear preferences, and changes in fishing grounds. While qualitative in nature, the insights were thematically coded to inform model interpretation and management decisions.

3. Data analysis

The Schaefer surplus production model was applied to estimate MSY and the corresponding optimum fishing effort (Emsy). Data analysis was conducted using Microsoft Excel and R software (version 4.2.1). Regression analysis was performed to derive the Schaefer model parameters (a and b), based on the relationship between total catch (C) and effort (E), not CPUE vs E. This ensures methodological consistency with the standard MSY formula. Model validation included visual inspection of residuals and calculation of R^2 to assess fit. This model assumes a quadratic relationship between catch and effort, where catch increases with effort up to a maximum (MSY) and then declines due to stock depletion **(Tarigan *et al*., 1970)**. The model is expressed as:

$$C = aE - bE^2$$

Where, C = catch (kg); E = effort (number of standard fishermen); a, b = parameters estimated from regression analysis.

From this, the following formulas were used:

$$MSY = \frac{a^2}{4b}, \quad E_{MSY} = \frac{a}{2b}$$

To account for uncertainty, 95% confidence intervals were calculated for the estimated parameters (a, b) and propagated into the MSY and Emsy estimates using parametric bootstrapping (n = 1000 iterations). The final values are reported with their respective confidence bounds.

CPUE values were plotted against effort to visualize the parabolic production curve, and regression analysis was used to derive model parameters and assess fit. The Schaefer model was selected for its simplicity and effectiveness in data-limited fisheries. While the Fox model may better capture nonlinear biomass dynamics, the Schaefer model remains widely used and interpretable in small-scale fisheries contexts **(Agus *et al*., 2021; Avendaño *et al*., 2022; Charbonneau *et al*., 2025)**. Although this study did not include spatial analysis, future research is encouraged to integrate geospatial mapping of fishing effort with CPUE metrics to identify localized overfishing hotspots and guide area-specific management strategies **(Wicaksono *et al*., 2023)**.

This approach emphasizes the removal of extraneous variability arising from differences in vessel power, gear type, fisher skill, and environmental fluctuations **(Bernasconi *et al*., 2015; Forrestal *et al*., 2019; Sulistyaningsih *et al*., 2020)**. Although this study relied primarily on effort-based standardization due to limited auxiliary data, vessel- and gear-related covariates were harmonized to ensure comparability across sampling years. Such standardization aligns with FAO's best-practice guidelines, which recommend adjusting nominal CPUE to reflect genuine abundance indices **(Chang *et al*., 2017)**. Future work could incorporate spatiotemporal and environmental covariates (e.g., sea surface temperature, chlorophyll) to further refine standardized CPUE, as demonstrated by **Yu *et al*. (2019)** and **Zhong *et al*. (2022)**. Although generalized linear models (GLM) or GAMs offer advanced capabilities to correct for multiple covariates, this study prioritized a parsimonious model (Schaefer) due to the limited structure and availability of historical data in the study area. Future research should explore these alternative models when longer time-series and spatial data become available.

RESULTS

1. Catch and effort trends (2021–2024)

The catch and effort data for octopus fisheries in Torosiaje Village during 2021–2024 reveal a dynamic fluctuation in harvest levels and fishing intensity (Table 1). Total annual catches ranged from 2,640 kg in 2024 to 24,900 kg in 2022, with corresponding fishing efforts between 333 and 345 standard fishers. The calculated catch per unit effort (CPUE) values showed notable variability, increasing sharply in 2022 to 74.82kg/ fisher, followed by a continuous decline to 7.65kg/ fisher in 2024. The logarithmic transformation of CPUE (ln CPUE) highlights the same downward trend, decreasing from 4.32 in 2022 to 2.03 in 2024. This pattern indicates a potential decline in stock abundance and catch efficiency, suggesting increased fishing pressure and reduced resource productivity. Table (1) presents the annual variation in catch, effort, and CPUE for octopus fisheries in Torosiaje Village during 2021–2024.

Table 1. Annual catch and effort for octopus fisheries in Torosiaje (2021–2024)

Year	Catch (C, kg)	Effort (E, Standard Fishers)	CPUE (kg/Fisher)	ln CPUE
2021	10,632	334	31.79	3.46
2022	24,900	333	74.82	4.32
2023	8,514	338	25.22	3.23
2024	2,640	345	7.65	2.03

Overall, the four-year dataset exhibits a moderate inverse relationship between fishing effort and CPUE, implying that incremental increases in effort may have led to diminishing marginal returns in catch rate.

2. Model estimation and fit

Regression analysis based on the Schaefer surplus production model produced the following relationship between catch per unit effort (CPUE) and fishing effort (E). The estimated coefficients were a= 1504.10 and b= –4.353, yielding a coefficient of determination (R^2) of 0.684. The negative b-value indicates that CPUE decreases with increasing effort, consistent with biological expectations. The relatively high R^2 demonstrates a strong correlation between fishing effort and CPUE, indicating that the model effectively represents the production dynamics of the octopus fishery. No significant autocorrelation was observed in the residuals, confirming the model's reliability for yield estimation.

3. Estimation of MSY and optimum effort (Emsy)

Using the standard equations of the Schaefer model, the optimum effort (Emsy) and maximum sustainable yield (MSY) were calculated based on the estimated parameters. The results indicate an optimum fishing effort (Emsy) of 172.74 standard fishers and a corresponding maximum sustainable yield (MSY) of 129,908kg per year. The catch–effort curve demonstrates a parabolic relationship, where yield increases proportionally with effort up to the Emsy level and subsequently declines as overexploitation occurs. These findings serve as biological benchmarks for regulating fishing pressure in Torosiaje's octopus fishery.

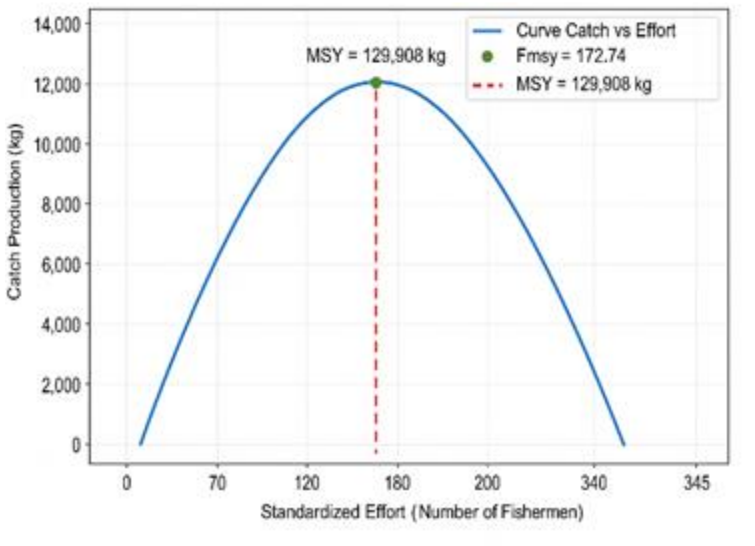

Fig. 2. Catch-effort curve for octopus fisheries in Torosiaje Village (2021–2024), based on the Schaefer surplus production model, indicating MSY and Emsy values

It is important to note that the estimated MSY of 129,908kg/ year is considerably higher than the highest recorded annual catch in the dataset (24,900kg in 2022). This gap may reflect the theoretical nature of MSY as a biological potential rather than an observed harvest, and also suggests underutilization in earlier years followed by recent overexploitation. It may also indicate limitations in data accuracy or stock variability that warrant cautious interpretation of the MSY benchmark.

The parabolic shape of the yield–effort curve confirms that octopus stocks in Torosiaje have a limited carrying capacity under the current exploitation levels. The decline in CPUE after 2022 suggests a potential biological stress on the stock, possibly resulting from increased harvesting of immature individuals or habitat degradation. Since the average current fishing effort (approximately 338 fishers) exceeds the estimated Emsy (172.74 fishers), the fishery appears to be operating under an overexploited condition. Without adaptive management, continued increases in fishing effort could further deplete stock biomass and reduce long-term productivity.

DISCUSSION

1. Biological and economic implications of MSY

The parabolic nature of the catch-effort curve illustrates the risk of exceeding sustainable effort levels, particularly in short-lived and fast-growing species such as octopus **(Leporati *et al*., 2015; Jurado-Molina *et al*., 2021)**. Despite its utility, applying MSY-based frameworks in artisanal contexts poses several challenges. One major concern is the potential for short-term income losses resulting from catch or gear restrictions. As noted by **Schacht and Voss (2023)**, sustainable fisheries management must balance biological targets with socio-economic realities to avoid compromising livelihoods.

Another critical issue is data quality. In data-limited fisheries like those in Torosiaje, historical catch and effort records are often incomplete or inconsistent, which may reduce the reliability of model outputs. Strengthening participatory monitoring and consistent data recording practices can help refine MSY estimates **(Roa-Ureta *et al*., 2021; Pirhadi *et al*., 2023)**.

Field observations and fisher interviews revealed increasing variability in octopus size and declining CPUE during peak seasons. These patterns are consistent with trends reported in other Indonesian regions such as Bone Bay and Barrang Lompo Island **(Ikhsan *et al*., 2023; Rahmatang *et al*., 2023)**, suggesting the possibility of recruitment overfishing or habitat degradation.

When fishing effort exceeds the Emsy threshold, landings tend to be dominated by smaller individuals. This not only reduces reproductive output and stock sustainability but also affects market value and income for fishers **(Pasisingi *et al*., 2023)**. In this context, MSY should be understood not only as a biological benchmark but also as an economic threshold providing guidance on the effort level that maximizes yield without undermining long-term profitability.

However, if MSY limits are imposed without adequate community engagement or compensatory mechanisms, they may be perceived as externally imposed and unfair, which can undermine compliance and policy effectiveness. Insights from LEK interviews supported these findings. Fishers reported smaller average octopus sizes and shifting preferred grounds after 2022, consistent with model indications of stock stress. Additionally, seasonal patterns described by local knowledge (i.e., peak abundance in March–May) matched observed CPUE peaks in early-year months, reinforcing the temporal relevance of effort regulation.

2. Co-management and local ecological knowledge (LEK)

Effective implementation of MSY-based regulations must be embedded within co-management frameworks. Evidence from Asturias, Spain, shows that co-managed octopus fisheries achieved greater compliance, improved monitoring systems, and enhanced fisher participation **(Pirhadi *et al*., 2023)**. Similarly, in Madagascar, community-driven seasonal closures led to increased CPUE and post-closure income **(Oliver *et al*., 2015)**. Comparable studies in other regions of Indonesia reported MSY values for octopus ranging from 45,000 to 98,000 kg/year depending on effort and habitat

(Agus *et al*., 2021; Wicaksono *et al*., 2023). The higher MSY value in this study may be influenced by localized productivity in Tomini Bay, yet further validation is needed.

Incorporating local ecological knowledge (LEK) further strengthens the adaptive capacity of fisheries governance. In Torosiaje, integration of local ecological knowledge (LEK) enhanced the accuracy of stock assessments and fostered stronger community engagement. Fishers contributed critical insights regarding habitat distribution, seasonal abundance, and gear efficiency **(Avendaño *et al*., 2022)**, which are vital for adaptive fisheries management. Successful co-management requires not only participation but also adaptive regulatory mechanisms, continuous feedback, and fair distribution of benefits **(Ainsworth *et al*., 2023)**. Without these components, co-management risks becoming symbolic rather than substantive.

Fishers' observations indicated that octopuses are increasingly found in deeper or less accessible reef zones, possibly due to disturbance in shallow habitats. Moreover, they noted a decline in octopus abundance near seagrass beds traditionally productive areas aligning with external pressures such as habitat degradation and juvenile harvesting. These qualitative insights from LEK were integrated to contextualize model outputs and guide adaptive management measures.

3. Minimum landing size (MLS) considerations

Minimum landing size (MLS) regulations are critical in ensuring that octopuses are harvested only after reaching reproductive maturity, thereby promoting long-term stock recovery. Studies have shown that MLS implementation can enhance recruitment and support future catches **(Pita *et al*., 2021)**. However, such measures may impose short-term income reductions, particularly for small-scale fishers with limited alternatives. **Monteiro *et al.* (2024)** also noted that MLS regulations targeting co-caught species may indirectly influence octopus harvests and market dynamics.

When regulations are seen as unjust, poorly communicated, or externally imposed, fishers are less likely to comply **(Wallace *et al*., 2015)**. Therefore, MLS enforcement should be accompanied by targeted education campaigns, compensation schemes, and livelihood diversification programs. In the context of Torosiaje, any MLS intervention must be tailored to the socio-economic realities of the Bajo community to ensure that sustainability goals do not come at the expense of survival.

4. Policy recommendations

The MSY and Emsy estimates derived from this study provide a quantitative foundation for sustainable and equitable octopus fisheries management in Torosiaje. However, biological reference points alone are insufficient. Effective implementation requires inclusive, community-driven governance frameworks that integrate scientific assessments with local participation and socio-economic safeguards **(Schacht & Voss, 2023)**.

Local fisheries management authorities, particularly the Department of Marine and Fisheries of Gorontalo Province should consider embedding MSY benchmarks into licensing systems, seasonal regulations, and gear restrictions. Combining LEK with scientific monitoring can improve legitimacy and adaptive capacity, while outreach and support programs are essential for ensuring compliance in resource-dependent communities. Failure to act on these insights could lead to stock depletion, income loss, and erosion of trust between stakeholders and regulators. Conversely, adaptive and participatory governance can promote long-term ecological resilience and socio-economic well-being.

To translate MSY/Emsy into actionable local policy, managers should consider regulating fishing licenses based on Emsy thresholds, limiting fishing days during peak spawning months, or piloting seasonal closures. In addition, social mitigation strategies such as compensatory schemes, alternative livelihoods (e.g., seaweed farming), and fisher cooperatives can enhance compliance and reduce economic vulnerability. Future studies should incorporate geospatial mapping of effort and habitat conditions, conduct longer time-series assessments, and test bioeconomic models that account for market dynamics and fisher behavior.

5. Study limitations

This study has several limitations. First, the reliance on fisher-reported data and limited time series introduces potential bias and restricts model robustness. Second, the lack of spatial data precludes analysis of localized overfishing hotspots. Third, MSY estimates are based on simplified assumptions of equilibrium and uniform effort, which may not fully reflect the variability of artisanal fisheries. Despite these limitations, the integration of LEK and the use of standard models provide a valuable preliminary basis for localized fisheries governance.

CONCLUSION

This study estimated the Maximum Sustainable Yield (MSY) of octopus in Torosiaje Village at 129,908 kg/year, with an optimum fishing effort (Emsy) of 172.74 standard fishermen. While the estimated MSY value (129,908 kg/year) exceeds historical catches, it reflects a theoretical maximum under optimal effort and assumes ideal conditions. The result should therefore be interpreted as a long-term biological benchmark rather than an immediate harvest target, especially given the recent declining trend in CPUE.These values provide a scientific benchmark for regulating harvest levels and fishing pressure in small-scale fisheries. However, the implementation of MSY-based strategies in artisanal contexts presents socio-economic challenges, including potential short-term income losses. To ensure effectiveness and fairness, such strategies must be supported by co-management frameworks, participatory monitoring, and the integration of local ecological knowledge (LEK).

Minimum landing size (MLS) regulations, while biologically beneficial, require complementary socio-economic measures such as community outreach and livelihood support to foster acceptance and compliance among fishers. To operationalize these findings, managers may consider limiting the number of active fishers to levels near the estimated Emsy (172.74), instituting seasonal closures during spawning months, and introducing a permit-based system that reflects sustainable effort thresholds. Ultimately, achieving sustainable octopus fisheries in coastal communities like Torosiaje demands a holistic governance approach that integrates ecological science with social equity, ensures stakeholder participation, and enhances the resilience of marine-dependent livelihoods. Future studies should integrate spatial effort mapping and socio-economic modeling to refine MSY-based management strategies in small-scale fisheries.

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