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Fisheries exploitation and management of the narrow-barred Spanish mackerel, *Scomberomorus commerson* (Lacepède, 1800), in the eastern Red Sea

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The narrow-barred Spanish mackerel, *Scomberomorus commerson*, is a highly valuable commercial species in the Red Sea. Annual landings along the Saudi Arabian Red Sea coast average approximately 2, 380 tonnes, generating nearly 35 million USD in revenue. Given this economic importance, effective fishery management is essential. This study assessed the growth, maturity, and mortality of *S. commerson* using fishery-dependent samples collected from the eastern Red Sea between 2022 and 2024. Total length (L, n = 4, 432) ranged from 10.0 to 151.0 cm, and total weight (W, n = 1, 683) varied from 9 to 17, 694 g. L–W relationships were $W = 0.0088 \times L^{2.90}$ for females and $W = 0.0143 \times L^{2.78}$ for males. The von Bertalanffy growth parameters, estimated via otolith reading, were L_∞ = 151.55 cm, K = 0.18 year^{-1}, and t_0 = –0.83 years. Median length at first maturity was 39.71 cm, with no significant difference between sexes. Mean natural mortality rate, averaged across three empirical models, was 0.27 year^{-1}. Total mortality rate, derived from a linearized decay model, was 0.58 year^{-1}, giving a calculated fishing mortality rate of 0.31 year^{-1}. Virtual population analysis provided age-specific fishing mortality rates as input for yield-per-recruit and spawning potential ratio (SPR) analyses. SPR analysis revealed that the current fishing pattern has reduced the spawning stock biomass to approximately 25% of its unfished level. The exploitation rate was 0.53, exceeding the limit reference point of 0.5. The fishery, dominated by handlines and gillnets, captures individuals across a broad size range, with immature fish comprising 17% of total landings. Most juveniles are taken incidentally as bycatch in the shrimp-trawl fishery. To promote stock recovery and long-term sustainability, management measures are recommended, including a 40% reduction in fishing effort, seasonal closures during spawning periods, and improvements in gear selectivity to minimize juvenile catch.

KEYWORDS
age reading, growth, kingfish, mortality, Saudi Arabian coast, Scombridae, stock assessment

1 Introduction

The narrow-barred Spanish mackerel, *Scomberomorus commerson* (Lacepède, 1800), is a pelagic migratory species belonging to the Scombridae family, inhabiting near the edge of the continental shelf to shallow coastal waters between the 10–70 m depth (Froese and Pauly, 2025). As an important commercial fish, it is commonly called "kingfish" and locally referred to as 'Dhirak' in the Red Sea region. The species is renowned for long–shore migrations (Randall, 1995) and holds high commercial importance in global fisheries (FAO, 1999), contributing significantly to catches in many regions.

Recent catch statistics from the Saudi Arabian Ministry of Environment, Water, and Agriculture (MEWA) and the Food and Agriculture Organization (FAO) (Alshaikhi et al., 2023; FAO, 2024) indicate that the average annual landings of *S. commerson* from the Saudi Arabian Red Sea coast totaled approximately 2, 380 tonnes over the period 2019–2023. With market prices exceeding 15 USD per kg and its position as one of the region's most popular fish species, the fisheries revenue from this species contributes nearly 35 million USD annually to the national economy. However, high market demand has driven intense fishing pressure, leading to substantial population declines in several regions (Govender et al., 2005), including the Gulf Cooperation Council (GCC) countries (Jayabalan et al., 2011). As a result, *S. commerson* is classified as Near Threatened (NT) by the International Union for Conservation of Nature (IUCN, 2020), reflecting its vulnerability to overexploitation.

The Red Sea harbors extensive coral reef ecosystems that play a critical role in supporting marine biodiversity and fisheries in the region. Saudi Arabia, which constitutes much of the Red Sea's eastern coastline, is home to a thriving small-scale artisanal fishery, especially around reef habitats, that substantially contributes to the local economy. Although there is substantial information on various aspects of *S. commerson*, including growth (Grandcourt et al., 2005; Roa-Ureta et al., 2019), age determination (Grandcourt et al., 2005), reproduction (Claereboudt et al., 2005), and stock status (Meriem et al., 2006; Roa-Ureta et al., 2019; Al-Shehhi et al., 2021), the majority of these studies are confined to the Arabian Gulf, the Gulf of Oman, and the Arabian Sea. There is a notable lack of fundamental life-history and stock assessment data for *S. commerson* in the Red Sea, and consequently, no species-specific management regulations are currently in place to safeguard its sustainable exploitation in this region. Given the high commercial importance of the species, this study aims to fill that gap by providing a comprehensive assessment of its life-history traits and population status in the Saudi Arabian Red Sea. Key aspects investigated include length-weight relationship, otolith-based age determination, age-length keys, growth parameters, size at first maturity, mortality rates, and preliminary stock assessment using the yield-per-recruit analysis and its extension, the spawning potential ratio analysis. The results are intended to inform effective, evidence-based management and conservation strategies for this commercially valuable species.

2 Materials and methods

2.1 Study area and biological data collection

Monthly sampling of *S. commerson* was carried out from March 2022 to November 2024 at nine major landing sites distributed along a 1, 300 km stretch of the eastern Red Sea coastline, extending from Duba in the north to Jizan in the south (Figure 1). These sites were selected based on fisheries statistics provided by the MEWA, as well as preliminary field surveys. During 2022 and 2023, a total of 1, 683 specimens were collected from commercial fisheries and examined in the laboratory. The type of fishing gear used to capture the specimens (e.g., gillnets, handlines, and trawls) was also recorded. For each specimen, total length (L) was measured to the nearest mm, and total weight (W) was registered to the nearest g using an electronic balance. An additional 1, 159 and 1, 590 specimens were collected from shrimp trawl bycatch in 2023 and from landing sites in 2024, respectively; for these specimens, only L was recorded. Initial exploratory data analysis indicated that both L and W data were right-skewed, a common pattern in biological measurements such as growth, likely due to the lower frequency of older and larger individuals. Formal statistical tests confirmed violations of the assumptions of normality (Shapiro–Wilk test) and homoscedasticity (F-test for equality of variances), supported by visual inspection of normal quantile plots (Quinn and Keough, 2002). Notably, the distribution shapes of L and W were similar between sexes. To address these violations and enable valid comparisons of central tendency, a natural log transformation was applied to both L and W measurements. Welch's t-test was then used to compare the mean log-transformed values between sexes. This test was selected because it does not assume equal variances between groups and is robust to moderate departures from normality, particularly with large sample sizes, as in this study (Quinn and Keough, 2002).

2.2 Sex and maturity

Sex and maturity status of sampled fish were determined according to Nikolsky (1976), using macroscopic examination of gonads under standardized lighting conditions to ensure consistency. Maturity stages were visually assigned using a seven-stage macroscopic scale: 0 – Undetermined sex; 1 – Immature; 2 – Resting; 3 – Developing; 4 – Maturing; 5 – Mature; and 6 – Spent. Individuals classified as stage 2 or higher were considered "mature", while those in stages 0 and 1 were designated as "immature." An exact binomial test was performed to compare the observed sex ratio to the expected 1:1 proportion (Wilson and Hardy, 2002). To evaluate temporal and seasonal variation in sex ratios, a log-likelihood ratio test (G-test) was employed (Quinn and Keough, 2002). The median length at first maturity, defined as the L at which 50% of individuals in the population are sexually mature (L_{50}), was

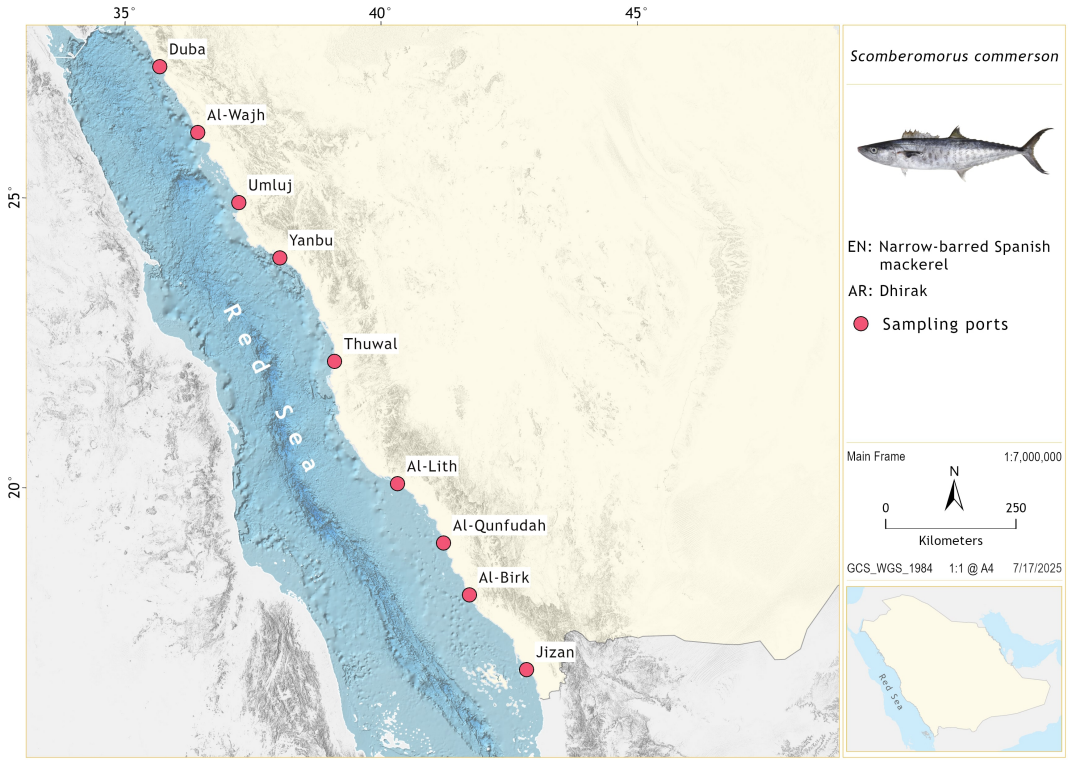


FIGURE 1
Map showing the ports where *S. commerson* specimens were sampled along the eastern Red Sea.

estimated using logistic regression (Quinn and Keough, 2002) by modeling the relationship between L and the binary maturity status:

$$P = \frac{e^{a+b\times L}}{1 + e^{a+b\times L}}$$

where P is the probability that an individual is mature at a given L, and a and b are model coefficients. A generalized linear model with a binomial error distribution and a logit link function (Agresti, 2019) was applied separately for females and males to estimate these coefficients. Once the coefficients were obtained, L_{50}, corresponding to the inflection point of the logistic curve, was calculated as:

$$L_{50} = \frac{-a}{b}$$

Uncertainty in the L_{50} estimate is not straightforward to evaluate, as the standard error of the ratio of a and b is not directly available (Roa et al., 1999; Aydın and Tıraşın, 2023). To address this, nonparametric confidence intervals (CIs) for L_{50} were derived using 5, 000 bootstrap samples and the bias-corrected and accelerated (BCa) bootstrap method (Efron and Tibshirani, 1993), following the approach of Aydın and Tıraşın (2023). These BCa bootstrap CIs were then used to assess whether L_{50} differed significantly between females and males by examining whether their ranges overlapped. Juvenile individuals of undetermined sex were included in the estimation of L_{50} for both sexes, under the assumption that their presence reflects the shared immature size structure of the population and that they contribute equally to the logistic model fitting for males and females.

2.3 Otolith extraction and reading

Sagittal otoliths (n = 131) were extracted from *S. commerson* specimens ranging from 10 to 151 cm L. Individuals selected for ageing were chosen randomly from routine samples collected throughout the study period, with the aim of representing the broadest possible size range observed in the landings. Sampling was not stratified by location or season, nor guided by prior biological assumptions regarding growth patterns. Although efforts were made to include specimens across the full size spectrum, relatively few very large individuals were available in the catch; consequently, only a limited number of otoliths were obtained from the largest size classes. This distribution reflects the size composition of the sampled fishery rather than intentional size-selective sampling. Each otolith was cleaned, marked, and embedded in resin to facilitate precise sectioning. Thin transverse sections (approximately 400–500 µm thick) were prepared using a low-speed saw, with thickness adjusted as needed based on microscopic inspection to ensure optimal clarity for annuli observation. Final polishing was performed by grinding the sections with an EcoMet™ 30 Twin Manual Grinder Polisher (Buehler). The polished sections were mounted on glass slides using CrystalBond™ 509 adhesive to maintain stability during analysis. Age determination was performed under a Leica M205C stereomicroscope at 40x magnification. Annuli were defined as alternating opaque and translucent bands visible under transmitted light, with the opaque band interpreted as the annual growth mark. The edge type was classified according to the relative

completeness of the outermost translucent or opaque zone at the otolith margin. Annuli were counted along the ventral margin of the sulcus acousticus, extending from the nucleus to the proximal edge of the otolith (Figure 2). To enhance accuracy, otolith images were digitally processed, and readings were performed independently by two experienced readers. Each reader made two nonconsecutive annulus counts for all otoliths without prior knowledge of the specimen's size or previous readings. The coefficient of variation (CV) and average percent error (APE) were then calculated to assess precision and reproducibility between readers (Campana, 2001). An age-length key was developed from otolith-derived age estimates and corresponding L measurements, enabling the conversion of aggregated L frequency data into age frequency distributions for subsequent analyses (Ogle, 2016).

2.4 Length-weight relationship and growth

The relationship between W and L was modeled using the nonlinear allometric equation (Quinn and Deriso, 1999):

$$W = a \times L^b$$

where a is the coefficient of proportionality and b is the allometric exponent that describes how W changes with L. Assuming a multiplicative error structure, the parameters a and b were estimated through linear regression analysis of the natural log-transformed W and L data. An analysis of covariance (ANCOVA) was conducted to test for significant differences in the a and b estimates between males and females. To assess deviations from isometric growth ($b = 3$), the 95% CI for the estimated b value was examined to determine whether it included 3 (Quinn and Deriso, 1999).

To describe the growth of *S. commerson*, L-at-age (L_t) data obtained from otolith readings were analyzed using the von Bertalanffy (1938) Growth Model (VBGM), according to the following equation (Quinn and Deriso, 1999):

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

where L_∞ is the asymptotic L, K is the growth coefficient, t is the observed age, and t_0 represents the theoretical age at which fish L is zero. The VBGM was fitted separately for each sex, as well as for the combined dataset, using nonlinear regression (Ritz and Streibig, 2008), assuming independent, additive, and normally distributed errors. The normality of residuals from the fitted models was assessed using normal quantile plots and the Shapiro–Wilk test, while the homogeneity of residual variances between sex-specific models was evaluated using an F-test. Differences in the estimated growth parameters between males and females were tested using the likelihood-ratio test framework (Kimura, 1980; Cerrato, 1990). The resulting test statistic was compared to the chi-square distribution with the appropriate degrees of freedom. A significant test result, indicating a better fit of the full model with sex-specific parameters over the reduced model with pooled data, was interpreted as evidence of sexually dimorphic growth. Additional methodological and statistical details are provided in Kimura (1980); Cerrato (1990), and Quinn and Deriso (1999).

2.5 Mortality

The total mortality rate (Z) was estimated using the classical nonlinear exponential decay model, which assumes a constant rate of decline in the abundance of a fish cohort over time (Sparre and Venema, 1998; Quinn and Deriso, 1999):

$$N_t = N_0 \times e^{-Zt}$$

N_t represents the number of fish at age t, while N_0 denotes the initial population size. Assuming a multiplicative error term, the model was linearized by applying a natural logarithmic transformation, enabling analysis via linear regression (Sparre and Venema, 1998; Quinn and Deriso, 1999). The dependent variable, N_t, was estimated by scaling (raising) the observed sample numbers (otolith-derived age data) to match the annual landings of the species in the Red Sea, based on official statistics from MEWA and FAO (Alshaikhi et al., 2023; FAO, 2024). This raising procedure was considered necessary because the aged sample represented only a subsample of the total catch; therefore, the observed age frequencies were proportionally adjusted to approximate the age composition of the full annual landings prior to mortality estimation. To account for interannual variability and provide a more stable estimate, the

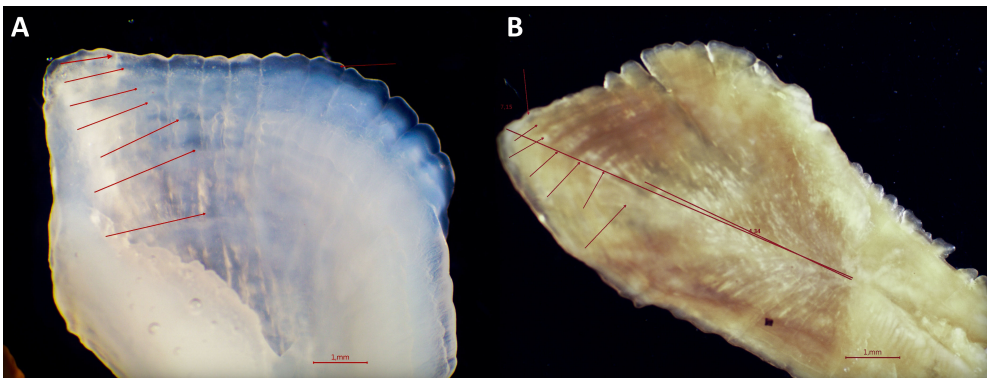


FIGURE 2
Otolith shape of age group 7 of *S. commerson* in the eastern Red Sea. **(A)** Otolith from a specimen of 127 cm total length; **(B)** otolith from a specimen of 122.5 cm total length, both from female individuals sampled from Jizan. Red arrows indicate the hyaline growth bands forming the annuli.

calculations were based on the average of the landings from five consecutive years (2019–2023). Initial ascending N_t values representing fish that were not fully recruited to the fishery were excluded from the analysis.

Following the recommendations of Quinn and Deriso (1999); Kenchington (2014), and Maunder et al. (2023), the natural mortality rate (M) for *S. commerson* was estimated as the average of values obtained from three empirical methods, two proposed by Hamel and Cope (2022) and one by Then et al. (2015), rather than relying on a single approach:

$$M = {}^{5.4}/_{t_{max}}$$

$$M = 1.55 \times K$$

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

In these equations, t_{max} represents the species' longevity (maximum age), and K and L_{∞} are the VBGM parameters. Otolith readings and previous studies suggested a minimum t_{max} value of 18 years for *S. commerson*. All three methods were recently endorsed in a comprehensive review by Maunder et al. (2023), which evaluated available approaches for estimating M in fish stocks. Given that Z is the sum of M and the fishing mortality rate (F), the F for *S. commerson* was calculated by subtracting the M value from the Z estimate: $F = Z - M$.

The F estimated as described above was assumed to be constant across all age groups, consistent with the Z and M estimates. To derive age-specific estimates of fishing mortality, commonly referred to as the fishing pattern or F-at-age array, Virtual Population Analysis (VPA) was employed. This approach, designed to reconstruct historical population dynamics, estimates the number of fish alive in each age class by solving the Baranov catch equation retrospectively, starting with the oldest age group (Sparre and Venema, 1998; Quinn and Deriso, 1999). The analysis incorporated the same age-assigned landings data used previously to estimate Z through linear regression analysis of a pseudo-cohort. In other words, fish of different ages, representing several consecutive cohorts, were treated analytically as if they belonged to a single cohort for the purpose of the VPA. The model also incorporated the previously derived estimates of M and F, with the latter used as the initial estimate of terminal F.

2.6 Stock status evaluation

A preliminary assessment of the stock status of *S. commerson* along the eastern Red Sea coast of Saudi Arabia was conducted using yield-per-recruit (Y/R) analysis, along with estimates of the spawning potential ratio (SPR) and exploitation rate (E). SPR is a key indicator of reproductive potential under current fishing pressure. Defined by Goodyear (1993), it is the equilibrium spawning stock biomass (SSB) per recruit (SSB/R) at a given F, relative to the SSB/R in an unfished population. This metric builds on the traditional models of Thompson and Bell (1934) and Beverton and Holt (1957), extending their Y/R and biomass-per-recruit (B/R) frameworks. Like B/R, SPR calculations follow the same principles but focus only on the mature, spawning portion of the stock (Gabriel et al., 1989; Goodyear, 1993). SPR ranges from 1 (or 100%) in an unfished state ($F = 0$) and declines toward 0 as F increases. Both predictive models assume that the stock is in a state of equilibrium, meaning that recruitment, natural mortality, and growth remain relatively constant over time. Additionally, it is assumed that the fishing pattern has remained stable for a sufficient duration such that all age classes have been exposed to the same exploitation regime since recruitment.

A Thompson and Bell model (TBM) (Gabriel et al., 1989; Sparre and Venema, 1998) was applied to estimate the Y/R and SPR of the female component of the *S. commerson* stock under the current fishing pattern. Input data included age-specific fish numbers (the same dataset used in VPA), mean weights-at-age, reference F-at-age array (obtained from VPA), and a constant M across all ages. Proportions of mature female fish in each age class were estimated using logistic regression, and SSB was computed accordingly. Following the evaluation of the current state of the stock, the analysis was extended to predict the potential effects of changes in fishing effort on future yields and reproductive output. Changes in effort were simulated by scaling the reference F-at-age array with a fishing mortality factor (F-factor), a vector of incremental values ranging from 0 to 2, spaced by small increments. For example, an F-factor of 0.5, representing a 50% reduction in current fishing effort, was applied by multiplying all age-specific F values by 0.5, yielding corresponding predictions for catch, yield, biomass, and SSB. An F-factor of 1 reflected the current fishing pattern and served as the baseline for comparison.

The Y/R analysis provides two key reference points: F_{max}, the rate producing maximum Y/R and considered a limit reference point (LRP) indicating unsustainable fishing pressure if exceeded (Caddy and Mahon, 1995); and $F_{0.1}$, a more precautionary target reference point (TRP), defined as the F at which the Y/R curve slope is 10% of the slope at the origin (Quinn and Deriso, 1999). The TRP represents the desired level of stock biomass (SB) or F, aimed at achieving long-term sustainability and optimal yield while maintaining the stock's health and productivity (Caddy and Mahon, 1995; Prager et al., 2003; Haddon, 2011). Y/R analysis focuses on growth overfishing but does not account for the impact of fishing on the reproductive capacity of the stock (Clark, 1991; Mace, 1994; Quinn and Deriso, 1999). SPR analysis complements this by evaluating recruitment overfishing through changes in SSB under fishing pressure (Mace and Sissenwine, 1993; Quinn and Deriso, 1999; Walters and Martell, 2004). A minimum SPR of 0.4 is widely recommended as a TRP, with the corresponding F denoted as $F_{40\%}$ to prevent stock depletion and mitigate the risk of recruitment overfishing (Goodyear, 1993; Mace, 1994; Clark, 2002). An SPR of 0.3, reflecting increased risk of recruitment failure, is used in this study as the LRP (Walters and Martell, 2004).

The E was calculated as the ratio of F to Z. In assessing the sustainability of the observed E estimate, a value of 0.5 is commonly used as an LRP, representing the upper threshold of sustainable fishing pressure that should not be exceeded. This benchmark is based on the principle that F should not surpass M, expressed as $F/M \leq 1$ (Thompson, 1993; Froese et al., 2016).

All statistical analyses and graphical visualizations were conducted using R software version 4.4.3 (R Core Team, 2025), with a 5% significance level applied to all statistical tests.

3 Results

3.1 Sex ratio and length-weight relationship

Of the 1, 683 dissected *S. commerson* specimens, 944 were identified as female, 589 as male, and 150 were sexually immature and therefore of undetermined sex. An exact binomial test revealed that the overall female-to-male sex ratio (F:M) of 1.6:1 deviated significantly from the expected 1:1 ratio. According to the log-likelihood ratio test (*G*-statistic), this overall ratio did not vary significantly across years or between summer and winter seasons. Females consistently outnumbered males across all age classes, with the predominance becoming increasingly pronounced in older age groups, particularly beyond age 5. *L* measurements (n = 4, 432) ranged from 10.0 to 151.0 cm, while *W* measurements (n = 1, 683) varied from 9 to 17, 697 g. Welch's *t*-test indicated no significant differences in mean *L* or mean *W* between sexes (Table 1). The *L* frequency distribution of *S. commerson* from the eastern Red Sea, stratified by sex, is shown in Figure 3.

The analysis of covariance of *L*-*W* data revealed significant differences in the *a* and *b* values between sexes. The estimated values of *a* (95% CI) and *b* (95% CI) were 0.00885 (0.00817–0.00959) and 2.90 (2.88–2.92) for females (n = 944), and 0.01428 (0.01246–0.016346) and 2.78 (2.75–2.81) for males (n = 589), respectively (Figure 4). Both sexes exhibited a negative allometric growth pattern.

3.2 Maturity

The L_{50} (95% BCa CI) was estimated at 39.94 (38.57–41.29) cm for females and 39.60 (37.86–41.28) cm for males. Comparison of

TABLE 1 Summary statistics for total length and weight of *S. commerson* collected at nine ports along the eastern Red Sea coast from Duba to Jizan between 2022 and 2024.

Statistics	Total length (cm)				Weight (g)			
	Juvenile	Female	Male	Combined	Juvenile	Female	Male	Combined
n	150	944	589	1683	150	944	589	1683
Mean	20.4	58.1	59.4	55.4	55	1, 704	1, 594	1, 530
Median	20.0	53.8	61.0	54.0	68	900	1, 240	910
SD	4.4	21.4	19.7	22.5	48	2, 395	1, 476	2, 048
Minimum	10.0	19.5	15.4	10.0	9	41	26	9
Maximum	38.0	151.0	127.0	151.0	370	17, 697	11, 146	17, 697

Statistics are presented separately for juveniles (individuals of unidentified sex), females, males, and the combined sample. *n* and SD denote the number of specimens in each category and standard deviation, respectively.

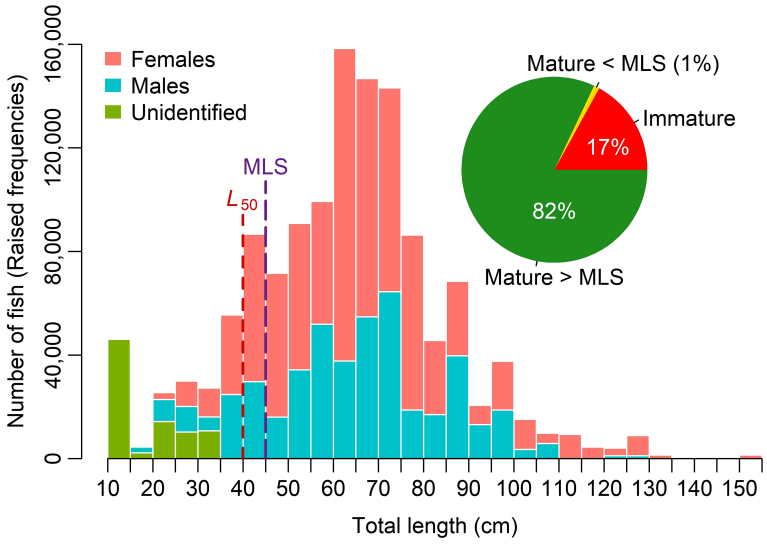


FIGURE 3
Total length (*L*) frequency distribution (in 5 cm intervals) of *S. commerson* from the eastern Red Sea, stratified by sex. Data were adjusted (raised) based on annual landings reported in MEWA-FAO official statistics (Alshaikhi et al., 2023; FAO, 2024). Estimated proportions of immature fish ($L < 40$ cm), mature fish below the minimum landing size (MLS) of 45 cm ($40 \text{ cm} \leq L < 45$ cm), and mature fish above the MLS ($L \geq 45$ cm) in the overall landings are also shown.

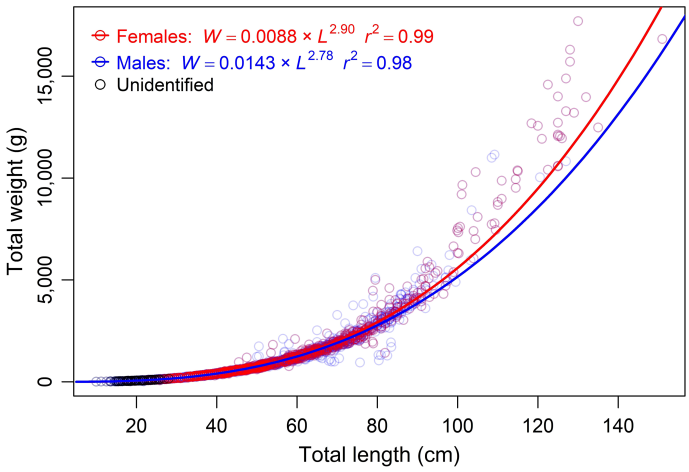


FIGURE 4
Total length-weight relationship of female and male *S. commerson* sampled from the eastern Red Sea.

the nonparametric BCa 95% confidence intervals, generated separately for each sex via bootstrapping, revealed no significant difference in L_{50} between sexes. The overall L_{50}, estimated from the logistic model, was 39.71 cm, with a BCa 95% CI of 38.55 to 40.86 cm (Figure 5). When the observed L frequency data were adjusted to match annual landings reported in MEWA–FAO statistics for the Red Sea (Alshaikhi et al., 2023; FAO, 2024), individuals classified as immature ($L < L_{50}$) accounted for approximately 17% of the total annual catch (Figure 3). Conversely, fish assumed to be mature ($L \geq L_{50}$) comprised 83% of the catch.

3.3 Age and growth

Otolith readings indicated that the youngest individual was a male less than one year old, measuring 15.5 cm in L, while the oldest was an 18-year-old female with a L of 151 cm (Table 2). The maximum age recorded for males was 10 years, corresponding to a L of 127 cm. Older and larger individuals (> 5 years and > 90 cm) were predominantly female (Figure 3). The precision between readers was high, with an APE of 5.17% and a CV of 3.6%. These values indicate good reproducibility and fall well within the range typically considered acceptable in otolith-based age determination studies (Campana, 2001).

The VBGM parameters, estimated separately for each sex and combined, are summarized in Table 3. A likelihood ratio test revealed no statistically significant difference between the reduced model (with combined data and shared parameters) and the full model (with sex-specific parameters). Consequently, the differences in parameter estimates between sexes were deemed non-significant. Modeling the growth of *S. commerson* using a single, sex-combined growth curve was therefore considered statistically more parsimonious and appropriate than fitting separate curves for each sex. For the combined dataset, the estimated VBGM parameters were: L_∞ = 151.55 cm, K = 0.18 year^{-1}, and t_0 = −0.83 years (Figure 6; Table 3).

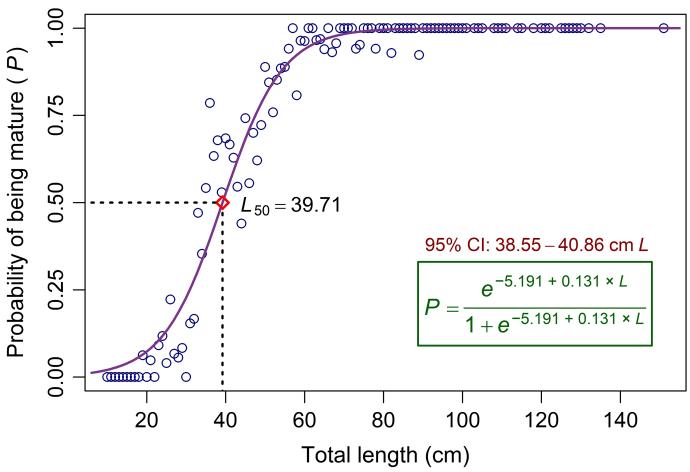


FIGURE 5
The estimated median total length at first maturity (L_{50}) of *S. commerson* sampled from the eastern Red Sea. The curve shows the fitted logistic model to the binomial maturity data of both sexes. Circles represent the observed proportions of mature specimens within each L class. The red diamond square marks the estimated L_{50} on the logistic curve. CI denotes confidence intervals.

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TABLE 2 Age-total length (*L*) key for *S. commerson* from the eastern Red Sea, showing the number of individuals at each age within defined *L* classes.

L class (cm)	Ages (years)												
	0	1	2	3	4	5	6	7	8	9	10	12	18
10-14.9	2												
15-19.9	3												
20-24.9	1												
25-29.9	5												
30-34.9	3	2											
35-39.9	4	1											
40-44.9		1											
45-49.9		8	1										
50-54.9		4											
55-59.9		5	3										
60-64.9		3	2										
65-69.9		4											
70-74.9			4	1									
75-79.9			5		1								
80-84.9				3	1								
85-89.9				5	5								
90-94.9				3	5	2							
95-99.9					2	3							
100-104.9					1	2	1	2					
105-109.9						5	1						
110-114.9						2	2	1					
115-119.9							1	1					
120-124.9							1	2	1	1			
125-129.9								3	6	3	2		
130-135.9											1		
135-139.9												1	
150-154.9													1

TABLE 3 Estimates of von Bertalanffy growth model parameters for female, male, and combined *S. commerson* from the eastern Red Sea.

Parameter	Estimate	SE	95% CI	RSE
Females				8.521
L_∞ (cm)	153.19	6.963	141.30 – 169.47	
K (year^{-1})	0.181	0.021	0.141 – 0.225	
t_0 (years)	−0.790	0.179	−1.184 – −0.472	
Males				7.424
L_∞ (cm)	137.47	11.904	118.21 – 173.66	
K (year^{-1})	0.216	0.043	0.133 – 0.316	
t_0 (years)	−0.820	0.221	−1.370 – −0.429	
Sexes combined				8.172
L_∞ (cm)	151.55	5.803	141.29 – 164.82	
K (year^{-1})	0.183	0.017	0.150 – 0.219	
t_0 (years)	−0.830	0.133	−1.119 – −0.586	

Parameter estimates are accompanied by standard error (SE), 95% confidence interval (CI), and residual standard error (RSE), calculated as the square root of the residual mean square.

3.4 Mortality rates

The Z (95% CI) estimated from the linearized exponential decay model using regression analysis was 0.577 (0.486–0.667) year^{-1}, with a coefficient of determination (r^2) of 0.96. The M estimates obtained from the three empirical methods were closely aligned. The method based on t_{max} produced an estimate of 0.3 year^{-1}; the method based on the VBGM parameter K yielded 0.284 year^{-1}; and the third one, incorporating both K and L_∞, estimated M at 0.227 year^{-1}. The mean (± SD) across these methods was calculated as 0.270 (± 0.038) year^{-1}. Using this average M and the estimated Z, the resulting F was 0.307 year^{-1}.

Age-specific F estimates for *S. commerson* from VPA, along with the number of survivors, deaths due to natural causes, and catch at each age, are presented in Table 4. The F-at-age array ranged from 0.058 year^{-1} between ages 0 and 1 to a peak of 1.292 year^{-1} at age 10 (Table 4). Although F values fluctuated across age classes, a general increasing trend was observed with age. Notably, fishing mortality during the first year of life was minimal, suggesting

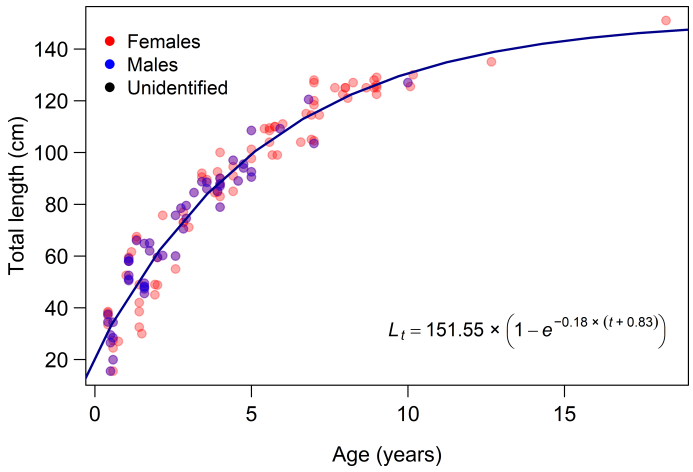


FIGURE 6
Observed total length-at-age (L_t) data for *S. commerson* from the eastern Red Sea with the fitted von Bertalanffy growth curve.

selective fishing practices that spare juveniles in the eastern Red Sea. The highest fishing pressure was concentrated on age 7 and older fish, aligning with the size classes preferred by commercial fisheries (Table 4). A separate VPA was conducted for the female component of the stock to generate an *F*-at-age array for input into the SPR analysis. The pattern of *F* estimated from the female-only VPA closely mirrored the trend observed in the combined sex analysis (Figure 7). Age-specific *F* values for females ranged from 0.025 year^{-1} at age 0 to a maximum of 1.292 year^{-1} at age 10, indicating that older females are subject to the highest fishing pressure.

3.5 Stock status

The results of the Y/R and SPR analyses based on the TBM for female *S. commerson* are presented in Figure 8. In this figure, the left Y-axis represents the SPR, while the right Y-axis displays the total Y/R, expressed as the expected yield from a single recruit. The figure illustrates the decline in SSB/R, relative to the unfished level, as a function of the *F*-factor. The current fishing pattern, represented by an *F*-factor of 1.0, corresponds to the present *F*-at-age array derived from the VPA. Variations in yield and reproductive potential for different *F*-factor multipliers are also depicted in the figure. At the current fishing intensity, SSB/R is reduced to approximately 25% of its unexploited level, placing the SSB below both LRPs. The *F*-factor values corresponding to the SPR-based TRP and LRP, i.e., $F_{40\%}$ and $F_{30\%}$, were estimated at 0.6 and 0.8, respectively. These findings suggest that, for the SSB to rebuild to the TRP threshold (SPR = 0.4) and remain within safe biological limits, all current age-specific fishing mortalities would need to be reduced to 60% of their present levels. In other words, achieving this target would require an approximate 40% reduction in fishing effort across all age classes, thereby allowing the SSB to recover to a sustainable level. The estimated F_{max}, the Y/R-based LRP, was associated with an *F*-factor of 0.78, yielding a peak Y/R of approximately 989 g, slightly higher than the current Y/R estimate of 974 g. Beyond this point, yield declined consistently with increasing *F*-factor. The more conservative TRP, $F_{0.1}$, was obtained at an *F*-factor of 0.5, with an expected Y/R of 938 g.

The current *E* for the overall stock, derived from the mortality estimates, was 0.532, exceeding the LRP threshold of 0.5 and indicating a possible state of overexploitation for the eastern Red Sea stock of *S. commerson*. Age-specific *E* values, obtained through the VPA, are presented in Table 4. With the exception of ages 0, 4, and 6, the *E* estimates for the remaining age classes also exceeded the LRP, further supporting the assessment of excessive fishing pressure on this stock.

3.6 Fishery characteristics

Handlines and gillnets were identified as the primary fishing gears used in the capture of *S. commerson* along the Saudi Arabian

TABLE 4 Estimates of virtual population analysis (VPA) parameters for female *S. commerson* from the eastern Red Sea.

VPA outputs	Age classes											
	0	1	2	3	4	5	6	7	8	9	10	11+
Survivors (10^5)	29.254	15.48	8.01	4.669	2.152	1.121	0.7	0.388	0.179	0.082	0.017	0
Natural Losses (10^5)	9.588	5.973	3.129	1.708	0.897	0.436	0.247	0.146	0.075	0.034	0.011	0.008
Catch (10^5)	2.029	7.801	4.34	1.633	1.62	0.595	0.174	0.166	0.134	0.063	0.054	0.009
Fishing mortality (*F*)	0.058	0.36	0.383	0.264	0.498	0.376	0.195	0.313	0.496	0.503	1.292	0.301
Total mortality (*Z*)	0.334	0.636	0.659	0.54	0.774	0.652	0.471	0.589	0.772	0.779	1.568	0.577
Exploitation Rate (*E*)	0.175	0.566	0.581	0.489	0.644	0.577	0.414	0.531	0.643	0.646	0.824	0.522

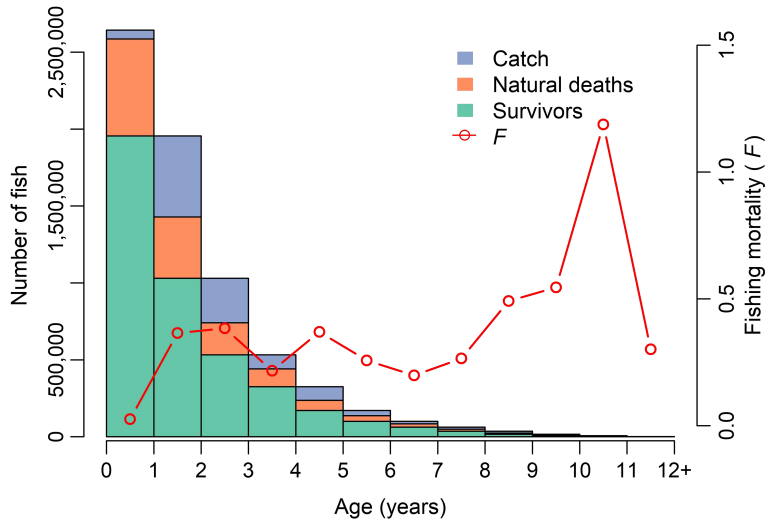


FIGURE 7
Age-structured virtual population analysis (VPA) output for the female component of the *S. commerson* stock in the eastern Red Sea, showing estimates of survivors, natural losses, catch, and *F* across age classes.

Red Sea coast (Figure 9). Although not specifically targeting this species, shrimp trawls contributed substantially to the catch of juvenile individuals, primarily those below the L_{50}, most of which were below age 1 (Figure 9). Handlines and gillnets captured fish across nearly all *L* classes above 30 cm and age 0. However, gillnet catches of large individuals exceeding 100 cm in *L* and age 6 were notably scarce. All specimens younger than age 1 were immature. As previously noted, immature individuals made up nearly 17% of the total landings, while approximately 73% were mature fish (Figure 3). According to the MEWA regulations, the minimum legal landing size (MLS) for *S. commerson* is 45 cm *L* (MEWA, 2021). Based on this threshold, 72% of the catch exceeded the MLS ($L \geq 45$), indicating general compliance with legal harvest sizes. Notably, only 1% of the landings comprised mature individuals below the MLS ($L < 45$ cm).

4 Discussion

S. commerson holds substantial commercial value in global fisheries (FAO, 1999) and is subject to intense fishing pressure due to strong market demand (Kaymaram et al., 2013). It is also among the primary targets of the traditional commercial fishery in the Red Sea. In adjacent waters such as the Arabian Gulf, high exploitation levels driven by unregulated fishing have led to overfishing of *S. commerson* stocks (Jayabalan et al., 2011; Kaymaram et al., 2013; Alrashada, 2022). Notably, signs of stock recovery have recently been observed following the implementation of effective management interventions (AlMusallami et al., 2025). Despite the continued high demand for *S. commerson* in the Red Sea, data on its life history traits and fishery biology, essential for

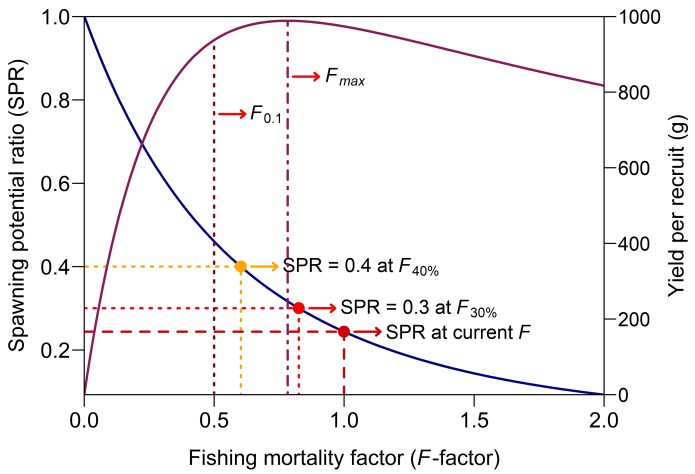


FIGURE 8
Relationship between spawning stock biomass-per-recruit (SSB/R) and yield-per-recruit (Y/R) as a function of the fishing mortality factor (*F*-factor). The dark blue curve represents SSB/R (corresponding to the left Y-axis for SPR), and the dark red curve represents Y/R (corresponding to the right Y-axis). The *F*-factor is a series of incremental values ranging from 0 to 2 (in steps of 0.001), used to simulate changes in fishing effort by multiplying the reference *F*-at-age array (with *F*-factor = 1 representing the current fishing pattern). The figure also marks the SPR values associated with key biological reference points, including the current *F*, F_{max}, $F_{0.1}$, $F_{40\%}$, and $F_{30\%}$.

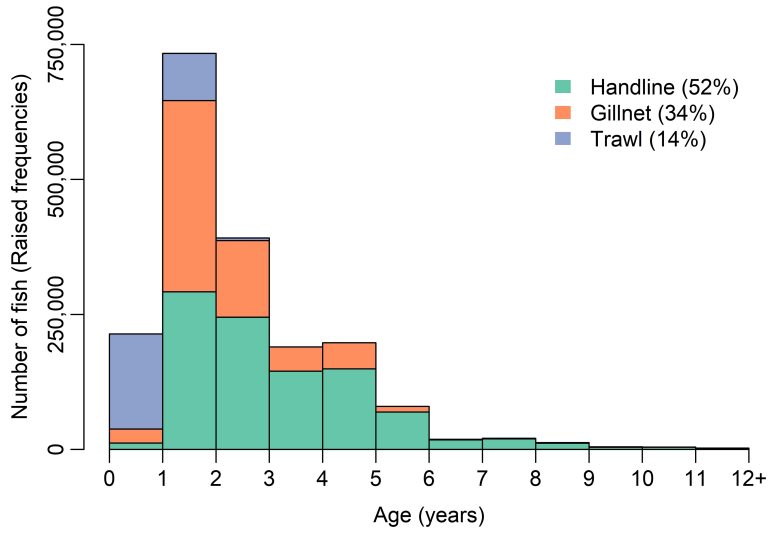


FIGURE 9
Age distribution of *S. commerson* from the eastern Red Sea, stratified by gear type. The number of fish in each age class was estimated by raising the otolith-derived age frequencies to match annual landings reported for the Saudi Arabian coast of the Red Sea (Alshaikhi et al., 2023; FAO, 2024).

evidence-based management, remain limited. The present study provides the first comprehensive assessment of *S. commerson* in the eastern Red Sea, offering key population parameters, stock status indicators, and biological insights that enable comparisons with studies conducted elsewhere in its range.

The length distribution data collected from the eastern Red Sea in this study align well with findings from previous research conducted in adjacent and distant regions, including the Arabian Gulf and Oman Sea (Shojaei et al., 2007; Kaymaram et al., 2013; Alrashada, 2022), the Mediterranean Sea (Mohsen et al., 2020), the Bay of Bengal, India (Pillai et al., 1996), the Gulf of Boni, Indonesia (Mallawa and Amir, 2019), Australia (McPherson, 1992; Newman et al., 2012), and other global locations (see Table 5). In the eastern Red Sea, *S. commerson* exhibited a negative allometric growth pattern, as indicated by the estimated *L-W* relationship parameters for females (b = 2.90) and males (b = 2.78). Moderate regional variations in allometric growth patterns have been documented for this species. For example, studies from the Arabian Gulf reported slightly higher b values for combined sexes, with estimates of 2.98 (Shojaei et al., 2007) and 2.93 (Ali Fakhri et al., 2015). In contrast, combined sex estimates from the Oman Sea (b = 2.84; Taghavi Motlagh et al., 2008) and the Mediterranean Sea (b = 2.85; Mohsen et al., 2020) were marginally lower than the value obtained for females in the present study, but somewhat higher than that estimated for males. It is worth noting that, unlike the present study, which used total length (*L*), all the referenced studies employed fork length (*FL*) measurements, which may contribute to observed differences in the *L-W* relationship parameters. While *FL* is generally preferred for species with forked tails, no *L-FL* conversion data are currently available for *S. commerson* in the Red Sea. This may represent a minor source of uncertainty, underscoring the need for region-specific *L-FL* conversion studies in the future.

The L_{50} estimate of 39.71 cm for combined-sex data in this study suggests a substantially smaller size at maturity for *S. commerson* in the eastern Red Sea compared to FL_{50} estimates (70–91.3 cm; Table 5) reported from other regions: the Oman Sea (Dudley et al., 1992), the Arabian Gulf (Grandcourt et al., 2005; Alrashada, 2022; AlMusallami et al., 2025), and the Bay of Bengal (Rohit and Abdussamad, 2013). These regional differences may reflect spatial and temporal variability, including environmental factors, varying fishing pressures, or differences in the timing of sampling efforts. Early maturation has also been documented in other Red Sea species, such as *Nemipterus japonicus* (Bakhsh, 1994) and *Variola louti* (Kadengal et al., 2025). This pattern may represent an adaptive response to the Red Sea conditions; for example, elevated water temperatures can increase metabolic and growth rates, potentially triggering earlier maturity (Goldberg et al., 2019).

In this study, *S. commerson* was estimated to attain an L_∞ of 151.55 cm, with individuals living up to 18 years in the eastern Red Sea. Table 5 presents a comparison of VBGM parameters reported across the species' distribution range, alongside the estimates derived here. Literature values for L_∞, typically based on *FL*, vary substantially, from approximately 110 cm to nearly 194 cm, reflecting geographic and methodological differences. The Red Sea population's L_∞ falls at the mid-range, consistent with estimates from adjacent regions such as the Oman Sea and the Arabian Gulf (Table 5). The K estimated here was 0.18 year^{-1}, indicating relatively slow growth in the eastern Red Sea population, similar to the recent findings in the northern Arabian Gulf (K = 0.14 year^{-1}, AlMusallami et al., 2025). In contrast, all other studies from the same region have reported much faster growth (Table 5), with a K value up to 0.78 year^{-1} (Pillai et al., 1993). The lowest K value of 0.1 year^{-1} was recorded off the coast of Thailand, the Indian Ocean (Cheunpan, 1988), underscoring the pronounced variability in growth dynamics across populations. This variability may reflect differences in environmental conditions, fishing pressure, and adaptive strategies. In particular, the oligotrophic nature of the Red Sea, characterized by persistent pycnoclines, high salinity, and weak benthic–pelagic coupling, has been linked to reduced growth

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TABLE 5 Summary maturity, growth, and mortality parameters of *S. commerson* from the literature and the present study.

Sea	Country	Year	FL_{50} (cm)	FL_{∞} (cm)	K (year^{-1})	t_0 (years)	Mortality (year^{-1})			Source
							Z	M	F	
Arabian Gulf	United Arab Emirates (UAE)	2011-2023	78.7	135.3	0.14	−2.3		0.26		AlMusallami et al. (2025)
Arabian Gulf	Saudi Arabia	2022	91.3	156	0.24	−0.352	1.40	0.43	0.97	Alrashada (2022)
Australian east coast	Australia	2021		130.19 (♀) 114.18 (♂)	0.29 (♀) 0.35 (♂)					Tanimoto et al. (2021)
Mediterranean	Egypt	2020		161.67	0.24	−0.05	0.95	0.38	0.56	Mohsen et al. (2020)
Gulf of Carpentaria	Australia	2020		126.86	0.24					Bessell-Browne et al. (2020)
Arabian Gulf and Oman Sea	Saudi Arabia	2019		135.5	0.240			0.26		Roa-Ureta et al. (2019)
Gulf of Boni	Indonesia	2019		167	0.55	−0.89	1.84	0.76	1.08	Mallawa and Amir (2019)
Southern Mozambique and KwaZulu-Natal, South Africa	South Africa	2017		130.46 (♀) 119.22 (♂)	0.31 (♀) 0.28 (♂)	−1.35 (♀) −1.85 (♂)				Lee and Mann (2017)
Northern Arabian Gulf	Iran	2015		148	0.5		0.97	0.56	0.41	Niamaimandi et al. (2015)
Northern Arabian Gulf	Iran	2015		143.85	0.31	−0.63				Ali Fakhri et al. (2015)
Dar es Salam, Tanzania	Tanzania	2014		122	0.68	0.17	1.44	0.43	1.01	Johnson et al. (2014)
Arabian Gulf and Oman Sea	Iran	2013		151	0.46		1.93	0.54	1.39	Kaymaram et al. (2013)
Arabian Sea and Bay of Bengal	India	2013	70	162	0.78					Rohit and Abdussamad (2013)
Arabian Gulf and Oman Sea	Oman	2012		175.26	0.45		1.98	0.50	1.48	Darvishi et al. (2012)
Arabian Gulf	GCC	2011		176	0.4	−0.45	1.59	0.50	1.09	Jayabalan et al. (2011)
Oman Sea	Iran	2008		178	0.28	−0.36	0.95	0.36	0.59	Taghavi Motlagh et al. (2008)
Arabian Gulf and Oman Sea	Iran	2007		140	0.42	−0.26	1.47	0.49	0.98	Shojaei et al. (2007)
Oman Sea	Oman	2005		146.4	0.216	−2.618	0.901 (♀) 0.892 (♂)	0.376 (♀) 0.490 (♂)	0.534 (♀) 0.402 (♂)	Govender et al. (2005)
Oman Sea	Oman	2005		140.4 (♀) 118.8 (♂)	0.31 (♀) 0.60 (♂)	1.501 (♀) 0.730 (♂)	0.901 (♀) 0.892 (♂)	0.376 (♀) 0.490 (♂)	0.534 (♀) 0.402 (♂)	McIlwain et al. (2005)
Southern Arabian Gulf	UAE	2005	86.3 (♀) 72.8 (♂)	138.6	0.21	−1.9	0.88	0.26	0.62	Grandcourt et al. (2005)
Bay of Bengal	India	1996		148	0.42	0.0	1.34	0.53	0.99	Pillai et al. (1996)
South Africa	South Africa	1995					0.75	0.50	0.25	Govender (1995)
Arabian Sea	India	1993		146	0.78					Pillai et al. (1993)
Oman Sea	Oman	1992	75-80	138.3	0.362	−1.16				Dudley et al. (1992)

(Continued)

TABLE 5 Continued

Sea	Country	Year	FL_{50} (cm)	FL_{∞} (cm)	K (year^{-1})	t_0 (years)	Mortality (year^{-1})			Source
							Z	M	F	
Bay of Bengal	India	1989		193.8	0.2					Kasim and Ameer Hamsa (1989)
Bay of Bengal	India	1989		177.5	0.38					Thiagarajan (1989)
Indian Ocean	Sri Lanka	1989		146	0.37					Dayaratne (1989)
Indian Ocean	Thailand	1988		110	0.1					Cheunpan (1988)
Red Sea	Saudi Arabia (*L*)	2022-2024	39.94 (♀) 39.60 (♂)	151.55	0.18	−0.83	0.58	0.27	0.31	Present study

FL_{50}, fork length at first sexual maturity; FL_{∞}, asymptotic fork length; K and t_0, von Bertalanffy growth model parameters; Z, total mortality; M, Natural mortality; F, Fishing mortality; ♀ and ♂, females and males.

and reproductive output in several regional species (Longhurst, 2007; Acker et al., 2008; D'Agostino et al., 2021; Cibic et al., 2022). Such ecological constraints likely contribute to the moderate growth in the eastern Red Sea population of *S. commerson*.

The reported mortality rates across different regions (Table 5) exhibit substantial variability, reflecting contrasts in exploitation pressure, environmental conditions, and fishing practices. Z values range from 0.58 year^{-1} in the eastern Red Sea (this study) to as high as 1.98 year^{-1} in the Arabian Gulf (Darvishi et al., 2012). F also shows considerable variation; intense fishing pressure is evident from the estimates, such as 1.48 and 1.39 year^{-1} reported in the Arabian Gulf (Darvishi et al., 2012; Kaymaram et al., 2013), whereas more moderate exploitation is reflected by values around 0.25 year^{-1} off South Africa (Govender, 1995). The present study also estimates a relatively low F of 0.31 year^{-1} for *S. commerson* in the eastern Red Sea in 2022. While regional differences in fishing pressure and habitat account for much of the observed variation in mortality, methodological differences in mortality estimation among studies may also contribute. Diverse data sources, analytical approaches (e.g., catch curve, tagging studies, model-based methods), and assumptions about M or growth can significantly influence the resulting estimates and should be carefully considered when interpreting and comparing findings.

Based on the Y/R estimates from the TBM analysis for female *S. commerson*, the current fishing pattern substantially exceeds F_{max} (Figure 8), indicating the stock is experiencing growth overfishing. This condition implies that individuals are being harvested at a rate that prevents them from attaining their maximum growth potential, leading to reduced Y/R and diminished long-term productivity of the stock. The analysis further indicates that the Y/R-based LRP F_{max} could be achieved at an F-factor of 0.78, representing a fishing effort nearly 22% lower than the current level. Notably, even with this reduction in effort, the corresponding Y/R value is estimated at 989 g, slightly higher than the current Y/R of 974 g. This highlights the potential for optimizing yield while easing fishing pressure. The more precautionary TRP $F_{0.1}$ is associated with an F-factor of 0.5, corresponding to a 50% reduction in fishing effort. At this level, the expected Y/R is 938 g, only marginally lower than the current yield, but with the benefit of significantly improved reproductive sustainability. If growth overfishing persists, further increases in fishing pressure will likely lead to recruitment overfishing, where the reproductive capacity of the population is impaired. The results of the SPR analysis provide evidence that recruitment overfishing may already be occurring, as the current fishing pattern reduces the SSB to approximately 25% of its unexploited level, which is below the LRP (Figure 8). SPR values below 0.3 are considered indicative of a high risk of recruitment overfishing (Walters and Martell, 2004). Given that the current SPR is below this critical threshold, there is justified concern regarding the long-term sustainability of the stock if current exploitation levels persist. Without effective management intervention to reduce fishing pressure, the stock may experience further declines in reproductive capacity, threatening its ability to replenish and maintain stable yields.

It should be noted, however, that the TBM assumes a steady-state fishery, characterized by a stable fishing pattern over time. This presumes that F and other key input parameters have remained relatively constant long enough for the stock to reach an equilibrium condition. In this study, reliance on only seven years of landings data (2017–2023) and the absence of a longer, species-specific time series might be a potential limitation in strictly meeting that assumption. Nevertheless, annual landings of *S. commerson* from the Saudi Arabian Red Sea coast, 2, 247, 2, 453, 2, 285, 2, 264, 2, 134, 2, 412, and 2, 803 tonnes, were remarkably consistent and exhibited minimal fluctuation (SD: 218 tonnes) over this period (Alshaikhi et al., 2023; FAO, 2024). Moreover, no significant technological improvements or shifts in fishing practices occurred during this time, as the fishery continued to operate primarily with traditional handlines and gillnets. Taken together, these findings suggest that the steady-state assumption underlying the TBM Y/R model is likely reasonable in this regional context, lending confidence to the interpretations of growth- and recruitment-related overfishing derived from this analysis.

The current E for the overall stock, based on mortality parameters estimated in the present study, was 0.53, exceeding the commonly accepted LRP of 0.5 and indicating a possible state of overexploitation. Age-specific E estimates, derived from the VPA, further reinforce this finding, supporting the conclusion that the stock is experiencing unsustainable fishing pressure. These results are

consistent with the outcomes of both the Y/R and SPR analyses, collectively raising concern that *S. commerson* in the eastern Red Sea is subject to excessive exploitation. Similar trends have been reported for this species in other parts of its distribution range. In the northern Arabian Gulf and the Oman Sea, Darvishi et al. (2012) documented an E value of 0.74, suggesting severe fishing pressure. Comparable findings were noted by Kaymaram et al. (2013) and Shojaei et al. (2007), who found E values of 0.72 and 0.64, respectively. Likewise, high E estimates of 0.66 and 0.69 were reported by McIlwain et al. (2005) and Jayabalan et al. (2011) for the western and southern Arabian Gulf and the Oman Sea, respectively. A similar value of 0.69 was also found more recently by Alrashada (2022) in the Saudi Arabian Gulf waters. Additional evidence of overexploitation comes from Mallawa and Amir (2019), who estimated an E value of 0.59 for *S. commerson* in the Gulf of Boni, Indonesia, and from Johnson et al. (2014), who documented an even higher value of 0.70 in Tanzanian waters of the western Indian Ocean. Collectively, these findings underscore widespread concerns regarding the overexploitation of this species across its regional stocks.

Size-structured catch analysis showed that handlines predominantly targeted *S. commerson* individuals above the L_{50}, whereas gillnets captured a broader spectrum of L and age classes, including younger, sub-mature fish. In contrast, shrimp trawls, though not targeting this species, contributed substantially to juvenile bycatch, particularly fish below the MLS. This pattern highlights the selectivity of traditional gears, such as handlines, which target larger, mature fish and significantly reduce the incidence of undersized captures. Meanwhile, shrimp trawls appear to unintentionally capture juvenile fish, underscoring the role of bycatch in early life-stage retention and the effectiveness of gear selectivity in minimizing juvenile mortality. These findings are consistent with reports from the Oman Sea and the Arabian Gulf, where overexploitation signals, including elevated fishing mortality, substantial capture of immature fish, and reduced biomass, have been documented (Dudley et al., 1992; Grandcourt et al., 2005; McIlwain et al., 2005; Shojaei et al., 2007; Al–Shehhi et al., 2021).

In Saudi Arabian waters, the MEWA serves as the competent authority for fisheries management. The MEWA issues commercial fishing licenses and controls the total number of fishing vessels permitted to operate along the Red Sea coast. The small-scale fishery, which accounts for the majority of fishing effort targeting *S. commerson*, operates year-round, weather permitting. There are currently no limits on the number of lines, hooks, or hook sizes, and no catch quotas for commercial fishers targeting this species. Gillnet fisheries, although not specifically regulated for *S. commerson*, must comply with a minimum stretched mesh size of 64 mm, which indirectly influences selectivity. The only species-specific technical measure currently in place is an MLS of 45 cm L (MEWA, 2021). In contrast, shrimp trawling, which incidentally captures juvenile *S. commerson*, is highly restricted both spatially and temporally. Trawling is legally permitted only in the southern Red Sea ports of Al Qunfudhah and Jizan (Figure 1), and is subject to an annual seasonal closure from April to August. Trawl nets are required to use a minimum codend mesh size of 40 mm. Despite these restrictions, no catch limits are currently applied to the shrimp trawl fishery (Santucci et al., 2024; Gireesh et al., 2025).

While these measures contribute to general fisheries regulation, they remain insufficiently tailored for this particular species. Consequently, achieving sustainable management of the *S. commerson* stock along the Saudi Arabian Red Sea coast requires a combination of biologically informed and practically achievable management actions. Priority measures include restricting or prohibiting shrimp trawling in nursery grounds, refining gear selectivity to reduce the capture of juveniles, and introducing effort controls aimed at gradually reducing excessive fishing pressure. While our stock assessment results indicate that a reduction in fishing effort of approximately 40% would theoretically bring the exploitation rate closer to sustainable levels, we recognize that such a reduction may not be immediately feasible given current socioeconomic and operational realities. Therefore, this figure should be viewed as an indicative management benchmark, emphasizing the magnitude of reduction needed to restore the stock, rather than as a fixed regulatory target. In practice, progress toward sustainability could be achieved through incremental management interventions, such as phasing in effort reductions, establishing seasonal closures during peak spawning periods, and implementing gear selectivity measures. Given the transboundary nature of *S. commerson* populations, regional coordination among the Red Sea and Gulf countries will be essential to ensure consistency and effectiveness of management actions. A gradual shift toward precautionary, ecosystem-based fisheries governance would help protect vulnerable life stages and enhance the long-term resilience of this commercially important species.

5 Conclusions and recommendations

This study constitutes the first comprehensive assessment of *S. commerson* in the Red Sea, encompassing key population parameters and an integrated evaluation of stock status. The preliminary assessment indicates that current fishing effort along the Saudi Arabian Red Sea coast exceeds the optimal level, placing the stock under overfishing pressure and threatening its long-term productivity if current practices persist. Moreover, immature individuals, comprising 17% of total landings, are largely captured incidentally as bycatch in shrimp trawl operations along the southeastern coast. The socio-economic importance of this fishery underscores the urgency of effective management; average annual landings of approximately 2, 380 tonnes, valued at nearly 35 million USD, contribute substantially to local livelihoods and food security.

Recommended actions include strict enforcement of the existing MLS regulation, supported by sustained monitoring and outreach efforts to ensure compliance. Bycatch reduction strategies, including bycatch reduction devices and spatial or seasonal closures in trawling areas, should be implemented to protect juvenile recruits in nursery habitats. Gradual and adaptive effort control, for instance, through refining gear selectivity, limiting fishing intensity, and introducing seasonal closures during peak spawning, would help realign exploitation rates towards sustainable benchmarks (e.g., $F_{40\%}$ and $F_{0.1}$). While model projections indicate that an effort reduction of approximately 40% would be required to fully restore the stock, this figure should be interpreted as an indicative management

benchmark, reflecting the degree of adjustment needed rather than an immediate policy mandate. Future work should include population genetic studies to clarify stock structure along the Saudi Arabian Red Sea coast, enabling more region-specific management strategies. Finally, robust, long-term data collection should be maintained, and future stock assessments should incorporate environmental and climate-related factors to better understand dynamics under changing marine conditions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval was not required for the study involving animals in accordance with the local legislation and institutional requirements because the samples were obtained from commercial fish markets.

Author contributions

MD: Supervision, Conceptualization, Writing – review & editing, Funding acquisition, Resources, Writing – original draft, Project administration, Methodology. ZO: Formal analysis, Visualization, Investigation, Data curation, Writing – review & editing, Writing – original draft, Methodology. SK: Investigation, Writing – review & editing, Formal analysis, Writing – original draft. ET: Formal analysis, Visualization, Investigation, Data curation, Validation, Software, Writing – review & editing, Writing – original draft, Conceptualization, Methodology.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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