



Towards sustainable management: growth and population assessment of the deep-sea shrimp *Aristeus alcocki* Ramadan, 1938, in Southwestern Indian waters

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Abstract

This study examines the population dynamics, growth parameters, exploitation status, and yield potential of *Aristeus alcocki*, a commercially significant deep-sea shrimp species in the North Indian Ocean. The species, identified as a prime candidate for certification by the Marine Stewardship Council, underscores the need to comprehend its fishery status for sustainable management. However, in recent years, frequent rise and falls in the landings and its corresponding CPUE has raised concern about the species. So, this study was designed to clarify the growth performance, stock status, and population dynamics of the mentioned species gathered from Kollam off Sakthikulangara along the Kerala coast, India. In this study, catch and effort data from 2007 to 2022 were utilized for the CMSY++ analysis, while biological data and population parameter estimations were based on data from 2017 to 2022. Size distribution analysis revealed peak abundances within specific size groups, with a sex ratio of 3.46 skewed towards females. Sex-specific differences were evident in length-weight relationships, with rapid growth rates observed for both. Findings of length-weight relationship analysis suggested a negative allometric growth trend for male ($b=2.69$), female ($b=2.61$), and pooled ($b=2.69$) *A. alcocki*. Population parameters were evaluated utilizing the TropFishR package. Evaluation of VBGF-based growth parameters (L_{∞} and K) for male, female, and pooled categories indicated a higher asymptotic length for females (22.1 cm) compared to males (13.7 cm), and a higher growth coefficient in males (0.74 yr^{-1}) compared to females (0.73 yr^{-1}). The growth performance index (ϕ') remained consistent above 2.2 across these categories. Total instantaneous mortality ($Z=3.34 \text{ yr}^{-1}$), fishing mortality rate ($F=1.86 \text{ yr}^{-1}$) was estimated for pooled *A. alcocki* through length-converted catch curve analysis. The current exploitation rate (0.56) was found to be lesser than the $E_{\max}$ value (0.75) derived through Thompson and Bell analysis for pooled data. Thomson and Bell analysis revealed that standing stock (45.6%) and spawning stock biomass (32.9%) of which the earlier was below the reference limit (50%) while the latter was above the reference point limits of 25% respectively. The CMSY/BSM method revealed that the stocks of red ring fishery harvested by trawls in Kerala are currently in a healthy state ($B_{\text{cur}}/B_{\text{msy}} = 1.23$), with a sustainable exploitation of $F_{\text{cur}}/F_{\text{msy}} = 0.52$ which is well below the critical threshold of 1. Based on these findings, the study suggests maintaining the existing fishing pressure to safeguard the stability of the *A. alcocki* population, underscoring the crucial need to grasp the species' current fishery status for sustainable management.

Keywords Spawning stock biomass · Exploitation rate · TropFishR · Biological reference point · BSM

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Introduction

The primary goal of fishery stock assessment is to assess the status of a fish stock and offer scientific recommendations to ensure its sustainable management in fisheries. While fishing stocks have the potential for renewal, their status is affected by various factors. Key aspects such as exploitation rate, fishing season, and catch sizes are influenced by fishing activities and can be administered to promote the stock's sustainability. An in-depth understanding of the stock's condition allows researchers and fisheries managers to forecast potential yields and determine the necessary effort for sustainable resource utilization (Hilborn and Walters 1992; Beverton and Holt 1957). Effective stock assessment is crucial for balancing the ecological and economic aspects of fisheries management (Quinn and Deriso 1999).

Growth in crustaceans is irregular and influenced by various biotic components (like maturity, age, food quality and quantity, presence of predators, moult frequency, and growth increments) and abiotic parameters (such as salinity, dissolved oxygen, photoperiod, and temperature) (Hartnoll 2001; Dall et al. 1990; Lizarraga et al. 2008). Short-lived species like shrimps rely heavily on environmental fluctuations for their population dynamics, with regional differences in population structure often attributed more to environmental diversity than to genetic factors (Miazaki et al. 2021; García and Reste 1981). Estimating age data directly or through age frequency poses challenges since shrimps do not possess durable hard structures (King 2013; Cadrin and Secor 2009). As a result, population parameters are typically derived from length-frequency data. The length-weight relationship is a key method that provides reliable biological data and is crucial in fishery assessments. It helps determine the "condition factor," a measure of growth and feeding intensity (Ricker 1975) and has significant implications for the reproductive cycle in species (Froese 2006; Welcome 1979).

Deep-sea shrimps such as *Aristeus alcocki*, generally known as the 'Indian deep-sea shrimp, locally known as red ring' is a significant target species within the family Aristeidae, inhabiting the depths of the North Indian Ocean. Characterized by its deep-sea habitat, *A. alcocki* thrives at bathymetric ranges between 300 and 500 m, making it a prominent catch for deep-sea bottom trawlers operating in the region. The species is a prime candidate for certification by the Marine Stewardship Council, highlighting the importance of understanding its fishery status for sustainable management. *A. alcocki* contributed 20% to the total deep-sea shrimps during 2007–2020 and catch trend analysis of the landings and cpue showed a stable position during 2022 (Chakraborty et al. 2022). However, recent fluctuations in landings and corresponding catch per unit effort (CPUE)

have raised concerns about the sustainability of this fishery. In light of these concerns, a comprehensive study was undertaken to assess the growth performance, stock status, and population dynamics of *A. alcocki* along the southwest coast of India.

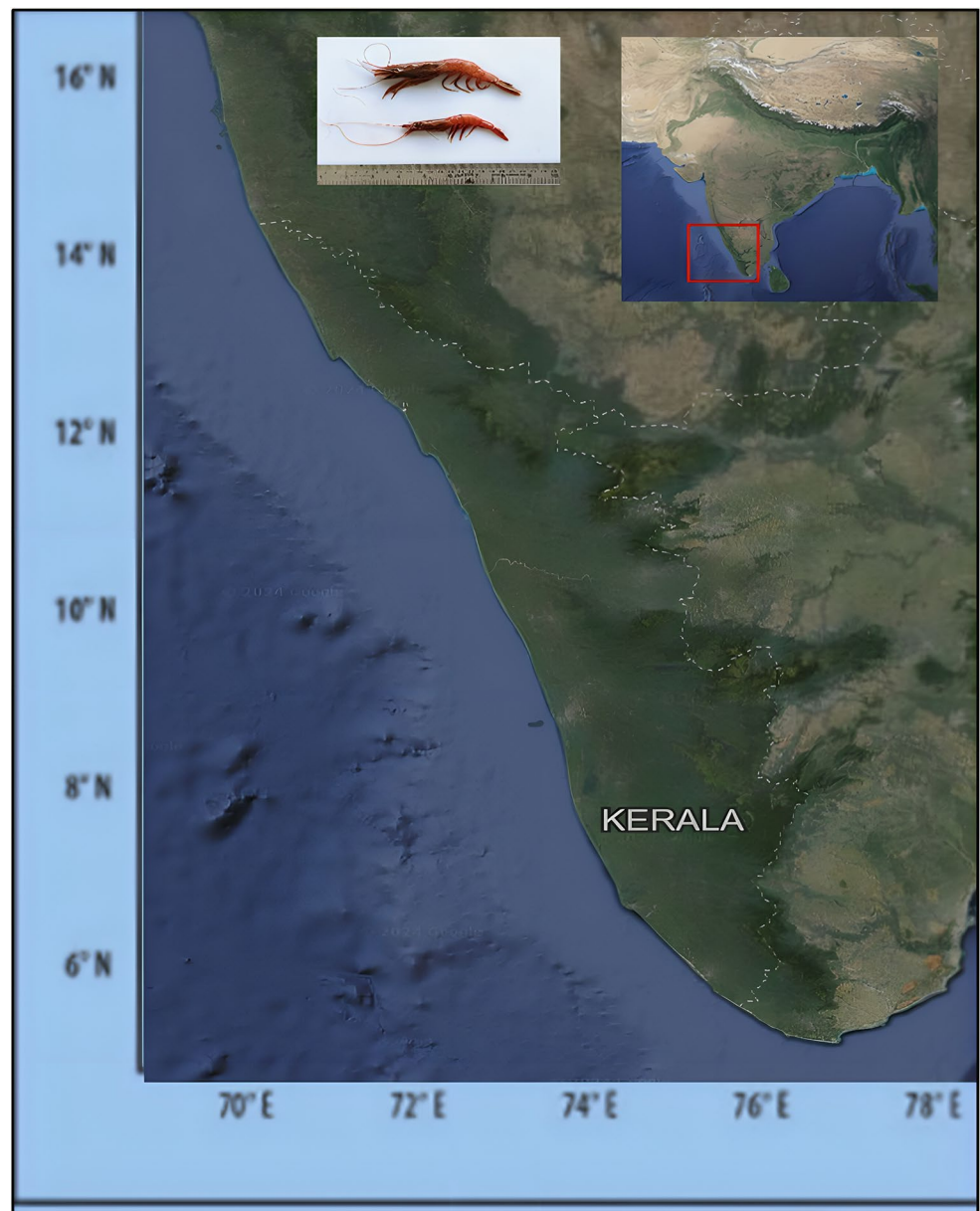
A wide range of studies have been carried out on *A. alcocki* along the southwestern coast of India, covering various aspects such as its identification distinct from *A. semidentatus* (Suseelan 1989), morphological analysis, and molecular phylogeny (Chakraborty et al. 2015). Truss morphometry (Purushothaman et al. 2018a), reproductive biology (Purushothaman et al. 2018b), food and feeding (Purushothaman et al. 2020), and genetic diversity studies have also been reported (Purushothaman et al. 2020b). And a study by Chakraborty et al. (2018a) provided information regarding the population parameters of *A. alcocki*. Information on the biometric parameters of the species is crucial for analyzing its developmental changes and obtaining accurate catch estimates through statistical models (Rao 1988). Therefore, this study aims to describe the life history parameters, spawning potential ratio (SPR), exploitation status, reference points for sustainable fishery management of *A. alcocki* based on commercial catches from the southwest coast of India.

Materials and methods

Study area and data collection

Aristeus alcocki specimens sourced from the eastern Arabian Sea were collected from commercial multiday trawl hauls landed at the Sakthikulangara fisheries harbor (8°56'60.78"N/76°32'34.27"E) off the coast of Kollam, Kerala (Fig. 1). In this study, catch and effort data from 2007 to 2022 were utilized for the CMSY++ analysis, while biological data and population parameter estimations were based on data from 2017 to 2022. Sampling was conducted every two weeks spanning from 2017 to 2022, with the exception of June and July, coinciding with the yearly fishing ban enforced by the Kerala Department of Fisheries within marine waters. The unprocessed samples were carefully transported into the laboratory maintaining freshness where *A. alcocki* was identified following the literature of Suseelan (1989) and Chan et al. (2017). Sex determination was assessed by examining the thelycum in female and petasma in males. A total of 3084 female and 900 male specimens were used for recording the dimensions, including total length (TL: measured from the rostrum tip to the telson tip) and carapace length (CL: measured from the posterior orbit margin to the outer carapace end), were meticulously measured to the nearest 0.01 mm utilizing electronic digital

Fig. 1 Location of sampling area of *A. alcocki* along southwest coast of India



calipers. Furthermore, the total body wet weight (W) was accurately recorded to the nearest 0.0001 g utilizing a Mettler Toledo, ME203E (Mettler, Greifensee, Switzerland) electronic weighing balance.

The sex ratio of *A. alcocki* was analysed using the Chi-square test (χ^2) (Snedecor and Cochran, 1967) based on the data from 2017 to 2022. Monthly length-frequency data of the specimens between January 2017 and December 2022 was collected at fortnightly intervals and raised to the monthly estimates of Kerala by multiplying with the raising factors derived using landing data collected from the National Marine Fishery Resources Data Centre (NMFDC) of the Central Marine Fisheries Research Institute (CMFRI),

Kochi. Catch and effort data for the period 2007–2022 were also sourced from the FRAEED - CMFRI, Kochi. Catch per unit effort (CPUE) was derived from this data to analyze the fishing trend of *A. alcocki* from Kerala. Subsequently, length frequency dataset was aggregated into groups delineated by 0.5 cm length-class intervals. The length-frequency distribution of the sample was used to estimate the total catch for the sampling day, based on the sample weights. The data collected from different sampling days within a month were combined to calculate the total catch in numbers, which was then extrapolated to estimate the monthly catch. This data was used to analyse the growth parameters of *A. alcocki* for TropFishR analysis.

Length-weight relationship

The parameters ('a' and 'b') defining the connection among total length and wet weight were calculated separately for male, female and pooled *A. alcocki* using the best modeling approach following the method suggested by Dash et al. (2023a). The suitability of nonlinear power regression model and the log-transformed linear model was determined by evaluating the variance distribution structure of the residuals. An information theoretic criterion, i.e., Akaike Information Criterion (AICc) was used for multi-model comparison following the method recommended by Dash et al. (2023b).

$$\text{Linear Model, } \log(W) = \log(a) + b \times \log(L) + \epsilon, \epsilon \approx \text{normal}(0, \sigma^2) \quad (1)$$

$$\text{Nonlinear Model, } W = a \times L^b + \epsilon, \epsilon \approx \text{normal}(0, \sigma^2) \quad (2)$$

Where *W* is the body weight in g, *L* is the total length of the shrimp in cm and *a* and *b* are the model coefficients.

The coefficient 'b' provides valuable information about the shrimp's condition and helps determine whether somatic growth is isometric (*b*=3) or allometric (*b*<3; negative allometric and *b*>3; positive allometric) (Ricker 1973; Spiegel 1991).

Analysis of covariance (ANCOVA) was employed (TropFishR) package (v 1.6.4) to test the homogeneity (equality) of regression slopes between male and female individuals.

The Fulton's condition factor (*K*) of the shrimps was determined from the relationship (Fulton 1902)

$$K = 100 W/L^3$$

Growth parameters

The TropFishR package (Taylor and Mildenerger, 2017) was adopted to evaluate the growth and population parameters (mortality parameters as well as the biological reference points) of *A. alcocki*. TropFishR is a package that includes procedures like Electronic Length Frequency Analysis (ELEFAN), length-converted catch curve (LCC), and cohort analysis (CA).

The Von Bertalanffy (1938) growth function parameters (*L_∞*, *K*, and *t₀*) were estimated using two innovative optimization methods within the ELEFAN framework: ELEFAN with simulated annealing (ELEFAN S.A.) and ELEFAN with a genetic algorithm (ELEFAN G.A.), both integrated into the Tropical Fisheries Analysis (TropFishR) package (v1.6.4). The method yielding the best scoring fit (highest *R_n* value) was selected for further analysis in this study. Notably, the newly implemented ELEFAN approaches

(ELEFAN S.A. and ELEFAN G.A.) facilitate the optimization of the VBGF (Mildenberger et al. 2017). The growth parameters were assessed for male, female and pooled data of *A. alcocki*. These estimations were conducted by fitting the VBGF model to the length frequency data as described by Taylor and Mildenerger (2017):

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

L_t is the length of a fish at age *t*, *L_∞* is the asymptotic length in cm, *K* is the growth rate and *t₀* is the theoretical age when length=0. Here *S(t)-S(t₀)* was set to zero as the amplitude of seasonal growth oscillation is assumed to be minimum in a tropical fishery (Froese and Pauly 2000).

The parameter *t_{anchor}* in ELEFAN within TropFishR is used to define the fraction of the year where yearly repeating growth curve crosses length zero for a given cohort. The range of initial seed values for *t_{anchor}* was 0 to 1.

The growth performance index (*Ø'*) was calculated based on the growth parameter estimates following the equation: (Pauly and Munro 1984)

$$\varnothing' = \log K + 2 \log L_{\infty}$$

Prior value of *L_∞* required by TropFishR and an initial seed value of *L_∞* was calculated from the following formula proposed by Pauly (1984).

$$L_{\infty} = L_{max}/0.95$$

Where, *L_{max}* is the observed maximum length of the shrimp, which was taken from the mean of the 1% of largest shrimp present in the sample.

The approximate maximum age (*t_{max}*) is the life span that shrimp of a given population would reach. Using the parameters of the von Bertalanffy growth function, Pauly (1980) calculated it as:

$$t_{max} = t_0 + 3/K$$

Optimum length of exploitation (*L_{opt}*)

The optimum length (*L_{opt}*), representing the percentage of fish caught at their ideal size, is generally slightly greater than *L_m*. It can be readily determined using growth and mortality parameters or through empirical equations proposed by Froese and Binohlan (2000).

$$L_{opt} = ((3/(3 + M/K)) * L_{\infty}$$

Where, *L_∞* is asymptotic length, *M* is natural mortality rate and *K* is growth coefficient.

Fishing mortality parameters and exploitation ratio

The growth parameters determined for pooled sex by ELEFAN G.A method ($L_{\infty}=23.6$ cm and $K=0.73$ yr⁻¹) were used to analyse the population parameters. The total instantaneous mortality rate (Z) was derived utilizing the length-converted catch curve analysis method outlined by Pauly (1983), employing the aggregated length frequency dataset. Additionally, the instantaneous natural mortality rate (M) was calculated using the empirical formula developed by Then et al. (2015), necessitating the utilization of the VBGF growth parameters for accurate implementation:

$$M = 4.118 \times k^{0.73} \times L_{\infty}^{-0.33}$$

The selection of this formula over other empirical formulations was made due to its superior accuracy in predicting maximum ages, particularly when precise estimations are unavailable, as noted by Hordyk et al. (2015a). Subsequently, utilizing the estimated Z and M values, the instantaneous fishing mortality rate, F, was determined via the equation: $F=Z - M$. The exploitation ratio (E) was then computed using the expression $E=F/Z$ (Ricker 1975) representing the proportion of the population subjected to fishing pressure that eventually succumbs to exploitation.

The stock size was determined using Jones' length-converted cohort analysis (CA), an enhanced version of Pope's virtual population analysis (VPA) tailored for length data, which is incorporated into TropFishR. This cohort analysis necessitates the parameters a and b from the length-weight relationship, the estimated value of F, along with other estimates derived from prior analyses. The CA calculates stock size by using the total estimated catch in terms of numbers. Once these parameters are determined, the total weight of the sample is calculated by multiplying the number of individuals in each length class by the respective weight for that class. A raising factor is calculated by dividing the reported total catch (in numbers) by the sum of the total weight for each length class over the study period. This factor is employed to estimate the number of species that would have been captured, based on the distribution pattern observed in the samples. This is done by multiplying the frequencies within each length class by the expansion factor. It is essential that the catch vector accurately represents the entire stock, and the cohort analysis does not allow for length classes exceeding L_{inf} . Here, length frequency, L_{∞} , and K are input parameters used. Cohort analysis estimates stock size by using the total catch in numbers as a reference, providing insights into natural mortality, fishing mortality, and the number of survivors within each length group (Taylor and Mildenerger 2017).

In this study, the Thompson and Bell model was employed to establish biological reference points and to devise input control strategies, such as limiting fishing effort. The parameter F was adjusted within the Thompson and Bell model to determine fishing mortality, which was then used to estimate yield and biomass trajectories. All analyses were conducted using the TropFishR package within the statistical computing software 'R' (version 3.4.2).

Biological reference points

The estimated exploitation values were then compared to a reference threshold of 0.5, which Gulland (1971) proposed as the upper limit for sustainable exploitation of a species. The relative yield per recruit and relative biomass per recruit at various fishing levels were estimated using the TropFishR package. The estimated fishing mortality (F) values were then compared with reference points derived from the Thompson and Bell model, including: (a) the fishing mortality that produces the maximum biomass per recruit (F_{max}), (b) the fishing mortality corresponding to a 50% reduction in the biomass of the unexploited population ($F_{0.5}$), and (c) the fishing mortality associated with 10% of the initial slope of the yield-per-recruit curve ($F_{0.1}$). Maximum sustainable yield (MSY), maximum economic yield (MSE) total standing stock biomass and spawning stock biomass (SSB) at different fishing levels were estimated using Thompson and Bell bioeconomic model (TBEM).

Length-Based spawning potential ratio (LB-SPR)

The LB-SPR analysis was conducted using the LB-SPR R package, with the estimated values of L_{∞} , M, K, and the M/K ratio from TropFishR serving as input parameters. The analysis aimed to estimate the length at first sexual maturity (L_{m50}) for the assessed species, ensuring that all individuals (100%) are able to spawn at least once before being caught. This approach is intended to support the rebuilding and maintenance of healthy spawning stocks. The values of L_{m50} and L_{m75} in terms of total length were referred from the work of Purushothaman et al. (2018b).

Stock status of *A. alcocki*

The stock status of *A. alcocki* was assessed using a Bayesian State-Space Model (BSM) based on the Schaefer model (Schaefer 1954), following the methodology outlined by Froese et al. (2017). The analysis utilized the CMSY++R package to obtain preliminary estimates of essential fisheries reference points, including the Maximum Sustainable Yield (MSY), fishing mortality at MSY (F_{msy}), biomass at MSY (B_{msy}),

relative stock size (B/B_{msy}), and exploitation rate (F/F_{msy}). This assessment incorporated long-term catch and abundance time-series data (expressed as catch per unit hour, CPUH), species resilience, and qualitative stock status information for *A. alcocki* over the period 2007 to 2022. The BSM utilized a Monte Carlo method to select the most plausible biomass trajectory for future years, based on a modified Schaefer surplus production model as described in the equation below.

$$B_{t+1} = B_t + 4 \left(\frac{B_t}{k} \right) r \left(1 - \frac{B_t}{k} \right) B_t - C_t$$

Where, B_{t+1} is the biomass in the next year, B_t is the present biomass and C_t is the present year catch where, B_{t+1} is the biomass in the next year, B_t is the present biomass and.

C_t is the present year catch, r is the intrinsic population r at e and k is the carrying capacity. The modified Schaefer surplus production model uses an extramultiplier of $4B_t/k$ (which is 1 at $0.25k$ but becomes zero at zero k), that linearly decreases recruitment towards zero at zero k only when the biomass falls below $0.25k$ (i.e., $B_t/k < 0.25$). JAGS program with the Markovchain Monte Carlo process was used to sample the probability distributions of the parameters (Plummer 2003; Thorson 2014). The managerial reference point (MSY , F_{msy} , B_{msy}) was derived using the geometric means of the resulting density distributions for r , K , and MSY .

Results

Deepsea shrimp fishery

Along the Kerala coast, two distinct types of deep-sea prawn trawling operations exist, differentiated by their target prawn species. One operation focuses on the ‘red ring’ prawn, conducted at depths greater than 350 m, while the other targets

deep-sea prawns, primarily pandalids, at depths ranging from 190 to 350 m off Kollam. Fishing trips typically last between 6 and 12 days. Trawlers targeting the ‘red ring’ operate continuously throughout the day, whereas those targeting other deep-sea prawns fish exclusively during daylight hours. The number of hauls per day ranges from 3 to 5, with each haul lasting 4 to 5 h. The fishery remains active for 6 to 8 months, from September to May, with peak activity between December to February.

Catch and effort of *A. alcocki*

The annual estimated average catch of *A. alcocki* during 2007–2022 was above 1800 tonnes with a cpue of 0.54 Kg/hr contributing to 19.9% in the total deep-sea catch. However, when considering only the effort spent specifically on deep-sea shrimp fishing, the CPUE would be twice as high. The annual catch trend of *A. alcocki* displays fluctuations rather than a consistent pattern of increase or decrease. Considering the catch of *A. alcocki* during the period from 2007 to 2022, decrease was observed in both catch and CPUE during 2016. Subsequently, a notable increase was noticed in 2017 with a steep fall during 2019–2020 which followed a rise in catch till 2022. The highest catch and CPUE of *A. alcocki* was recorded in 2018, while it showed a declining trend in the subsequent years. However, the trend reversed, with the catch increasing again and reaching to about 2200 tonnes by 2022, coinciding with an increase in CPUE. The graph depicting the curve of CPUE has been given in Fig. 2.

Length composition and length-weight relationship

The size distribution of *A. alcocki* ranged between the size class 6.8–22.8 cm TL (mean $\pm$ SD: 14.5 ± 4.11) in females and 6.8–12.8 cm TL (mean $\pm$ SD: 9.8 ± 1.947) in males based on the pooled data (2017–2022). The most abundant individuals belong to the size groups ranged between 14.3 and 16.3 cm and 8.8–9.8 cm TL for both females and males.

The length-frequency distributions of red ring shrimp during 2007–2022 by sex, are shown in Fig. 3. The K-S test indicated a significant difference between the length-frequency distributions of the sexes overall ($D_{obs} = 0.8387$, $D_{crt} = 2.2e-16$, $p < 0.05$). The TL ranged between 80 and 225 mm for females (mean $\pm$ SD: 155 ± 4.40 mm) and 65–130 mm for males (mean $\pm$ SD: 98 ± 1.94 mm). There was a significant difference ($t = 1.669$, $e-16$, $p < 0.05$) in the TL between sexes. Overall sex ratio obtained for the complete sample was 3.5:1.0 (22.5% males, 77.5% females) showed statistically significant difference from the expected 1:1 ($\chi^2 = 38.44$, $p < 0.05$). Throughout the study period, the monthly sex ratio indicated a higher proportion of females.

Length-weight relationship of the individuals of *A. alcocki* was represented in Fig. 4. The parameters (a and b)

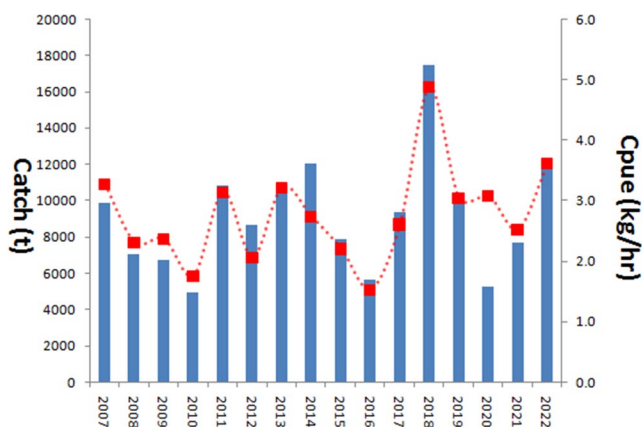
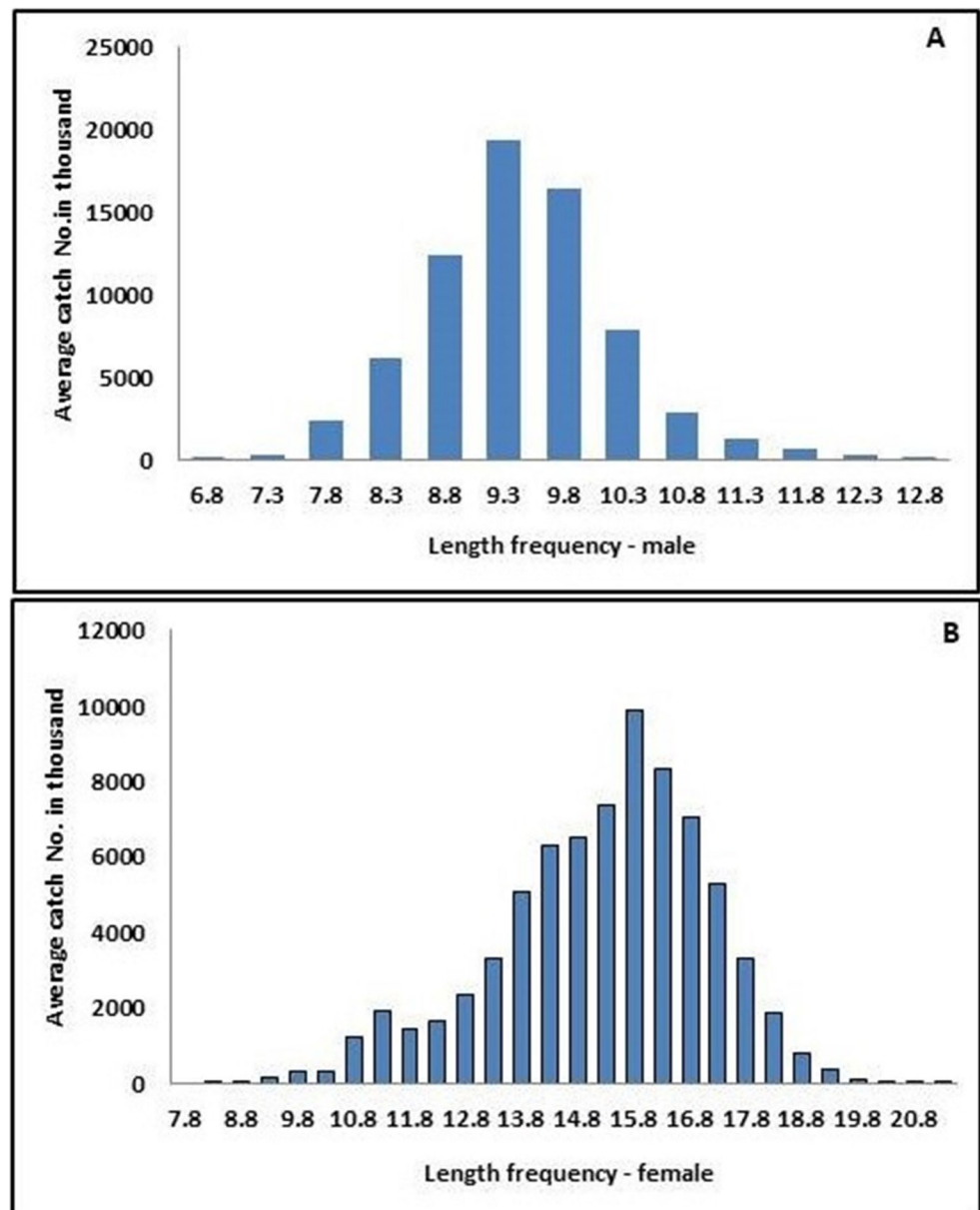


Fig. 2 Graph representing the curve of CPUE of *A. alcocki* from the period 2007–2022

Fig. 3 Total length (TL) frequency distribution of female and male *A. alcocki* along the southwest coast of India during 2017–2022



for the length-weight regression of female, male and pooled data of *A. alcocki* were calculated separately and represented as follows:

$$\text{Female: } W = 0.0161L^{2.56} (r^2 = 0.72)$$

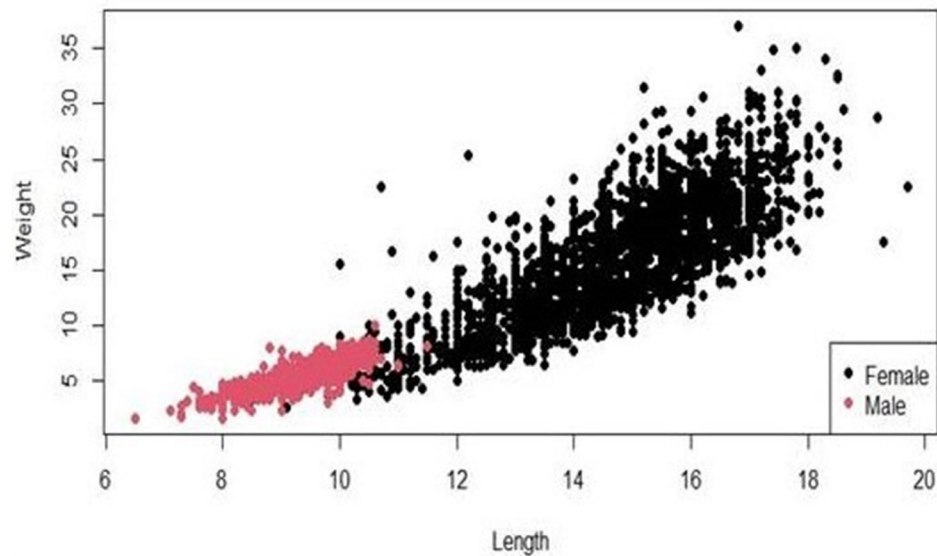
$$\text{Male: } W = 0.0131L^{2.69} (r^2 = 0.89)$$

$$\text{Pooled: } W = 0.0245L^{2.56} (r^2 = 0.88)$$

According to the statistical test ANCOVA, a high statistical significance ($p < 2.2 \times 10^{-16}$) was found in length, between sex and the interaction between length and sex ($p < 1.66 \times 10^{-16}$) of the species *A. alcocki*. Wald test for isometry (null hypothesis $b=3$) yielded a p value of 2.2×10^{-16} ($p < 0.05$) indicating significant results. Both females and males displayed similar patterns, exhibiting strong negative allometric growth.

Growth parameters

The growth parameters were estimated using the von Bertalanffy growth equation through the ELEFAN method, which includes both ELEFAN SA and ELEFAN GA within the TropFishR package. These two optimization techniques allow for the simultaneous estimation of the growth rate (K) and the asymptotic length (L_{∞}). In both ELEFAN methods, the most critical setting is the maximum number of generations, which was set to 100 in this study. The results are presented in Table 1. Initially, the parameters are selected randomly within the defined intervals, and as the process progresses, the variability in the parameters decreases, becoming more concentrated around local maxima (Fig. 5).

Fig. 4 Length-weight relationship of *A. alcocki***Table 1** Growth parameters, mortality, and exploitation rates of *A. alcocki* calculated by using tropfishr

Growth parameters	male	female	pooled
Asymptotic length, L_{∞} (cm)	13.69	22.06	15.15789
Growth coefficient, k (yr^{-1})	0.73	0.73	0.715839
Longevity, $t_{\max}$ (yr)	4.01	4	5
Growth performance index, ϕ'	2.14	2.55	2.22
Mortality and exploitation parameters			pooled
Natural mortality, M (yr^{-1})			1.48
Total mortality, Z (yr^{-1})			3.34
Fishing mortality, F_{cur}			1.86
$F_{\max}$			2.32
F_{01}			0.701
F_{025}			3.72
E_{cur}			0.556
$E_{\max}$			0.748
E_{01}			0.22
E_{025}			0.71
$L_c = L_{c_opt}(\text{cm})$			12.2
L_c/L_{∞}			0.542
F/M			1.256
M/K			2.02

Our study found that ELEFAN GA provided the best goodness of fit (Rn_max), and as a result, it was chosen to estimate the growth parameters for our subsequent analysis. The best fit to the length frequency distributions was obtained by the growth parameters as $L_{\infty} = 23.7$ cm, $K = 0.735 \text{ yr}^{-1}$, $Rn_max = 0.198$ for female individuals. Afterwards, t_0 was calculated as -0.0020 yr. The growth performance index of the female population was calculated as $\phi' = 2.61$.

The average estimated growth parameters for male individuals were 13.69 cm for L_{∞} and 0.731 yr^{-1} for the growth

coefficient (K). The growth performance index (ϕ') was 2.13, and the goodness of fit value (Rn_max) was 0.19. The value of t_0 was estimated as -0.0035 yr. Both sexes of *A. alcocki* entail 'K' values higher than 0.5 which showed fast growth rate.

There was significant difference found among L_{∞} , K , and t_0 values of sexes and pooled data. In *A. alcocki* maximum reported age ($t_{\max}$) determined was found to be around 4.01 yr and 4.02 yr for female and male respectively. The optimum length (L_{opt}) calculated for *A. alcocki* was 12.2 cm (Given the similar trends observed in the results, and to enhance clarity and brevity, only the detailed results from the ELEFAN/GA method are presented.)

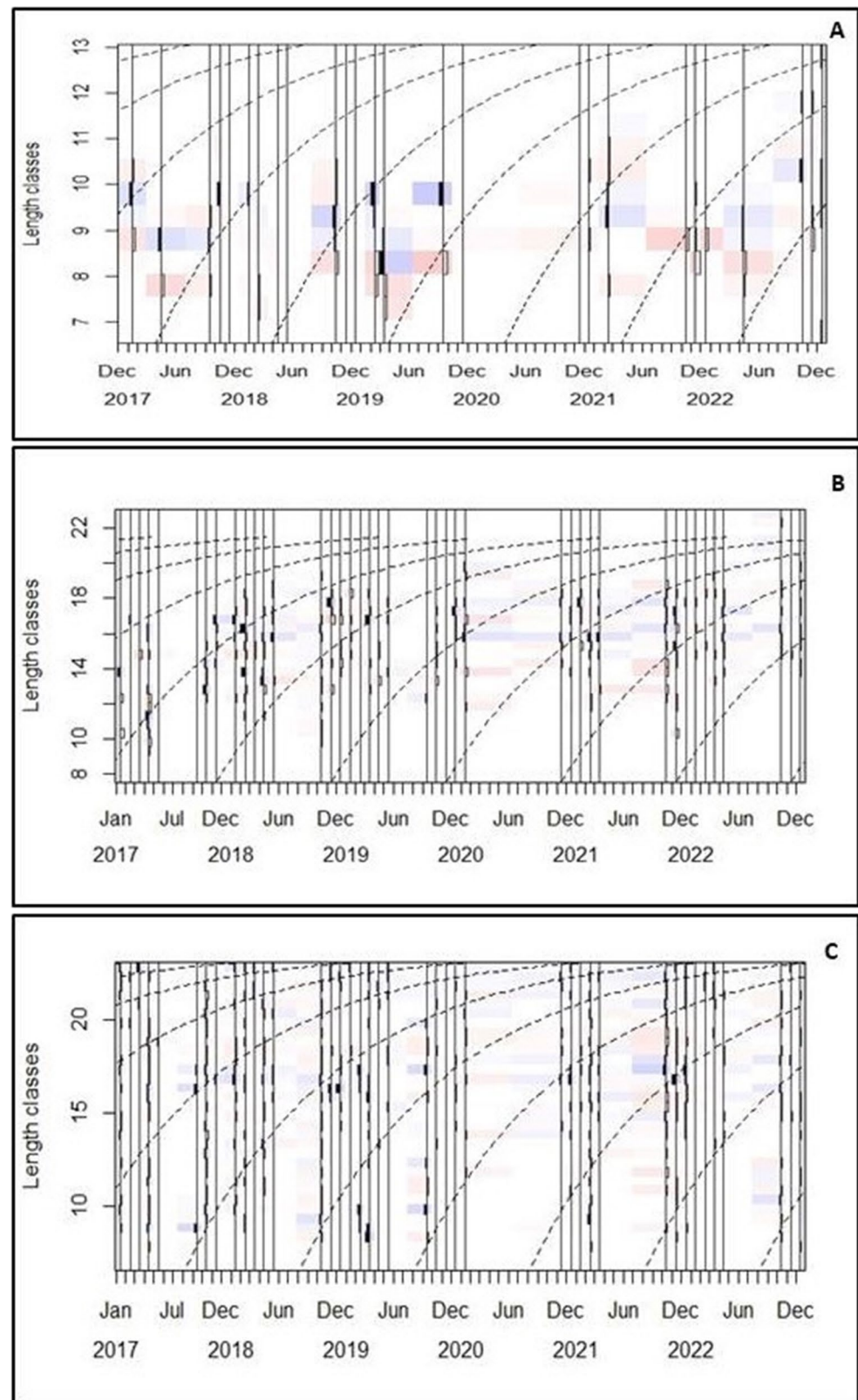
Yield per recruit

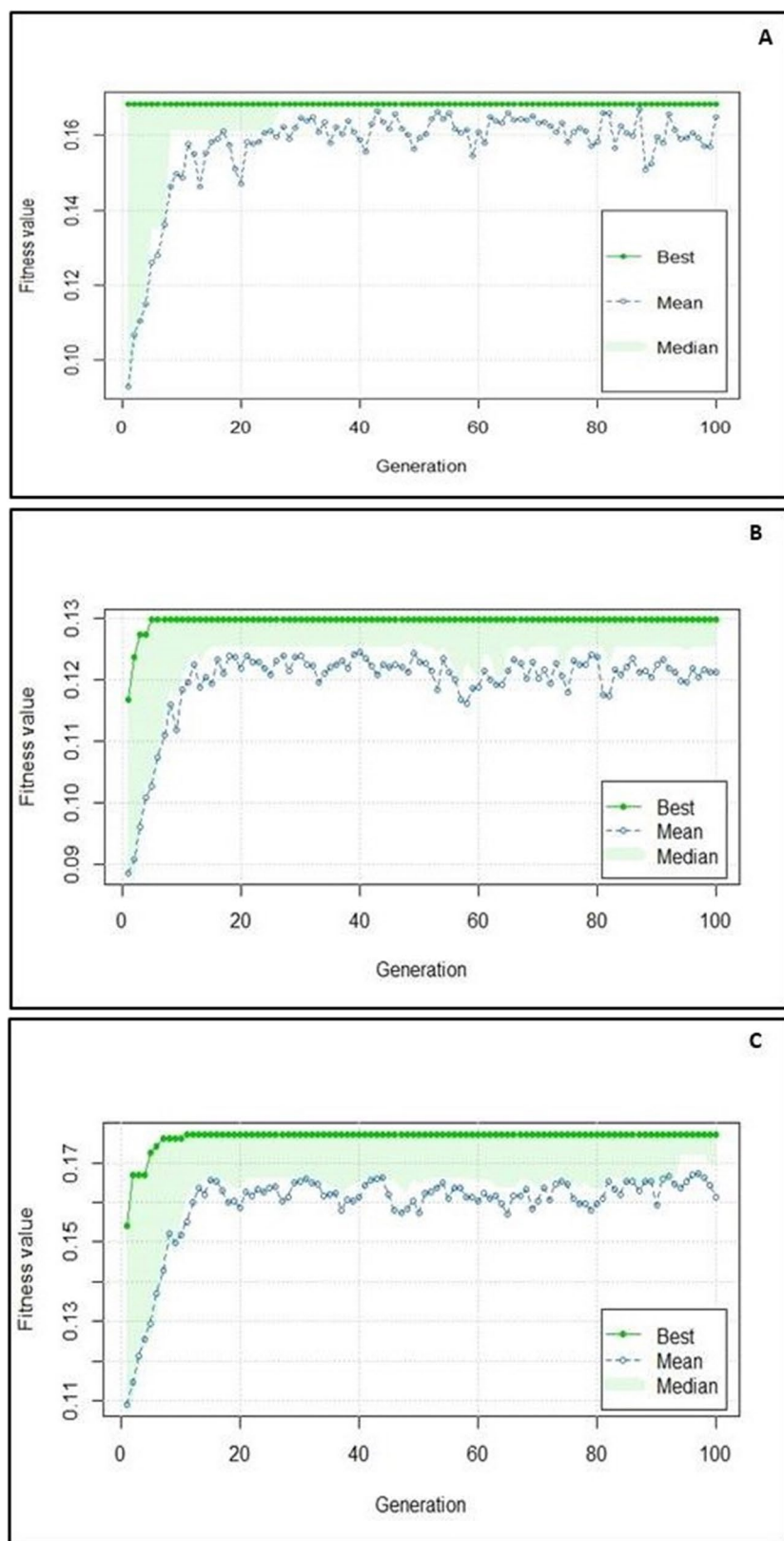
Virtual Population Analysis (VPA) illustrates the logistic-shaped fishing pattern across different length classes (represented by the red line in the plot) and provides the number of survivors and the fishing mortality for each cohort during the specified period. However, the exploitation started from the length group above 6.0 cm, fishing mortality reached in a noticeable level from the length group between 7.8 and 14.3 cm. The length group of 14.8–18.3 cm was more susceptible to the fishing gear, and the peak fishing mortality was observed within this length range (Fig. 6).

Exploitation and fishing mortality with biological reference points

The estimated value of total mortality for pooled *Aalcocki* (Z) based on a linearized length converted catch curve using TropFishR is 3.34 yr^{-1} . The natural mortality rate (M) was

Fig. 5 Graphical fit of the estimated growth curve of *A. alcocki* plotted using the length frequency data (ELEFAN G.A.) setting a moving average (MA)=5. **A:** $L_{\infty} = 22.06$ cm and $K = 0.73$ yr^{-1} for female; **B:** $L_{\infty} = 13.69$ cm and $K = 0.73$ yr^{-1} for male; **C:** $L_{\infty} = 15.16$ cm and $K = 0.72$ yr^{-1} year for pooled. ELEFAN method with genetic algorithms. Green dots indicate the running maximum value of the fitness function, while blue dots indicate the mean score of each iteration **A:** male; **B:** female; **C:** pooled *A. alcocki*



**Fig. 5** (continued)

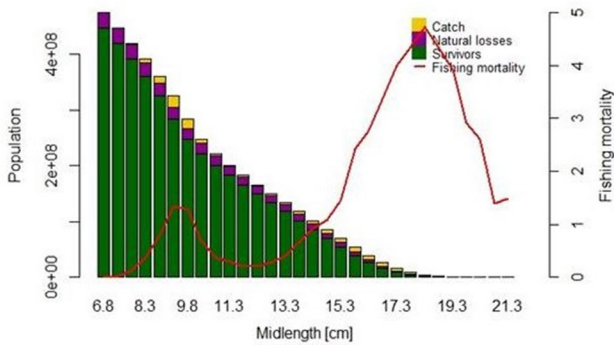
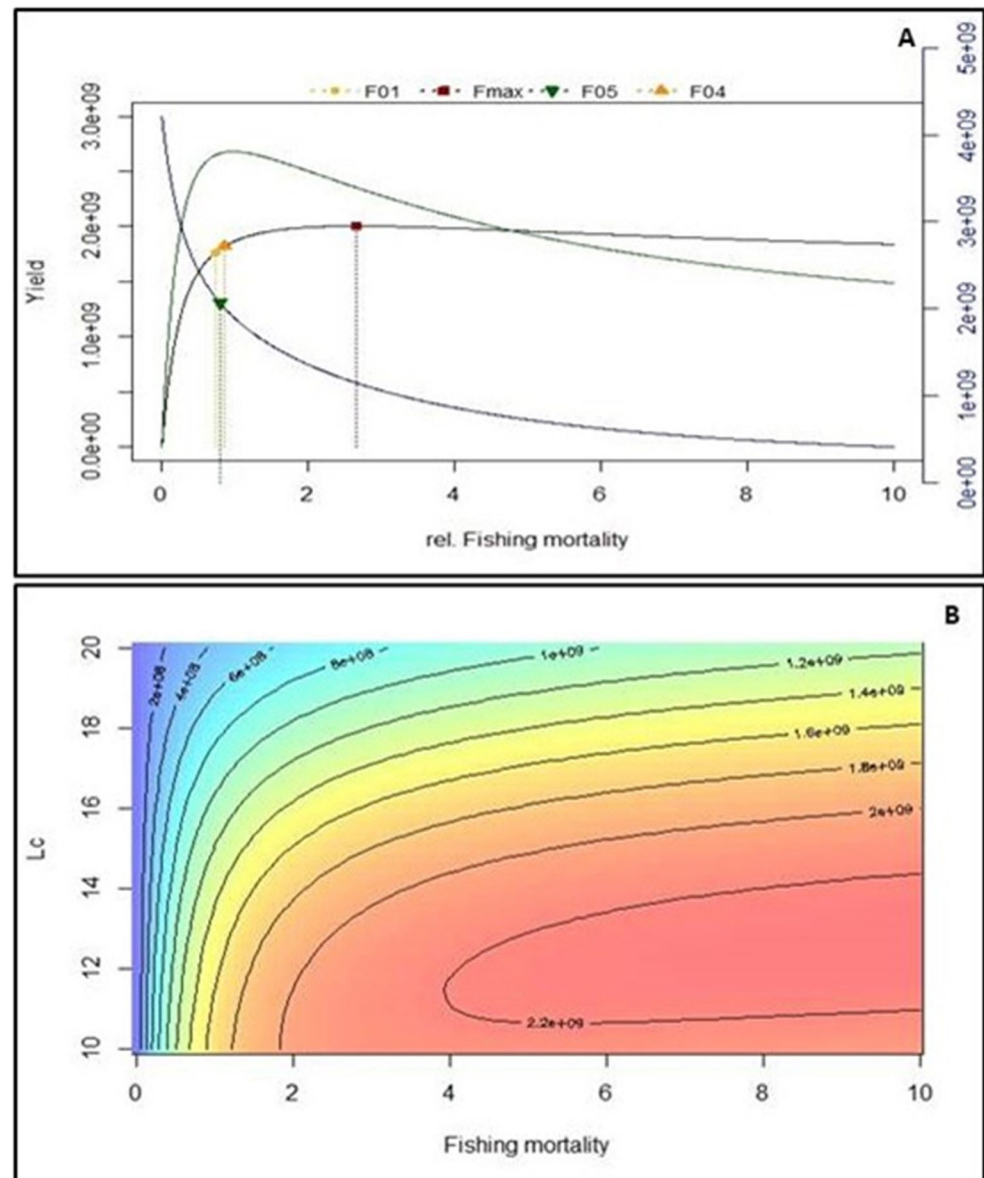


Fig. 6 Results of Jones' length-based cohort analysis (VPA) of *A. alcocki* with the reconstructed population structure (survivors, natural losses and catch) in numbers per length class. Fishing mortality rate by length class of the species indicated by a red line in the plot

Fig. 7 The result of TropFishR. **A:** yield and biomass per recruit analysis when $F_{0.5} = 0.75 \text{ yr}^{-1}$, $F_{0.1} = 0.70 \text{ yr}^{-1}$, $F_{\max} = 2.32 \text{ yr}^{-1}$; **B:** relative YPR contour map in response to different fishing mortality and different length at first capture (L_c)



determined as 1.48 yr^{-1} based on the method developed by Then et al. (2015). M was then subtracted from Z to obtain the fishing mortality rate (F) of 1.86 yr^{-1} . The graphical outputs of the catch curve and YPR model are depicted in Fig. 7, respectively. Biological reference points for fishing mortality and exploitation were also represented in Table 1.

The current fishing mortality calculated for the pooled data ($F_{\text{cur}} = 1.86 \text{ yr}^{-1}$) was lower than the maximum reference fishing mortality ($F_{\text{max}} = 2.32 \text{ yr}^{-1}$) with proxy F_{msy} ($F_{0.1} = 0.7 \text{ yr}^{-1}$ and $F_{0.5} = 0.75 \text{ yr}^{-1}$). The calculated current exploitation rate ($E_{\text{cur}} = 0.56$) was lesser than the maximum reference exploitation ($E_{\text{max}} = 0.748$) with proxy E_{max} ($E_{0.1} = 0.22 \text{ yr}^{-1}$ and $E_{0.5} = 0.24 \text{ yr}^{-1}$). Based on the Thompson & Bell model, biologically maximum yield may be attained when the F_{max} and E_{max} values are 2.32 yr^{-1} and 0.75 respectively.

Length converted catch curve analysis revealed that 50% of the shrimp species vulnerable to fishing mortality ($L_{C_{50}\%}$) at the TL of 12.8 cmor when it attain at age of $tc_{50}=1.064$ yr. The total length at 75% and 95% capture ($L_{C_{75}\%}$ and $L_{C_{95}\%}$) was computed as 14.2 cm and 16.1 cm, respectively and the corresponding age at $tc_{75}\%$ and $tc_{95}\%$ was also observed as 1.25 yr^{-1} and 1.56 yr^{-1} respectively. When $F_{0.5}$ and $E_{0.5}$ are at 0.75 yr^{-1} and 0.24 respectively, half of the stock biomass might also be acquired as the annual yield. When $F_{0.1} = 0.701\text{ year}^{-1}$ and $E_{0.1} = 0.22$ respectively, the biologically sustainable yield could be obtained (Fig. 8).

Spawning stock biomass and spawning potential ratio

Analysing the spawning stock biomass (SSB) of *A. alcocki* alongside the yield obtained in tonnes reveals that both standing stock and spawning stock biomass decrease with increasing yield. At the current yield level, the standing

stock biomass remains around 2000 tonnes and the corresponding spawning stock biomass remains above the limit, with a reference value of 32.9% which is higher than the maximum reference value of 25% (Fig. 9). Spawning Potential Ratio (SPR) of *A. alcocki* was at 0.51 for the year 2017–2022 which is far higher than the reference value of 0.40 (Fig. 10).

Stock status assessment

The Bayesian Schaefer surplus production model (BSM) applied to *Aristeus alcocki* provided critical insights into the stock's status and sustainability. Using catch and abundance data (CPUE, i.e., catch per unit effort) from 2007 to 2022, along with prior knowledge on resilience and depletion status, the analysis estimated key management parameters and indicators (Hilborn and Walters, 1992). While primarily used in data-poor scenarios to provide rough estimates of MSY and F_{msy} , the Bayesian Schaefer surplus production model

Fig. 8 The result of TropFishR. **A:** length-converted catch curve of pooled *A. alcocki*, estimated $Z=3.34\text{ yr}^{-1}$; **B:** the selectivity function of the catch curve

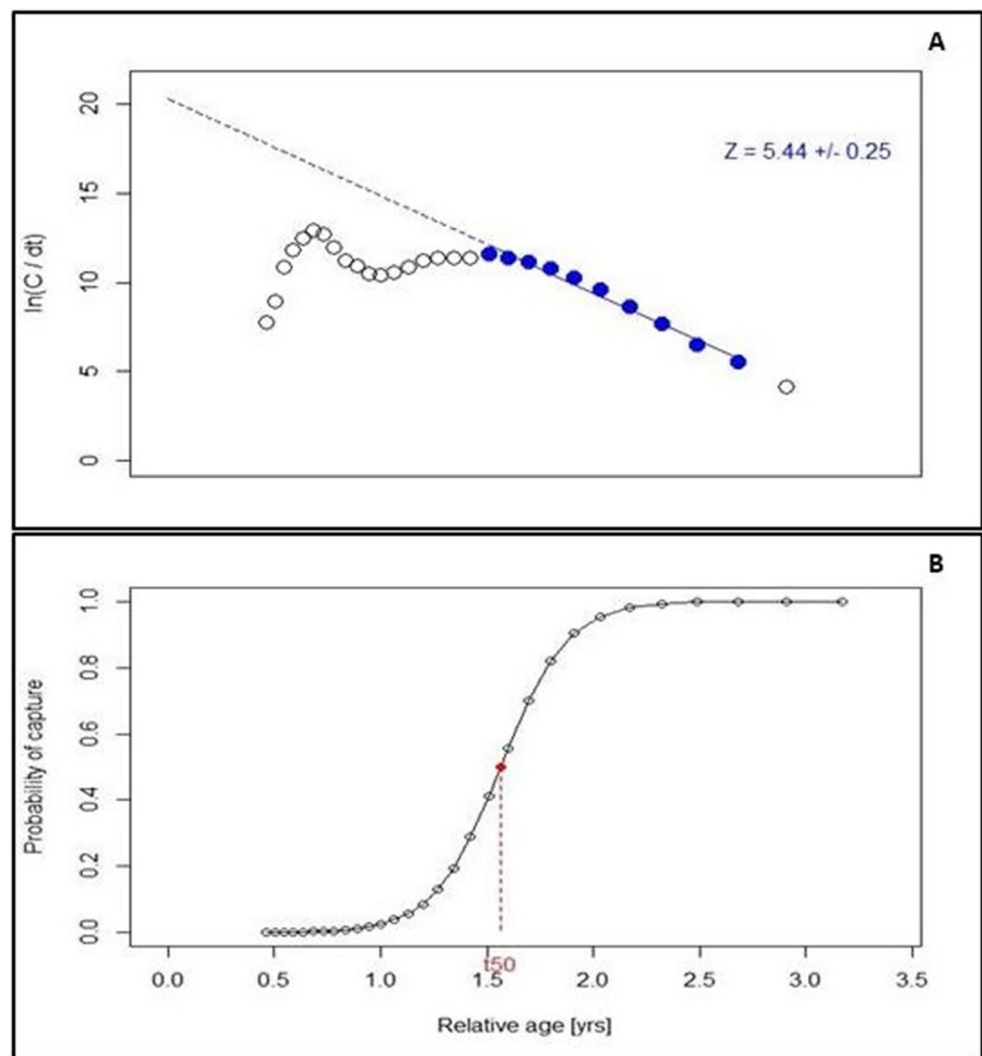


Fig. 9 Spawning stock biomass (SSB) of *A. alcocki*

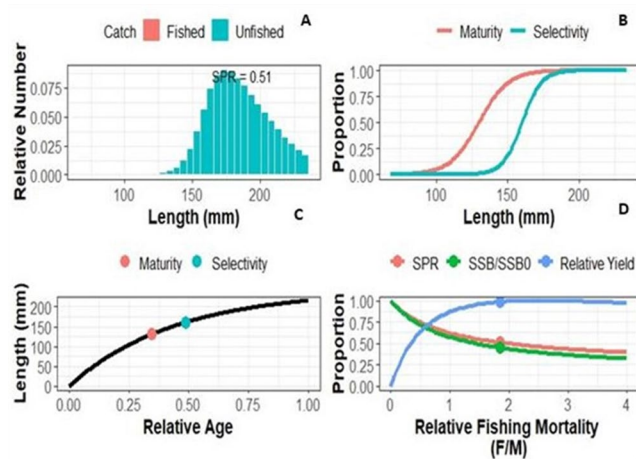
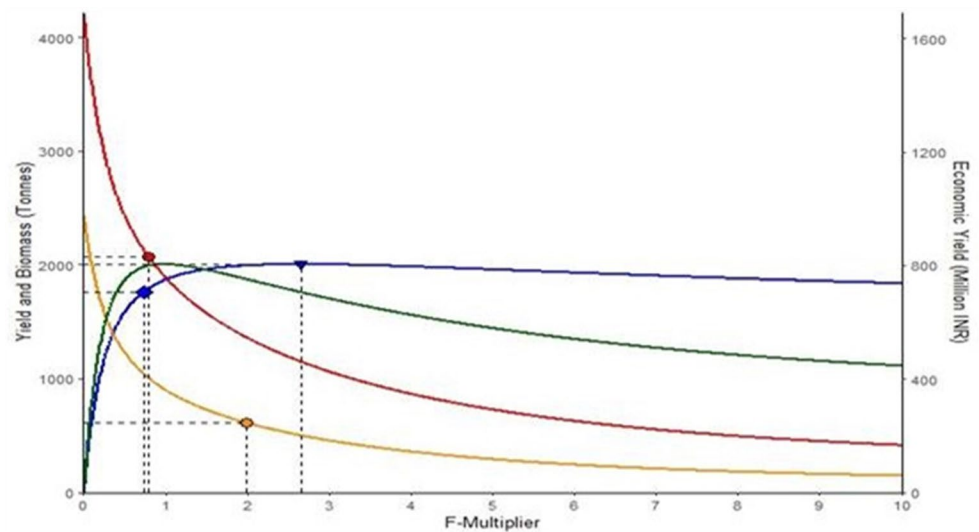


Fig. 10 Function plots: (A) the expected (equilibrium) size structure of the catch and the expected unfished size structure of the vulnerable population, (B) the maturity and selectivity-at-length curves, (C) the von Bertalanffy growth curve with relative age, and (D) the SPR and relative yield curves as a function of relative fishing mortality

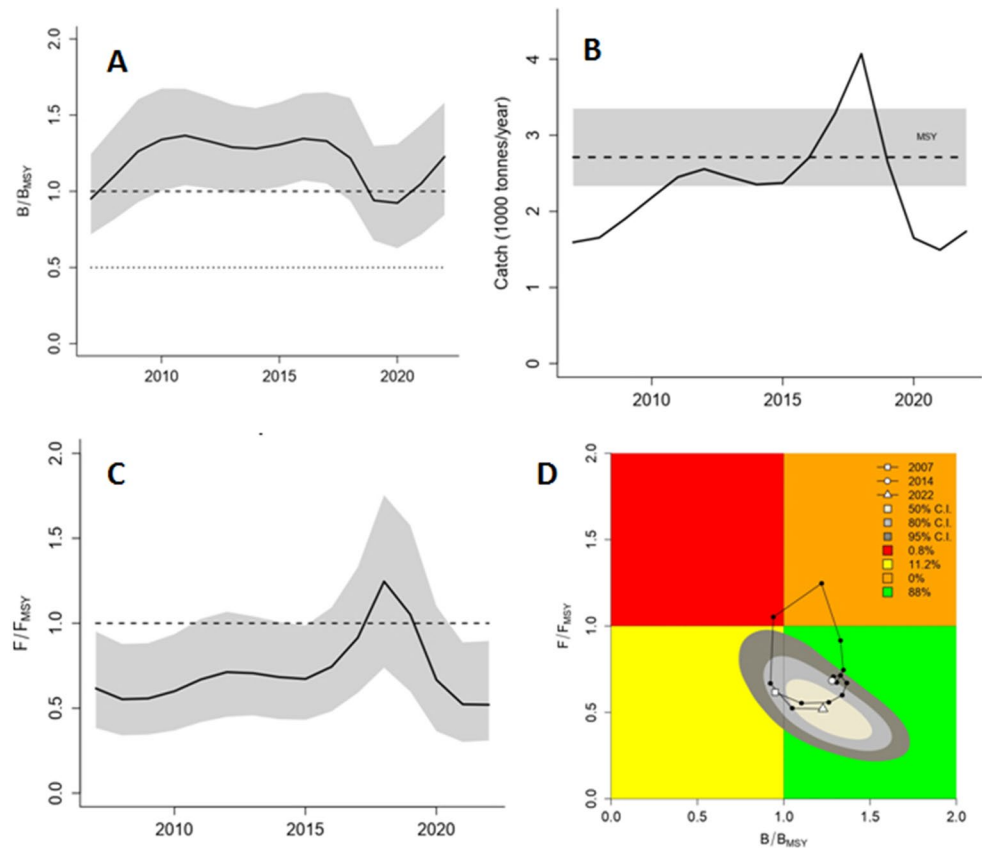
(BSM) can also complement data-moderate and data-rich approaches. Its utility lies in reconstructing the abundance and exploitation trajectories of a population over extended time frames. For *Aristeus alcocki*, initial estimates of depletion status (B/k), biomass status (B/B_{msy}), exploitation status (F/F_{msy}), and key management reference points (i.e., MSY, B_{msy} and F_{msy}) were obtained. These estimates were derived using catch and abundance data (CPUE, i.e., catch per unit effort) from 2007 to 2022, combined with prior knowledge on the species' resilience and depletion status. The findings are summarized in Table 2 and illustrated in Fig. 11. The results indicate that the current biomass relative to carrying capacity (B_{cur}/k) is 0.614 at a high level compared to

Table 2 Resilience, initial and current exploitation and stock biomass status (BSM approach)

Parameters	Mean	CI	Parameters	Mean	CI
r	0.84	0.617–1.13	MSY (1000 tonnes)	2.71	2.33–3.35
k or B_0 (1000 tonnes)	13.00	9.43–18.40	Catch(1000 tonnes)	1.82	
B_{cur} (1000 tonnes)	7.98	3.63–11.70	Catch/MSY	0.99	0.53–1.36
B_{msy} (1000 tonnes)	6.50	4.71–9.21	B_{cur}/k	0.61	0.30–0.77
F_{msy}	0.42	0.31–0.57	B_{cur}/B_{msy}	1.23	0.61–1.54
F_{cur}	0.52	0.31–0.89	F_{cur}/F_{msy}	0.52	0.44–1.56

the initial level (k) of 13.0 thousand tonnes ($B_{cur}/B_{msy}=1.23$) suggesting that the stock biomass is 23% higher than the level required to achieve MSY. The carrying capacity (K) is estimated at 13.0 thousand tonnes (95% CI: 11.3–21.8), with a maximum sustainable yield (MSY) of 2.71 thousand tonnes (95% CI: 2.36–3.79). The current fishing mortality (F_{cur}/F_{msy}) is 0.52, indicating that fishing pressure is almost half compared to the level required to attain MSY. The Kobe plot (Fig. 11D) revealed that there is a high probability (88%) that the stock in the final year of assessment (i.e., 2021) was in the green zone, which indicates that the stock biomass and fishing pressure are healthy and sustainable. The Kobe plot is also providing insight into the long-term performance of the stock, where it can be seen that the stock was in a rebuilding phase (yellow zone) for almost a decade from 2007 to 2014, during which the gradual decrease in targeted fishing pressure would have helped in the revival of stock biomass to a healthy and sustainable level (green zone).

Fig. 11 Relative stock biomass and exploitation status of *A. alcocki* from southwestern Indian waters using the BSM approach



Discussion

The present study using the catch and effort data of *A. alcocki* from 2007 to 2022 was analysed to gain a comprehensive understanding of the species' catch. The average yield of *A. alcocki* was recorded to be over 1800 tonnes during this period. Given that multiple deep-sea shrimp species are caught using a single gear in our tropical fisheries, analyzing the catch and effort of a single species may not yield optimal results. However, the fluctuations in annual catch and CPUE over the study period underscore the need for continuous monitoring and adaptive management strategies. The significant decline in catch during certain years followed by subsequent recoveries indicates the potential impact of environmental and anthropogenic factors on shrimp populations. Fluctuations in fishing efforts are primarily attributed to cyclonic storms in the Arabian Sea and the COVID-19 pandemic, which significantly reduced the number of active fishing days during the season. Additionally, the demand-driven nature of the fishery along the coast means that any change in demand directly impacts landings. The species is typically landed from September to May, with peak fishing activity occurring between December and February. Sustainable management practices should aim to stabilize these fluctuations to ensure a steady supply of this commercially valuable species.

The length-weight relationship established for the deep-sea shrimp species *A. alcocki* in the current study reflects the length classes observed in commercial catches during the specified period. Analysis of the calculated 'b' values for both male and female *A. alcocki* reveals their negative allometric growth ($b < 3.0$). It is clear that the species gain length compared to weight, given that ' b ' < 3 . However, the growth was more negatively allometric ($b < 3$) in females compared to males. This aligns with the findings of Mane et al. (2019), who reported that females, while typically larger in size than males, possess a relatively longer rostrum that grows at a faster rate. This disproportionate growth of the rostrum results in a lack of corresponding weight gain, leading to negatively allometric growth. Similarly, previous studies have noted that females tend to be heavier than males in certain crustacean species (Suseelan and Rajan 1989). Furthermore, the biological parameters ('a' and 'b') determined in this study corroborated well with the reports on *A. antennatus* (Deval and Kapiris 2016) while in other deepsea caridean shrimp, *Heterocarpus chani* showed positive allometry (Kuberan et al. 2022) from the Kerala coast. Effective fisheries management relies on accurate body weight data of species for catch regulation and biomass assessment. The b value is unique to each species and fluctuates with factors such as sex, age, seasonal changes, physiological conditions,

growth rates, and nutritional status. According to Bagenal et al. (1978), the value of parameter 'b' remains relatively stable throughout the year, whereas parameter 'a' may fluctuate based on biological and environmental factors. Parameter 'a' indicates body shape and condition for the same value of 'b' (Froese 2006). In the present study, *A. alcocki* exhibited a slight difference in 'a' values between the sexes, with males at 0.0131 and females at 0.0161.

The overall sex ratio (3.46 : 1.01) observed in the current study, based on data from 2017 to 2022, indicated a higher proportion of females. This finding aligns with the sex ratio calculated for *A. antennatus* caught at depths of 400–700 m, where a similar female bias was observed. In contrast, at greater depths (1000–3000 m), the ratio has been reported to favor males. However, for other deep-sea shrimps, such as *H. chani* caught in the same fishing area, the sex ratio was reported to be equal (Kuberan et al. 2022).

Based on the length composition data of *A. alcocki*, growth parameters were analyzed separately for males and females using the von Bertalanffy growth equation in the ELEFAN function of the TropFishR R package. The calculated asymptotic lengths (L_{∞}) were 13.69 cm for males and 22.06 cm for females, which align well with the maximum recorded lengths of 13.80 cm and 21.5 cm for males and females, respectively.

Large-sized female *A. alcocki* made up a significant portion of the catch in the commercial samples examined in this study. This pattern is similar to the persistent dominance of large females in the *A. antennatus* fishery in the Ligurian Sea, Italy. According to Garofalo et al. (2007), the largest sizes among deep-sea shrimps are the most commercially valuable. Although the length composition data for *A. alcocki* indicates that females reach commercially acceptable sizes, excessive harvesting of females may result in a population decline for this species.

Leena and Deshmukh (2009) estimated sex-specific growth parameters for the penaeid shrimp *Metapenaeus affinis* in the coastal waters off Maharashtra. The sex-wise differences in length asymptotes they reported are comparable to those observed in the present study. Although the growth coefficients for *A. alcocki* are similar (0.73) in both sexes, females achieve larger sizes than males. This difference is likely due to the feeding patterns of females, which appear to be more effective predators. When examining stomach fullness and food quality, female *A. alcocki* were observed to be more efficient predators than males. The stomach content weight of females ranged from 0.01 to 0.48 g, which was significantly greater than that of males, whose stomach content weight ranged from 0.012 to 0.13 g (Paramasivam et al. 2020).

The deep-sea shrimp *A. alcocki* exhibits a continuous breeding pattern, with new cohorts being added to the

population throughout the year. In the present study, the length at first recruitment was found to be in the range of 6.0–6.5 cm. The VPA results indicate that males in the size class of 8.3–9.8 cm and females in the size class of 17.3–19.3 cm experience the highest rates of fishing mortality. According to Paramasivam et al. (2018), the size at maturity for females of *A. alcocki* collected from the southwest coast of India ranges between 12.0 and 17.0 cm, with these females belonging to maturity stages III and IV. For males, the size at maturity was found to be between 8.0 and 9.0 cm. These findings suggest that both male and female *A. alcocki* have sufficient time to reach maturity, reproduce, and contribute offspring to the population.

The 'optimum length' (L_{opt}) indicates the size at which a stock's average weight and population number are at their highest, a key factor in sustainable fisheries management. For *A. alcocki*, the L_{opt} of 12.2 cm aligns with the L_m values reported by Paramasivam et al. (2018) for similar species. This could ensure that newly recruited individuals have the opportunity to join the stock before being exposed to fishing pressure.

The estimated total mortality (Z), fishing mortality (F), and current exploitation (E) rates for *A. alcocki* are lower than the biological reference points in the heavily fished waters off the Southwest coast of India. The natural mortality rate (M) could be defined as the instantaneous rate of population decay on an annual basis due to fisheries-independent factors such as predation, starvation, disease and senescence. M is one of the most important parameters that critically influence the outcome of fisheries stock assessment. Nevertheless, it is also the most difficult parameter to estimate due to a dearth of unbiased tagging data or age-composition data in the absence of fishing (Maunder et al. 2023). There is evidence that suggests that M varies over time, age and sex of the species (Gislason et al. 2010); yet, for ease of analysis and modeling simplicity, a constant M is usually assumed for a stock (Johnson et al. 2015). Gulland (1983) noted that species with higher natural mortality can generally tolerate higher fishing mortality since the fishery targets those that would otherwise succumb to natural causes. The natural mortality rate for *A. alcocki* (1.48), being close to the fishing mortality rate (1.86), indicates that the fishery is sustainable at current levels. These findings provide valuable insights for the effective management and sustainability of the *A. alcocki* fishery. M , calculated from general empirical relationships based on life history theory, has been well reviewed by Then et al. (2015) and Maunder et al. (2023) and the same has been used in the present study. The approach simply assumes that 99% of the fish in an unexploited stock die due to only natural causes when they reach L_{max} which results in an overall survival of 1% at t_{max} (Srinath 1998; Alagaraja 1989). Effective resource

management for *A. alcocki* can be achieved by incorporating scientific studies on mortality parameters, exploitation status, and spawning analysis.

The M/K ratio represents the relationship between natural mortality (M) and the growth coefficient (K) in fish populations. It is often used as a life-history invariant in fisheries science to predict biological parameters when direct estimates are unavailable. A typical M/K value of 1.5 indicates that the species grows throughout its life, reaching maximum size at maximum age (Jensens, 1996). In the case of *A. alcocki*, the M/K ratio value of 1.7 suggests a relatively high natural mortality rate compared to growth, which aligns with characteristics observed in many deep-sea crustaceans, where slow growth and high predation pressures in early life stages influence life-history strategies (Ragonese and Bianchini 2006). Empirical studies have shown that this ratio tends to remain relatively consistent among closely related stocks (Charnov 1993).

The life history parameters of *A. alcocki*, with an asymptotic length (L_{∞}) of 15.16 cm and a growth coefficient (K) of 0.73 yr^{-1} , classify it as a long-lived crustacean with a maximum age (t_{max}) of approximately 5 years. These traits indicate relatively slow growth, consistent with its classification as a moderately resilient species (Froese & Pauly 2000). For sustainable recruitment, a spawning potential ratio (SPR) between 35% and 45% is typically recommended for species with similar life-history traits (Goodyear 1993). In the present study, the LBSPR analysis revealed an SPR of 51% for *A. alcocki*. Clark (2002) suggests that for short-lived, highly resilient species, an SPR of 35–40% or lower is generally sufficient, whereas long-lived, low-resiliency species require a higher SPR, typically in the range of 50–60% or more, to prevent recruitment failure.

The Bayesian Schaefer Surplus Production Model (BSM) analysis of *Aristeus alcocki* indicates a healthy and sustainable stock, with biomass levels 23% above the MSY threshold ($B_{\text{cur}}/B_{\text{msy}} = 1.23$). The carrying capacity (K) is estimated at 13.0 thousand tonnes, and the MSY at 2.71 thousand tonnes. Current fishing mortality ($F_{\text{cur}}/F_{\text{msy}}$) is 0.52, suggesting that fishing pressure is well below the level required for MSY. The Kobe plot analysis shows an 88% probability that the stock was in the green zone in 2021, reflecting a sustainable biomass and fishing pressure (Gabriel and Mace 1999). Historical data also reveal a rebuilding phase from 2007 to 2014, during which reduced fishing pressure allowed the stock to recover to its current healthy state. These results highlight the effectiveness of reduced fishing pressure in stock recovery and the importance of maintaining sustainable fishing practices for long-term stock viability.

Conclusions

The deep-sea shrimp fishery along the southwestern coast of India is predominantly supported by *A. alcocki*, which plays a crucial role in the food supply. This study provides a thorough assessment of the mortality and exploitation rates of *A. alcocki* and offers recommendations for biological reference points. The findings suggest that *A. alcocki* is currently being exploited at an optimal level, but this also indicates a potential risk of overexploitation in the future. The Kobe plot reveals a high probability (88%) that the stock in the final assessment year (2021) is within the “green zone,” indicating healthy biomass and sustainable fishing pressure. Additionally, the stock exhibited a rebuilding phase from 2007 to 2014, during which reduced fishing pressure likely facilitated recovery. These findings suggest that the stock is currently in a sustainable state, with potential for a marginal increase in exploitation to maximize yield while maintaining ecological balance. This comprehensive analysis demonstrates that *A. alcocki* is being managed sustainably, with current measures supporting both stock conservation and potential for cautious exploitation increases.

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Declarations

Ethical statements This study adhered to the ethical standards of the Central Marine Fisheries Research Institute (CMFRI). It is noteworthy that this study did not involve the handling of live or endangered animals.

Conflict of interest The authors declare that they have no conflict of interest.

References

- Alagaraja K (1989) Letter to the editor. *Fishbyte* 7(3):2–3
- Bagenal TB, Tesch FW (1978) Age and growth. In: Bagenal T (ed) *Methods for assessment of fish production in fresh waters*. IBP handbook No. 3, 3rd edn. Blackwell Scientific, Oxford, pp 101–136
- Beverton RJH, Holt SJ (1957) On the dynamics of exploited fish populations. *Fisheries Investigations Ser II* 19:1–533
- Cadrin SX, Secor DH (2009) Accounting for Spatial population structure in stock assessment: Past, present, and future. *Fish Bull* 107(1):1–15
- Chakraborty RD, Purushothaman P, Kuberan G, Sebastian J, Maheswarudu G (2015) Morphological analysis and molecular phylogeny of *Aristeus alcocki* Ramadan, 1938 from the south-west coast of India. *Indian J Geo Mar Sci* 44(11):1716–1725
- Chakraborty RD, Purushothaman P, Maheswarudu G, Kuberan G, Sreesanth L, Ragesh N (2018) Population dynamics of *Aristeus alcocki* Ramadan, 1938 (decapoda: penaeoidea: aristeidae) from Southwestern India. *Reg Stud Mar Sci* 20:64–71
- Chakraborty RD, Sarada PT, Josileen J, Kuriakose S, Sreesanth L, Ragesh N, Augustine SK (2022) Saga of deep sea Prawn fishery of Kerala. *Mar Fisheries Inform Service Tech Ext Ser* 253:15–20
- Chan TY, Suseelan C, Holthuis LB (2017) Deep-sea shrimps of the Indian Ocean. *Smithson Contrib Zool* 645:1–38
- Charnov EL (1993) *Life history invariants: some explorations of symmetry in evolutionary ecology*. Oxford University Press, New York, USA, p 184
- Clark WG (2002) F35% revisited ten years later. *North Am J Fish Manag* 22(1):251–257. [https://doi.org/10.1577/1548-8675\(2002\)022%3C0251:FRYTNL%3E2.0.CO;2](https://doi.org/10.1577/1548-8675(2002)022%3C0251:FRYTNL%3E2.0.CO;2)
- Dall W, Hill BJ, Rothlisberg PC, Staples DJ (1990) Advances in understanding of the biology and management of prawns. *Aust J Mar Freshw Res* 41(1):49–65
- Dash G, Rath A, Das SK (2023a) Model selection for length-weight relationship in aquatic species. *Fish Res* 256:106585
- Dash G, Rath A, Das SK (2023b) AIC-based model comparison for biological studies. *Aquat Ecol* 57(1):45–58
- Deval MC, Kapiris K (2016) Biological parameters of the deep-water shrimp *Aristaeomorpha foliacea* and *Aristeus antennatus* (Decapoda: Aristeidae) in Antalya Bay, Eastern mediterranean. *Cah Biol Mar* 57:151–158
- Froese R (2006) Cube law, condition factor, and weight-length relationships: history, meta-analysis and recommendations. *J Appl Ichthyol* 22(4):241–253
- Froese R, Binohlan C (2000) Empirical relationships to estimate asymptotic length, length at first maturity and length at maximum yield per recruit in fishes, with a simple method to evaluate length frequency data. *J Fish Biol* 56(4):758–773
- Froese R, Demirel N, Coro G, Kleisner K, Winker H (2017) Estimating fisheries reference points from catch and resilience. *Fish Fish* 18(3):506–526
- Froese R, Pauly D (eds) (2000) *FishBase 2000: Concepts, designs, and data sources*. *WorldFish.ICLARM Contributions* 159, 1–344
- Fulton TW (1902) The rate of growth of fishes. *22nd Annual Report of the Fishery Board of Scotland* 141–241
- Gabriel WL, Mace PM (1999) A review of biological reference points in the context of the precautionary approach. In: Restrepo V (ed) *Proceedings of the Fifth National NMFS Stock Assessment Workshop*. NOAA Technical Memorandum NMFS-F/SPO-40, pp 34–45
- García S, Le Reste L (1981) Life cycles, dynamics, exploitation, and management of coastal Penaeid shrimp stocks. *FAO Fisheries Tech Paper* No 203:1–215
- Garofalo G, Guglielmo L, Sinopoli M (2007) Distribution and abundance of *Aristaeomorpha foliacea* and *Aristeus antennatus* (Crustacea: Decapoda) in the central mediterranean sea. *Hydrobiologia* 580:69–84. <https://doi.org/10.1007/s10750-006-0457-8>
- Gislason H, Daan N, Rice JC, Pope JG (2010) Size, growth, temperature and the natural mortality of marine fish. *Fish Fish* 11:149–158
- Goodyear CP (1993) Spawning stock biomass per recruit in fisheries management: Foundation and current use. In: Smith SJ, Hunt JJ, Rivard D (eds), *Risk evaluation and biological reference points for fisheries management*. *Canadian Special Publication of Fisheries and Aquatic Sciences* 120, 67–81
- Gulland JA (1971) The fish resources of the ocean. *Fish News Books* 1–244
- Gulland JA (1983) *Fish stock assessment: a manual of basic methods*. FAO/Wiley Series on Food and Agriculture, Rome, p 241
- Hartnoll RG (2001) Growth in crustacea: twenty years on. *Hydrobiologia* 449(1):111–122
- Hilborn R, Walters CJ (1992) *Quantitative fisheries stock assessment: Choice, dynamics, and uncertainty*. Springer, New York, p 570
- Hordyk AR, Ono K, Valencia SR, Loneragan NR, Prince JD (2015a) A novel length-based empirical estimation method of spawning potential ratio (SPR), and tests of its performance, for small-scale, data-poor fisheries. *ICES J Mar Sci* 72(1):217–231
- Jensen AL (1996) Beverton and holt life history invariants result from optimal trade-off of reproduction and survival. *Can J Fish Aquat Sci* 53:820–822
- Johnson K, Monnahan C, McGilliard C, Vertpre K, Anderson S, Cunningham C, Hurtado-Ferro F (2015) Time-varying natural mortality in fisheries stock assessment models: identifying a default approach. *ICES J Mar Sci* 72:137–150
- King M (2013) *Fisheries biology, assessment, and management*, 2nd edn. Wiley-Blackwell, Hoboken, p 382
- Kuberan G, Chakraborty RD, Sarada PT (2022) Length-weight relationship (LWR) and condition factor (K) of a deep-sea shrimp *Heterocarpus chani* Li, 2006 (Decapoda: caridea: Pandalidae) from the Southern Coast of Indian EEZ. *Thalassas: Int J Mar Sci* 1–9
- Leena PP, Deshmukh VD (2009) Biology and stock assessment of *Metapenaeus affinis* (Decapoda: Penaeidae) from the coastal waters of Maharashtra, India. *Indian J Mar Sci* 38(1):57–65
- Lizarraga L, Silverberg N, Soto LA (2008) Environmental controls on deep-sea shrimp distribution in the Gulf of Mexico. *J Shellfish Res* 27(4):987–994
- Mane S, Sundaram S, Hule A, Sawant M, Deshmukh VD (2019) Length-weight relationship of commercially important Penaeid prawns of Maharashtra, India. *Int Res J Sci Eng* 7(1):35–40
- Maunder MN, Hamel OS, Lee H-H, Piner KR, Cope JM, Punt AE, Ianelli JN, Castillo-Jordán C, Kapur MS, Methot RD (2023) A review of estimation methods for natural mortality and their performance in the context of fishery stock assessment. *Fish Res* 25:106489. <https://doi.org/10.1016/j.fishres.2022.106489>
- Miazaki MA, Garcia J, Rezende KF (2021) Population dynamics of short-lived species in variable environments. *Mar Ecol Prog Ser* 672:157–169
- Mildenberger TK, Taylor MH, Wolff M (2017) Tropfishr: an R package for fisheries analysis with length-frequency data. *Methods Ecol Evol* 8(11):1520–1527
- Paramasivam P, Chakraborty RD, Maheswarudu G, Kuberan G, Baby PK, Sreesanth L, Ragesh N (2018) Reproduction in the deep-sea penaeoid shrimp *Aristeus alcocki* Ramadan, 1938 (decapoda: penaeoidea: aristeidae) from Southwestern India. *J Crustac Biol* 38(1):1–13
- Paramasivam P, Chakraborty RD, Maheswarudu G, Kuberan G (2020) Feeding ecology of deep-water Arabian red shrimp, *Aristeus alcocki* Ramadan, 1938 (Decapoda: penaeoidea: Aristeidae) from Southwestern India (Arabian Sea). *Reg Stud Mar Sci* 40:101500
- Pauly D (1980) On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. *J Du Conseil Int Pour l'Exploration De La Mer* 39(3):175–192

- Pauly D (1983) Some simple methods for the assessment of tropical fish stocks. FAO Fisheries Tech Paper No 234:1–52
- Pauly D, Munro JL (1984) Once more on the comparison of growth in fish and invertebrates. ICLARM Fishbyte 2(1):21
- Plummer M (2003), March JAGS: A program for analysis of Bayesian graphical models using Gibbs sampling. In *Proceedings of the 3rd international workshop on distributed statistical computing* (Vol. 124, No. 125.10, pp. 1–10)
- Purushothaman P, Chakraborty RD, Kuberan G, Maheswarudu G (2020) Feeding ecology of deep-water Arabian red shrimp, *Aristeus alcocki* Ramadan, 1938 (Decapoda: penaeoidea: Aristeidae) from Southwestern India (Arabian Sea). Reg Stud Mar Sci 40:1–14
- Purushothaman P, Chakraborty RD, Kuberan G, Maheswarudu G, Baby PK, Sreesanth L, Pazhayamadom G (2018) Stock structure analysis of ‘*Aristeus alcocki* Ramadan, 1938 (Decapoda: Aristeidae)’ in the Indian Coast with truss network morphometrics. Can J Zool 96(5):411–424
- Purushothaman P, Chakraborty RD, Maheswarudu G, Kuberan G (2020b) Investigation of genetic diversity and stock structure of *Aristeus alcocki* Ramadan, 1938 (Decapoda: Aristeidae) populations in the Indian Coast with microsatellite markers. Fish Res 227:1–7
- Quinn TJ, Deriso RB (1999) Quantitative fish dynamics. Oxford University Press, New York, p p 542
- Ragonese S, Bianchini ML (2006) Trawl selectivity trials on the deep-water rose shrimp (*Parapenaeus longirostris*) in Sicilian waters. Hydrobiologia 557:113–119
- Rao GS (1988) Studies on biometric parameters for fishery management. Indian J Mar Sci 17(1):15–19
- Ricker WE (1973) Linear regressions in fishery research. J Fish Res Board Can 30(3):409–434
- Ricker WE (1975) Computation and interpretation of biological statistics of fish populations. Bull Fish Res Board Can 191:1–382
- Schaefer MB (1954) Some aspects of the dynamics of populations important to the management of the commercial Marine fisheries. Inter-American Tropical Tuna Commission 1:7–56
- Snedecor GW, Cochran WG (1967) Statistical methods, 6th edn. Iowa State University, Ames, p 593
- Spiegel MR (1991) Theory and problems of statistics. McGraw-Hill, New York, p p 508
- Srinath M (1998) Empirical relationships to estimate the instantaneous rate of natural mortality. Indian J Fisheries 45(1):7–11
- Suseelan C (1989) Taxonomic studies on deep-sea prawns of the Indian Ocean. Mem Zool Surv India 18(3):1–120
- Suseelan C, Rajan KN (1989) Stock assessment of the Kiddi shrimp (*Parapenaeopsis stylifera*) off Cochin, India. In: *Contributions to tropical fish stock assessment in India: FAO/DANIDA/ICAR National Follow-up Training Course on Fish Stock Assessment, 2–28 November 1987, Cochin*.
- Taylor MH, Mildenerberger TK (2017) TropFishR: stock assessment with length frequency data. J Open Source Softw 2(1):56
- Then AY, Hoenig JM, Hall NG, Hewitt DA & Handling editor: Ernesto Jardim (2015) Evaluating the predictive performance of empirical estimators of natural mortality rate using information on over 200 fish species. ICES J Mar Sci 72(1):82–92
- Thorson JT (2014) Standardizing CPUE data with a bayesian state-space model. ICES J Mar Sci 71(3):668–676
- Von Bertalanffy L (1938) A quantitative theory of organic growth (inquiries on growth laws. II). Hum Biol 10(2):181–213
- Welcome RL (1979) Fisheries ecology of floodplain rivers. FAO Fisheries Tech Paper No 187:1–375

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