Length-based population dynamics of the horseshoe crab *Tachypleus gigas* and management implications for shrimp fisheries in Kotabaru Waters, South Kalimantan, Indonesia

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Abstract

Shrimp fisheries in Kotabaru, South Kalimantan, represent an integral part of Indonesia's small-scale coastal fishing sector, primarily operating with trammel nets. While targeting penaeid shrimp, these fisheries frequently capture non-target species such as the horseshoe crab (Tachypleus gigas), resulting in incidental bycatch. Despite their ecological significance, localized management frameworks and monitoring efforts for T. gigas populations remain insufficient, particularly in data-limited fisheries. This study assessed the stock status of T. gigas in Kotabaru waters using a length-based approach. A total of 234 individuals, representing the size fraction vulnerable to trammel nets, were sampled between December 2024 and March 2025, of which 105 females were used for gonad maturity analysis. Key biological parameters were estimated, including the length–weight relationship, length at first maturity ($L_{50} = 22.17cm$), and length at first capture ($L_c = 21.47cm$, to support a length-based spawning potential ratio (LB-SPR) analysis. Results showed that T. gigas exhibits negative allometric growth ($b = 2.33$), indicating faster increase in length relative to weight. The estimated L_c was below the L_{50}, indicating that the catch is dominated by immature individuals. The LB-SPR model estimated a spawning potential ratio (SPR) of 14%, falling below the 20% limit reference point, which indicates recruitment overfishing. These findings highlight the vulnerability of horseshoe crabs to bycatch pressure and underline the need for improved fisheries management. Recommended measures include enhancing gear selectivity, implementing seasonal closures during spawning periods, and strengthening bycatch monitoring to support sustainable shrimp fisheries in Kotabaru waters. This study demonstrates the utility of the LB-SPR framework for assessing non-target bycatch species in data-limited conditions, providing a baseline for localized conservation strategies.

Keywords: *horseshoe crab, bycatch, fisheries management, spawning potential ratio, trammel net*

Introduction

Shrimp fisheries in Kotabaru, South Kalimantan, are part of Indonesia's extensive small-scale coastal fishing sector (Tony *et al*., 2020; Harlyan *et al*., 2024). The shrimp fishery in Kotabaru represents one of the key coastal fisheries in Indonesia's Fishery Management Area (FMA) 713, contributing significantly to regional production and livelihoods. Operated primarily with traditional gear such as trammel nets, these fisheries play a critical role in supporting local communities (Harlyan *et al*., 2025). Although targeting penaeid shrimp, these operations also interact with various non-target species, resulting in considerable bycatch. One of the most frequently encountered bycatch species is the horseshoe crab (*Tachypleus gigas*), an ecologically important marine arthropod (Harlyan *et al*., 2024). Globally, *T. gigas* is listed as Data Deficient (DD) on the IUCN Red List (IUCN, 2024), yet regional assessment across its distribution range indicates severe localized population depletions due to continuous habitat degradation and fishing mortality. Empirical studies in Southeast Asian coastal waters confirm that *T. gigas* represents a dominant component of the macro-invertebrate bycatch biomass in small-scale net fisheries (Vestbo *et al*., 2018; Fauziyah *et al*., 2021).

The intensive operation of small-scale shrimp fisheries, particularly those utilizing demersal trammel nets, frequently leads to the incidental capture of non-target benthic organisms. This operational overlap creates severe conservation

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pressures on vulnerable marine fauna, most notably the horseshoe crab (*Tachypleus gigas*), which shares identical foraging habitats with target penaeid shrimps. Horseshoe crabs have been reported as bycatches in the Kotabaru shrimp fishery since the 1970s, and recent observations indicate that they remain a persistent component of trammel net fisheries in the region (Tirtadanu *et al*., 2017, 2018; Harlyan *et al*., 2024). During peak recruitment and spawning months, which coincide with the northwest monsoon, catch monitoring indicates that *T. gigas* can account for up to 10% of total landing biomass in localized estuarine fishing grounds (Gonçalves *et al*., 2008; Harlyan *et al*., 2024).

Horseshoe crabs perform essential ecological functions, including sediment bioturbation and nutrient cycling, and are recognized for their conservative life history traits—slow growth, delayed maturity, and low reproductive output (Sari *et al*., 2020). As benthic predators and bioturbators, horseshoe crabs play a critical role in structuring macrofaunal communities and altering sediment chemistry through excavation (Tanacredi *et al*., 2009). Consequently, population declines of *T. gigas* could impair these vital ecological processes, highlighting the necessity for robust population assessments to guide localized management.

Globally, horseshoe crabs are increasingly recognized as species of ecological concern, with several populations in decline due to coastal development and incidental fishing mortality (Nelson *et al*., 2016). These characteristics render them particularly susceptible to population disturbances, even when not targeted. Repeated incidental capture, without adequate monitoring or mitigation, may lead to population decline, especially in areas where fisheries operate intensively and year-round (Razak and Kassim, 2017).

Despite these ecological threats, baseline data on the population parameters of *T. gigas* remain completely absent in Kotabaru waters. This lack of localized demographic information hinders the development of effective fisheries regulations. This study directly addresses this knowledge gap by evaluating the current stock status and reproductive potential of this species in this region (Bioinspecta, 2019). Conventional stock assessment methods, typically reliant on long-term time series or age-structured data, are rarely applicable in small-scale or data-limited fisheries (Dowling *et al*., 2016; Suresh *et al*., 2022). In such cases, length-based approaches offer a practical and cost-effective alternative, and in data-poor fisheries where long-term catch-per-unit-effort (CPUE) series are unavailable, these methods provide a reliable alternative for stock evaluation (Froese *et al*., 2017). The length-based spawning potential ratio (LB-SPR) approach is particularly beneficial for *T. gigas* because it requires only size-frequency data to estimate reproductive capacity relative to an unfished state, which is suitable for monitoring data-limited bycatch species (Hordyk *et al*., 2015).

Carapace length data, readily obtainable from fishery-dependent sampling, can give clues about size distribution, population structure, and the proportion of mature individuals. These indicators are essential for assessing reproductive potential and informing conservation efforts (Fitzgerald *et al*., 2018; Bradley *et al*., 2019). Length-based methods have proven particularly useful for non-target species assessments in tropical fisheries lacking standardized monitoring systems (Barua *et al*., 2022; Xu *et al*., 2023). This approach aligns with growing efforts to assess bycatch species in data-limited tropical fisheries using length-based indicators (Shephard *et al*., 2021).

In Kotabaru, the use of carapace length as a basis for evaluating the population condition of incidentally captured horseshoe crabs represents a practical step toward evidence-based management (Zauki *et al*., 2019; Rozaini *et al*., 2023). Understanding whether the current size structure indicates a healthy spawning population is crucial for guiding future mitigation strategies and supporting ecosystem-based fishery management (Mohamad *et al*., 2019; Rozaini *et al*., 2023).

This study aims to assess the population status of horseshoe crabs (*Tachypleus gigas*) in Kotabaru waters using a length-based approach by estimating key biological parameters, including length at first maturity (L_{50}), length at first capture (L_c), and spawning potential ratio (SPR). These results are expected to provide baseline information on size structure and reproductive composition and to contribute to the development of conservation measures for horseshoe crabs. The outputs of this study provide direct empirical evidence for designing targeted bycatch mitigation strategies, such as establishing temporal spatial closures during peak spawning periods and modifying trammel net mesh sizes to minimize the capture of immature horseshoe crabs.

Materials and Methods

The coastal waters of Kotabaru support an intensive small-scale penaeid shrimp fishery which frequently interacts with *T. gigas* as incidental bycatch. These areas, located within the Pulau Laut estuarine ecosystem of South Kalimantan, are characterized by extensive mangrove-fringed coastlines, tidal mudflats, and shallow muddy-sand substrates (Tony *et al*., 2020). These conditions provide critical foraging, nursery, and spawning habitats for benthic macro-invertebrates. Therefore, this might generate spatial overlap between target penaeid shrimp and horseshoe crab (*T. gigas*) populations, indicating highly vulnerable to fishing operations.

The field survey was performed from December 2024 to March 2025 across three distinct coastal communities, Pantai Village, Sungai Pasir Village, and Salino Village (Figure 1), which represent the primary landing sites for small-scale trammel net fisheries in Kotabaru. These locations were selected due to their operational fishing grounds directly cover distribution and high-encounter zones of *T. gigas* bycatch, ensuring representative sampling of the affected stock.

Data collection

A total of 234 horseshoe crab individuals were collected during the study period. For each specimen, the carapace length (CL) was defined as the maximum straight-line distance across the widest part of the prosoma and measured using a heavy-duty caliper (precision: 0.01mm). Concurrently, the body weight (W) was recorded using a calibrated electronic digital balance (precision: 0.1 g). All biometric recording protocols followed standardized morphometric procedures for marine arthropods to minimize measurement error (King, 2007).

Sex identification and sexual maturity stage evaluation were systematically conducted by examining external dimorphic markers and reproductive anatomy. Specimens were identified as mature females based on the distinct visibility of developing vitellogenic oocytes through the semi-translucent prosomal shell and the presence of larger, unmodified terminal abdominal appendages. In contrast, males were identified by the complete absence of visible internal ova, distinct modifications of the first two pairs of walking legs into claspers, and a diagnostic triangular gonopore shape (Moreau *et al*., 2014; Fauziyah *et al*., 2021; Chan *et al*., 2022).

The gonad maturity level of the 105 individuals identified as females were further classified based on the internal egg size criteria detailed in Table 1. All biological specimens used in this study were collected from routine commercial bycatches; no live animals were intentionally sacrificed for experimentation, and thus, formal animal ethical approval was not required.

Table 1. Gonad maturity level

Stages	Female
I (Immature)	-
II (Early maturation)	Egg diameter size range between 0.3 – 0.6 mm
III (Maturation)	Egg diameter size range between 0.6 – 1.5 mm
IV (Mature)	Egg diameter range between 1.6 – 2.3 mm

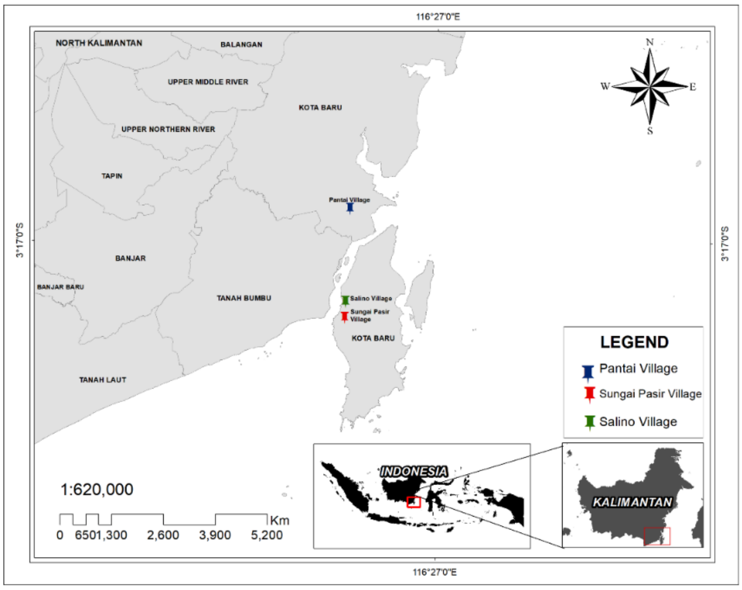

Figure 1. Kotabaru waters, South Kalimantan, Indonesia

Length-weight relationship

Concurrently, a participatory mapping survey was executed to document the spatial distribution of the trammel net fishery operations and track horseshoe crab bycatch occurrences. Structured, face-to-face interviews were conducted with 78 vessel captains utilizing local nautical charts to reconstruct their active fishing corridors based on spatial memory recall. The records gathered for each coordinate specifically represent the occurrence frequency and relative abundance (total number of individuals) of *Tachypleus gigas* captured as incidental bycatch per fishing trip. To ensure spatial accuracy and eliminate individual recall bias, the identified fishing coordinates were cross-verified using handheld Global Positioning System (GPS) devices during active field observations and cross-referenced through spatial consensus with senior fishers (Close and Hall, 2006). For the spatial analysis workflow, the validated geographic datasets were compiled, projected into the WGS 1984 UTM Zone 50S coordinate system, and imported into ArcMap 10.3 software to digitize 45 discrete fishing grounds, allowing the visualization of primary bycatch hotspots within Kotabaru waters (da Silva Lima *et al*., 2025).

The length-weight relationship was estimated using the equation (Froese, 2006; King, 2007):

$$W = aL^b \qquad (1)$$

Where W is the body weight (g), L is the carapace length (cm), a is the intercept, and b is the allometric growth coefficient. To estimate parameters a and b, the equation was transformed into a linear regression form (Froese, 2006; King, 2007):

$$\ln W = a + b \ln L \qquad (2)$$

The growth pattern was determined by testing whether b differs significantly from 3 using a t-test (Froese, 2006; King, 2007):

$$t_{test} = \frac{b - 3}{SE_b} \qquad (3)$$

Where SE_b is the standard error of b. If $b = 3$, growth is isometric; $b < 3$, growth is negative allometric; and if $b > 3$, growth is positive allometric. A negative allometry defines a condition where length increases more rapidly than weight; conversely, a positive allometry denotes a condition where weight increases more rapidly than length (King, 2007).

Length at first maturity (L_{50})

The length at first maturity (L_{50}), defined as the length at which 50% of individuals are sexually mature, was estimated using a logistic regression model (King, 2007):

$$P = \frac{1}{\left(1 + e^{-r(L - L_{50})}\right)} \qquad (4)$$

Where P is the proportion of mature individuals at length class L, L_{50} is the length at which 50% of individuals are mature, and r is the slope of the logistic curve.

The proportion of mature individuals was calculated for each length class based on gonad maturity stages, where individuals in stages III and IV were considered mature. The model was fitted using least-squares regression.

Length at first capture (L_c)

The length at first capture (L_c) defined as the length at which 50% of individuals are retained by the fishing gear, was estimated using a length-based approach derived from catch frequency data (King, 2007; Darvishi *et al*., 2018). The natural logarithm of the number of individuals in each length class ($\ln N$) was calculated and regressed against the mid-length of each class to estimate the descending limb of the catch curve. The regression model is expressed as:

$$\ln N = a - bL \qquad (5)$$

where N is the number of individuals in each length class, L is the mid-length class (cm), and a and b are regression parameters. The length at first capture (L_c) was estimated as the length corresponding to the point at which 50% of individuals are retained, derived from the fitted regression model.

Length Based Spawning Potential Ratio (LB-SPR)

The stock status of the horseshoe crab was evaluated using the length-based spawning potential ratio (LB-SPR) approach, following the empirical method developed by Hordyk *et al*. (2015). The analysis was conducted using the Barefoot Ecologist LB-SPR application (web-based tool: https://barefootecologist.com.au/lbspr), which requires length-frequency data and key life-history parameters as inputs. The parameters used in this study included the asymptotic length (L_∞), growth coefficient (K), natural mortality (M), the lengths at first maturity (L_{50}) and length at which 95% of individuals are mature (L_{95}) (Hordyk *et al*., 2015; Halim *et al*., 2020).

Growth parameters (L_∞ and K) were estimated using the von Bertalanffy growth curve (VBGF), derived through the FAO–ICLARM Stock Assessment

Tools (FISAT-II) by applying the Electronic Length Frequency Analysis I (ELEFAN I) module. Natural mortality (*M*) was estimated using the empirical formula proposed by Pauly (1980), which incorporates growth parameters and mean environmental temperature. The value of L_{50} was obtained from the logistic regression analysis, while L_{95} is estimated using the relationship as follows (Kindong *et al*., 2022):

$$L_{95} = 1.1 \times L_{50} \text{......................(6)}$$

Length-frequency data were grouped into size classes and used as input to estimate selectivity patterns and spawning potential ratio (SPR). The model outputs include the selectivity curve, maturity curve, and SPR value, which were applied to assess the exploitation status of the population.

The Spawning Potential Ratio (SPR) is expressed as a percentage, reflecting the condition of fish stocks under varying fishing pressures. An SPR of 100% indicates an unexploited or lightly exploited stock. Values below 20% signify an overexploited fishery, while values between 20% and 40% denote a moderately exploited status. An SPR greater than 40% suggests that the stock remains under-exploited (Prince *et al*., 2015).

Results and Discussion

From the total of 234 individuals collected, all specimens were used for growth and length-based analyses, while only females (n=105) were used for gonad maturity analysis. The determination of gonadal maturity was conducted based on defined maturity stages (Table 1). A total of 105 female individuals were examined for gonadal development and distributed across different maturity stages (Figure 2). Most female individuals were categorized as immature at Stage I (53%), whereas mature females were identified at Stages III and IV, calculated as 12% and 35% individuals, respectively. No specimens were observed at Stage II, which may reflect a rapid transition between maturity stages, resulting in a low probability of detecting Stage II individuals, or a sampling bias toward individuals at distinct development phases.

The absence of Stage II female *T. gigas* in the present study represents an interesting biological finding. This pattern is unlikely to indicate an interruption in ovarian development but is more plausibly explained by the timing of sampling and the reproductive cycle of *T. gigas*. Sampling was conducted from December 2024 to March 2025, coinciding with the northwest monsoon, which has been identified as the main spawning season of horseshoe crabs in western Indonesian waters (Sari *et al*., 2020; Fauziyah *et al*., 2021). During this period, adult individuals migrate to shallow estuarine habitats for spawning, and females are predominantly found in fully mature (Stage III) condition. Consequently, females in the transitional maturing stage (Stage II) are expected to occur only briefly and were likely underrepresented in the sampled population.

The absence of Stage II females may also reflect the relatively short duration of this developmental phase. Studies on horseshoe crabs and other chelicerates indicate that ovarian maturation can progress rapidly once environmental cues, such as increased rainfall and tidal fluctuations, initiate vitellogenesis (Brockmann and Smith, 2009). As a result, individuals may spend only a limited period in the intermediate maturing stage, reducing the likelihood of being encountered during periodic sampling. Sampling constraints may have further contributed to this pattern. Only 105 females were examined, all of which were obtained as bycatch from commercial trammel net operations. This sampling approach is likely to underrepresent females that have not yet joined spawning aggregations and remain in deeper offshore habitats.

In addition, gonadal maturity was determined using macroscopic characteristics, primarily based on the visibility of vitellogenic oocytes through the carapace. Females in the early stages of maturation may therefore have been classified less accurately, as subtle ovarian changes are difficult to detect without histological examination (Anderson *et al*., 2013). Taken together, these factors provide a more plausible explanation for the absence of Stage II females than a disruption in gonadal development. Instead, the predominance of mature females supports the view that the coastal waters of Kotabaru serve as an important spawning ground for *T. gigas* during the northwest monsoon.

Growth pattern estimation was carried out on 234 individuals by measuring their carapace length and weight. The relationship was described by the equation $W = 0.3455L^{2.3323}$ with a high coefficient of determination ($R^2 = 0.852$; $n = 234$) (Figure 3). To statistically verify the growth pattern, a partial t-test was performed. The statistical analysis confirmed that estimated b (2.3323) was significantly lower than isometric value of 3 $t_{test} = 4.81 > t_{table} = 1.96; p < 0.05$), definitely demonstrating a negative allometric growth pattern. This pattern indicates that length increases rapidly than weight in Kotabaru population. While this shift is often associated with environmental stressors or size-selective fishing mortality, particularly where smaller individuals dominate landings (Fauziyah *et al*., 2021; Chan *et al*., 2022). Studies from Malaysia and Brunei similarly documented negative allometry in *Tachypleus gigas* populations associated with intensive fishing pressure and habitat degradation (Razak and Kassim, 2017; Rozaini *et al*., 2023). Comparable allometric shifts were also found in *Carcinoscorpius rotundicauda* from South Sumatra, reflecting density-dependent growth compensation in disturbed estuarine habitats (Sari *et al*., 2020). Ontogenetic variations likely play a significant role, as juvenile and sub-adult horseshoe crabs show morphological shifts and carapace widening rates compared to fully mature adults. Furthermore, the high proportion of spent females (Stage IV) and immature individuals (Stage I) sampled during the northwest monsoon directly contributes to a lower average body mass relative to carapace length, as post-spawning individuals have depleted energy reserves and lack heavy, fully developed egg masses.

The estimated length at first maturity (L_{50}) for female horseshoe crabs was 22.17 cm (95%CI: 21.35-22.99 cm), derived from the logistic regression model ($\boldsymbol{R^2 = 61.94}$) (Figure 4), indicating a moderate fit of the model to the observed data. This suggests that while the model shows the general trend of maturity with increasing size, some variability remains due to biological and sampling factors.

Figure 5 illustrates the comparison between the length frequency distribution of horseshoe crabs in Kotabaru and the L_{50} value. The observed size distribution in Kotabaru, dominated by sub-adult individuals, aligns with previous reports from Peninsular Malaysia and Borneo, where frequent trammel net operations intercept juveniles migrating between foraging and spawning habitats (Zauki *et al*., 2019; Sarmiento *et al*., 2021). These findings indicate that fishing mortality affects individuals before they contribute to the reproductive pool, a condition that accelerates recruitment overfishing and reduces stock resilience (Prince Victor, *et al*., 2015; Xu *et al*., 2023).

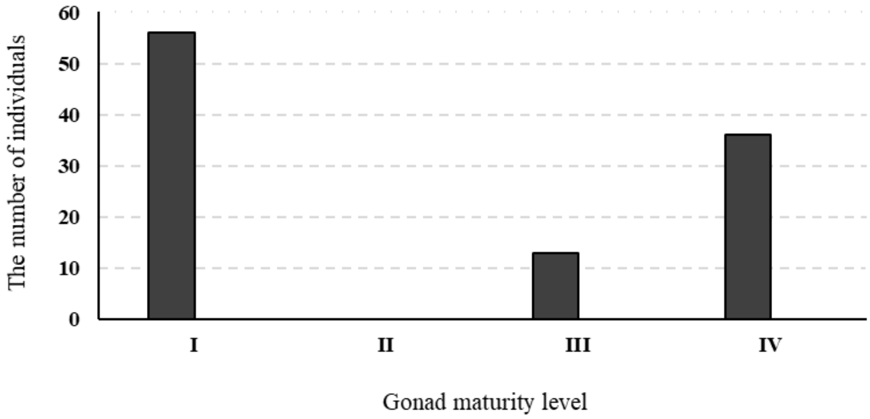

Figure 2. Gonad maturity level of *Tachypleus gigas*

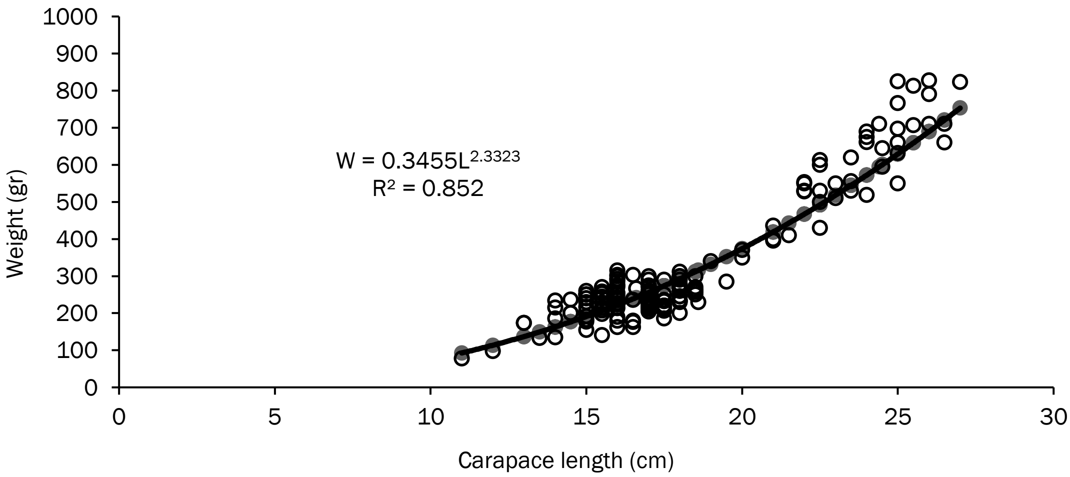

Figure 3. Length-weight relationship of horseshoe crab in Kotabaru waters shows a negative allometric growth pattern (b=2.33; R^2=0.852), where length increases faster than weight.

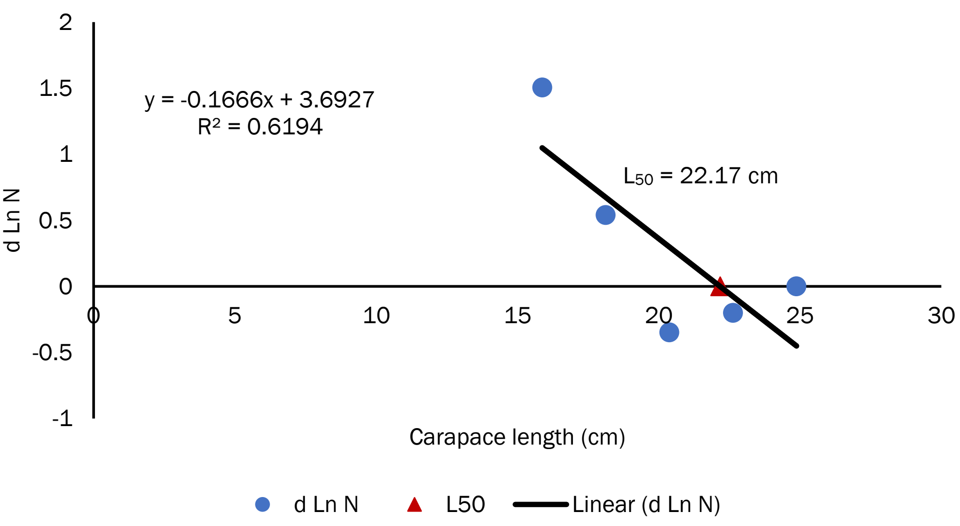

Figure 4. Logistic regression curve shows the relationship between carapace length and the proportion of mature individuals of *Tachypleus gigas* in Kotabaru waters. The estimated length at first maturity (L_{50}) is 22.17 cm, indicating the size at which 50% of individuals attain sexual maturity.

The length at first capture (L_c) is a key parameter for evaluating the exploitation status of non-target species taken as bycatch. In the shrimp fishery examined, horseshoe crabs were incidentally captured, and their L_c was estimated through regression between carapace length and successive length-class differences (Figure 6). The length at first capture (L_c) was calculated at 21.47 cm (95% CI: 20.62–22.32 cm) (Figure 6). Quantitative analysis of the size-frequency distribution revealed that 74.3% of the total individuals caught fell below the L_{50} threshold, empirically confirming that the bycatch is heavily dominated by immature sub-adults. This value of the length at first capture (L_c) is lower than the value of the length at first maturity (L_{50}), indicating that most horseshoe crabs caught as bycatch are immature individuals.

The relationship where L_c < L_{50} serves as an empirical indicator of growth overfishing (King, 2007; Barua *et al.*, 2022). Similar findings were documented for *Tachypleus gigas* in the Odisha coast, India (Behera and Chandra, 2025) and in coastal Malaysia (Nelson *et al.*, 2016), where immature individuals dominate bycatch due to non-selective gear and year-round fishing. Based on the life history of *Tachypleus gigas*, juveniles and sub-adults dominantly inhabit shallow nearshore estuarine for foraging before migrating to deeper offshore upon reaching maturity (Sari *et al.*, 2020). As a consequence, the small-scale trammel nets operation causes a high spatial overlap, capturing these immature horseshoe crabs. When these indicators are integrated with the critically low Spawning Potential Ratio (SPR = 14%), they reveal a sign of overexploitation. The fishery is experiencing a dual pressure: growth overfishing removes individuals before they can spawn ($L_c < L_{50}$), which directly drives recruitment overfishing by leaving insufficient spawning biomass (14% SPR) to rebuilding the stock.

The values of K and L_∞ for horseshoe crab were estimated using FISAT II with the ELEFAN I. Although the ELEFAN I growth parameters were derived from a relatively rapid seasonal sampling period (December 2024 – March 2025) (Figure 7). This period of sampling simply covered the peak abundance and active aggregation period of the species in Kotabaru waters, providing a highly representative of the population's length structure. The obtained goodness-of-fit score ($R_n = 0.375$) is moderate but acceptable and typical for wild marine arthropod populations. This value reflects the natural variation caused by seasonal molting (ecdysis), which creates naturally fragmented length-frequency distributions rather than continuous growth curves. The estimated M/K ratio of 2.65 is an intrinsic reflection of the evolutionary life-history strategy of *Tachypleus gigas*. As a K-selected organism with slow growth ($K = 0.3\ \mathrm{y}^{-1}$) and low natural mortality relative to growth, this high ratio indicates that the species possesses low biological resilience. It cannot rapidly compensate for additive anthropogenic mortality. Therefore, while our study did not directly quantify commercial fishing effort, the resulting 14% SPR strongly implies that even moderate, non-selective trammel net bycatch pressure is sufficient to severely deplete the spawning biomass of such a biologically fragile species.

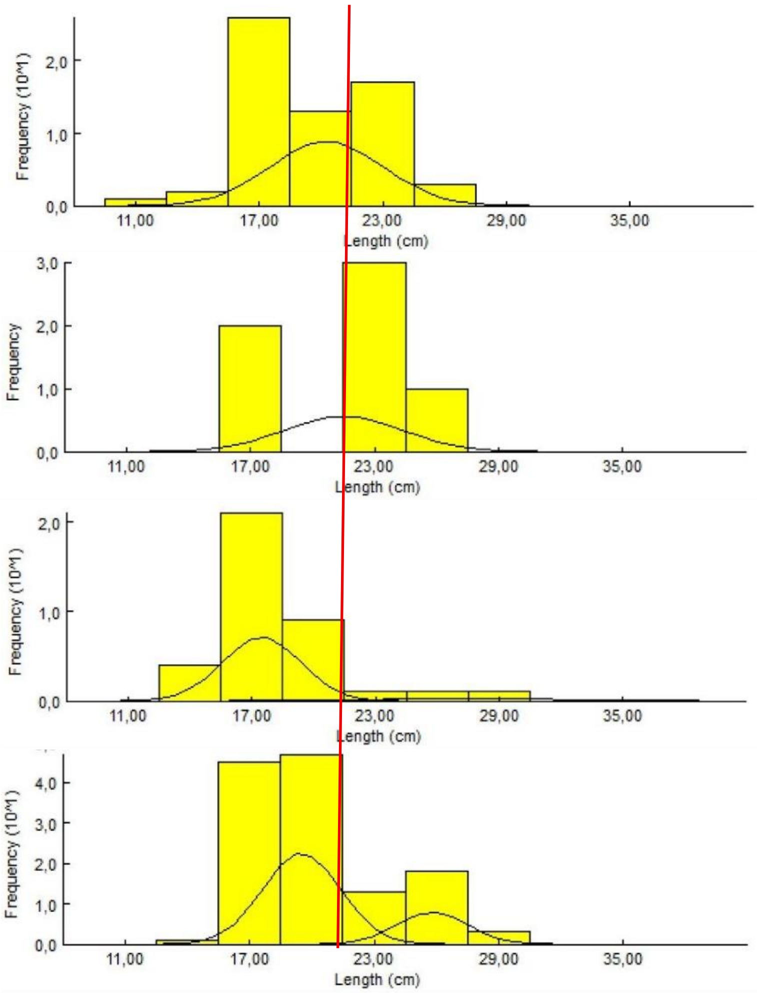

Figure 5. Length-frequency distribution of *Tachypleus gigas* in Kotabaru waters from December 2024 to March 2025. The vertical red line represents the estimated length at first maturity (L_{50} = 22.17 cm), showing that most individuals in the catch are below the maturity threshold.

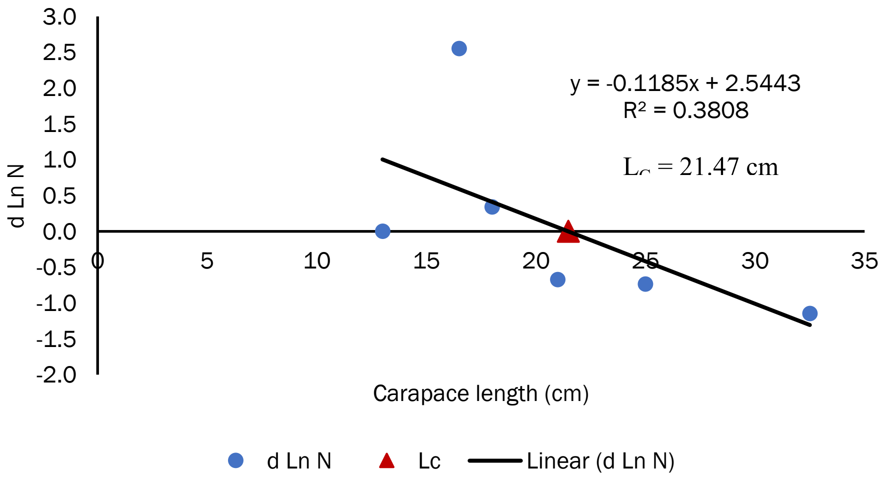

Figure 6. Estimation of length at first capture (Lc) based on the regression of ln-transformed frequency against carapace length. The estimated Lc is 21.47 cm, indicating that 50% of individuals are retained by the fishing gear at this size.

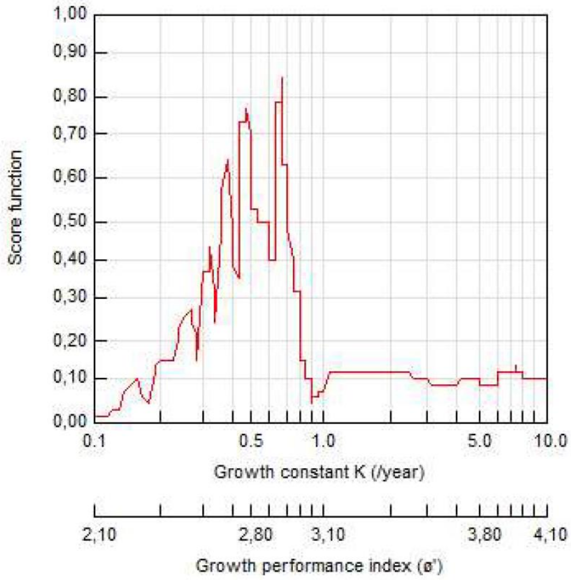

Figure 7. Von Bertalanffy Growth Function (VBGF) fitted to length-frequency data of *Tachypleus gigas* in Kotabaru waters using the ELEFAN I method. The estimated parameters are asymptotic length ($L\infty$ = 37 cm) and growth coefficient (K = 0.3 year^{-1}), indicating relatively slow growth.

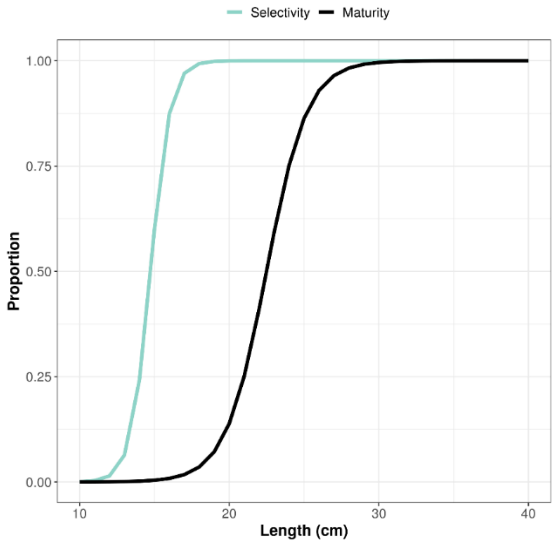

Figure 8. Gear selectivity and maturity curves of *Tachypleus gigas* derived from LB-SPR analysis. The selectivity curve lies above the maturity curve, indicating that fishing gear captures individuals before they reach sexual maturity.

These parameters, asymptotic length and growth coefficient, align with reported ranges for Southeast Asian *Tachypleus gigas* (Fauziyah *et al*., 2021; Razak and Kassim, 2017). These values confirm the species' slow-growing nature, typical of K-selected organisms. The natural mortality and M/K ratio suggest a moderate to high susceptibility to fishing mortality, indicating that the population may be vulnerable to fishing pressure, particularly under conditions of increased exploitation (Froese *et al*., 2017). Such parameter combinations have also been linked with low reproductive resilience in tropical arthropods, where small reductions in survival rates of sub-adult stages lead to steep collapses in recruitment (Kindong *et al*., 2022; Prince, Hordyk *et al*., 2015). Hence, Kotabaru's low SPR reflects both biological fragility and persistent fishing pressure.

In this analysis, the L_{50} calculated from the Lm value is 22.17 cm, while the L_{95} calculated from Kindong formula (Kindong *et al*., 2022) is 24.39 cm. By completing the calculations of several biological parameters, the barefoot ecologist tool provided the selectivity–maturity curve (Figure 8) that shows the gear selectivity of fishing gears applied in the Kotabaru waters. Based on the selectivity and maturity curves, the selectivity curve lies above the maturity curve. This indicates that the fishing gear captures individuals before they reach reproductive maturity, thereby reducing their contribution to the spawning stock. Similarly, the SPR value of the horseshoe crab landed in the Kotabaru landing sites was 14% (Figure 9). The estimated SPR of 14% is well below the commonly used biological reference point of 20%, indicating an overexploited condition. These results are consistent with the estimated growth and mortality parameters, which indicate limited resilience of the population under continued fishing pressure. It is suggested that the shrimp fishery in Kotabaru needs to be regulated so that the horseshoe crab can be conserved with proper monitoring and surveillance. Specific management measures may include increasing mesh size in trammel nets to reduce the capture of immature individuals, implementing seasonal closures during peak spawning periods, and establishing bycatch monitoring programs to improve data collection and support adaptive management.

The length-based analysis of *Tachypleus gigas* in Kotabaru waters provides clear evidence that this population is experiencing growth overfishing and reduced reproductive potential. The estimated spawning potential ratio (SPR) of 14% is far below the sustainability threshold of 30–40% proposed by Prince *et al*. (2015), indicating a population under significant fishing pressure. This is consistent with trends reported in other Asian horseshoe crab populations where unregulated bycatch and habitat modification have driven declines (Nelson *et al*., 2016; John *et al*., 2020).

In evolutionary terms, the life-history traits of horseshoe crabs, slow growth, delayed maturity, and low fecundity, make them extremely vulnerable to additive mortality (Sekiguchi and Shuster, 2009; John *et al*., 2020). Once mature adults are removed before spawning, recovery can take decades (Fitzgerald *et al*., 2018). The Kotabaru shrimp fishery exemplifies this vulnerability, as continued exploitation at current levels will likely drive further depletion of spawning stock biomass.

To directly mitigate the severe depletion of reproductive biomass (SPR = 14%) and protect immature cohorts ($L_c < L_{50}$), management implications must prioritize localized technical interventions. First, regarding gear selectivity, trammel net modifications should focus on implementing 'bound-foot' or raised leadline designs. By raising the net's lower groundline approximately 5–10 cm off the seabed using small dropper spacer lines, benthic-walking horseshoe crabs can safely pass underneath the gear, while pelagic and demersal penaeid shrimp targets remain catchable within the water column.

Second, although long-term reproductive monitoring is ideal, our direct observation of high mature/spent female ratios (Stages III and IV) from December to March confirms that the northwest monsoon acts as a highly active spawning and nesting window in Kotabaru waters. Therefore, a temporal-spatial closure targeting shallow sandy nearshore zones (within 2 nautical miles of Pantai, Sungai Pasir, and Salino villages) should be enforced during these four specific months. This seasonal closure will protect spawning aggregations from trammel net entanglement, allowing remaining mature individuals to maximize recruitment success and rebuild the depleted spawning pool.

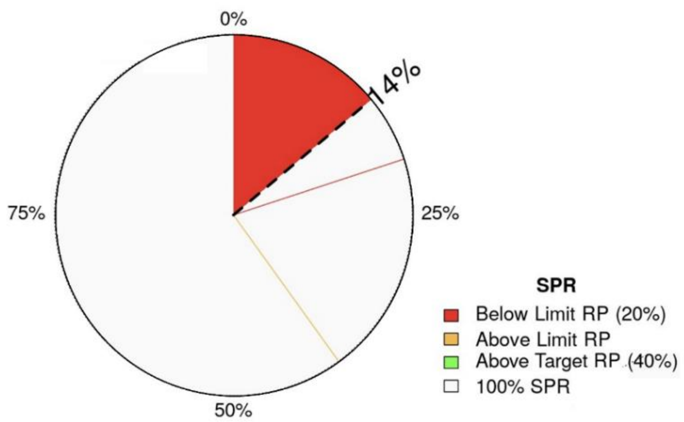

Figure 9. Length-based spawning potential ratio of *Tachypleus gigas* in Kotabaru waters. The estimated SPR value is 14%, indicating an overexploited stock condition with reduced reproductive potential.

The findings from this study underscore the urgent need to integrate horseshoe crab conservation into shrimp fishery management. Practical interventions should focus on increasing gear selectivity, protecting critical habitats, and incorporating bycatch monitoring in management plans. For example, modifications to trammel net mesh size have been shown to reduce bycatch of non-target species in similar small-scale fisheries. Studies on trammel net fisheries demonstrate that improving gear design can significantly lower non-target mortality without compromising shrimp yield (Cheng *et al*., 2023; Madia *et al*., 2024). Such modifications could be adapted for trammel net fisheries in Kotabaru.

Temporal closures during peak spawning months, combined with habitat protection of sandy and intertidal zones, can allow population recovery (Nelson *et al*., 2016; Rozaini *et al*., 2023). In addition, participatory co-management, where fishers are engaged in mapping, monitoring, and compliance, has proven effective in data-limited Indonesian fisheries (Dowling *et al*., 2016; Halim *et al*., 2020). These approaches could be piloted in Kotabaru to balance ecological and socioeconomic objectives.

It is important to acknowledge several limitations of this study. The LB-SPR approach assumes a steady-state population and representative length-frequency sampling, which may not fully reflect dynamic fishing conditions in small-scale fisheries. In addition, the use of fishery-dependent data may introduce sampling bias, particularly if certain size classes are more vulnerable to capture by trammel nets. The relatively short sampling period (December 2024–March 2025) may also limit the representation of seasonal variability in population structure. Therefore, the results should be interpreted with caution, and further long-term monitoring is recommended to improve stock assessment accuracy.

Conclusion

The present length-based assessment provides initial quantitative evidence of *Tachypleus gigas* overexploitation in Kotabaru waters. The combination of $L_c < L_{50}$, low SPR (14%), and negative allometry highlights an urgent conservation concern. Without management, continued bycatch mortality in shrimp trammel net fisheries will likely cause further reproductive collapse and local extinction risk. Integrating selective fishing practices and community-based monitoring is essential to restore spawning potential and sustain both *Tachypleus gigas* and the shrimp fishery in Kotabaru waters.

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