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Observations on the Biology and Fishery of the Marbled Spinefoot (*Siganus rivulatus* Forsskål & Niebuhr, 1775) in the Eastern Red Sea

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Abstract: This study aims to enhance our understanding of the marbled spinefoot (*Siganus rivulatus*) population along the Red Sea coast of Saudi Arabia. It investigates whether the stock is subject to overfishing and tests the hypothesis that current fishing mortality exceeds sustainable thresholds. A total of 6192 specimens were sampled during a comprehensive survey conducted from 2022 to 2024, utilizing a range of fishing methods, including handline, trap, gillnet, and demersal trawl fisheries. The sampled fish ranged in total length (*TL*) from 100 to 335 mm and in total weight (*W*) from 17 to 470 g. The length–weight relationship was $W = 0.0175 \times TL^{2.92}$. Growth parameters derived from the von Bertalanffy model were $TL_\infty = 43.5$ cm, $K = 1.12$ year^{-1}, and $t_0 = -0.18$ year. The median size at first maturity was estimated at 14.83 cm *TL* for both sexes. Virtual Population Analysis revealed fishing mortality rates ranging from 0.01 year^{-1} to 0.89 year^{-1} across age classes 1 to 5 years, with exploitation levels of 0.6, 0.55, and 0.5 at ages 3, 4, and 5, respectively, indicating slight overfishing. The annual average catch of marbled spinefoot along the Saudi Arabian Red Sea coast was approximately 211 tonnes, contributing an estimated 1.8 million USD to the national economy. Maintaining the current fishing effort at sustainable levels is essential to ensure the long-term viability of this stock.

Keywords: age reading; growth; mortality; rabbitfish; Saudi Arabian coast

Key Contribution: Life history parameters for *Siganus rivulatus* on the Saudi Arabian Red Sea coast, including growth, maturity, mortality estimates, and stock assessment, reveal a high level of exploitation of this commercially important species. To ensure the sustainability of the stock, effective fisheries management strategies are needed, including temporal fishing bans and size limits.

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1. Introduction

The marbled spinefoot (*Siganus rivulatus* Forsskål & Niebuhr, 1775) is an herbivorous marine species with commercial importance in small-scale fisheries in the Red Sea [1]. Its native range extends from South Africa to the Red Sea, encompassing areas such as Madagascar and the Seychelles. However, it has expanded into the eastern Mediterranean via the Suez Canal and is now commonly found from Egypt to Libya and Greece, including the Levantine rocky shores off Türkiye and Malta [2–4]. Typically inhabiting subtropical waters at depths between 1 and 30 m, *S. rivulatus* primarily feeds on green algae and forms schools in sheltered bays near rocky, algae-covered substrates, with its range extending to coral reefs at depths of up to 60 m [4].

The species reaches a maximum total length (*TL*) of 33.7 cm and total weight (*W*) of 482.5 g [5], with males reaching sexual maturity at 13.35 cm and females at 13.65 cm in *TL* [6]. Its lifespan is approximately eight years, and spawning occurs in the northern hemisphere from May to August [7]. *S. rivulatus* holds significant value for artisanal fisheries across its distribution, primarily captured using beach seines and gill nets. Although specific catch statistics are unavailable, the species is often abundant in areas where it is present and is currently listed as Least Concern on the IUCN Red List [4]. Nevertheless, studies have documented overexploitation in parts of its range, particularly in the Red Sea, with notable cases in Egypt [5,8].

The Red Sea is a semi-enclosed large marine ecosystem located between Africa and Asia, spanning approximately 2000 km in length and 30 to 280 km in width [9]. It connects the Mediterranean Sea to the Indian Ocean and is characterized by tropical climate features. Renowned for its rich biodiversity, which includes a very high number of fish species [10], the Red Sea hosts extensive coral reef systems that are vital for sustaining marine life in the region. Saudi Arabia, as the largest country bordering the Red Sea, occupies much of its eastern basin. In this region, small-scale artisanal fishing, particularly around coral reefs, dominates the fisheries sector and contributes substantially to the local economy. However, overfishing and lack of compliance with fishing regulations have jeopardized the sustainability of these fisheries, particularly since the 1990s [11]. The fishing pressure has resulted in declines in top carnivores, such as sharks and serranids, which are key targets for artisanal fishers. To safeguard these critical ecosystems, improved management practices are urgently required, including enhanced species-specific data collection and more effective regulatory measures [12].

In the Red Sea, *S. rivulatus* has significant commercial importance, standing as a popular species among consumers due to its availability at relatively affordable prices [5]. Reproductive studies highlight regional differences, with larger individuals and extended spawning seasons reported in the Red Sea compared to populations in the Mediterranean Sea and the Suez Canal [13]. In Saudi Arabia, the average market value of *S. rivulatus* in Jeddah and Thuwal is approximately 7 USD per kg [14]. Fisheries and stock assessments from FAO and MEWA sources indicate that Saudi Arabia's annual capture fishery production ranges between 24,775 and 75,150 tonnes [15].

Despite its commercial significance, *S. rivulatus* remains understudied in Saudi Arabian waters, with limited region-specific data on its population dynamics and exploitation status. Furthermore, anecdotal evidence, such as the frequent observations of small-sized individuals in local fish markets, has raised concerns about potential overfishing. To address this, the present study conducted an age-based assessment of the stock. While previous research in other parts of the Red Sea has reported signs of overexploitation [5,8], the extent and nature of fishing pressure on *S. rivulatus* along the Saudi coastline remain poorly documented. Understanding the growth patterns, mortality rates, and exploitation levels of this species is therefore essential for developing effective and sustainable management strategies in this region.

To address the growing concerns about fishing pressure, this study investigated whether the *S. rivulatus* stock in Saudi Arabian Red Sea waters is subject to overfishing. Specifically, it tested the hypothesis that *S. rivulatus* in this region experiences unsustainable fishing pressure, reflected in high fishing mortality and exploitation rates exceeding established biological reference points. This hypothesis was evaluated through an age-based stock assessment using Virtual Population Analysis, supported by estimates of key life-history parameters relevant to fisheries management.

2. Materials and Methods

2.1. Study Area and Biological Data Collection

Monthly sampling of *S. rivulatus* was conducted from 2022 to 2024 at eight landing sites along a 1300 km stretch of the eastern Red Sea coastline (Figure 1). The sampling sites were selected based on fisheries statistics provided by the Ministry of Environment, Water, and Agriculture (MEWA) and preliminary surveys [16]. Over the study period, 6192 specimens were obtained from commercial fisheries. For each fish, *TL* was measured to the nearest mm, and *W* was recorded to the nearest 0.1 g using an electronic balance. Sex and maturity status were determined through macroscopic examination of gonads under uniform lighting conditions to ensure consistency [13,17].

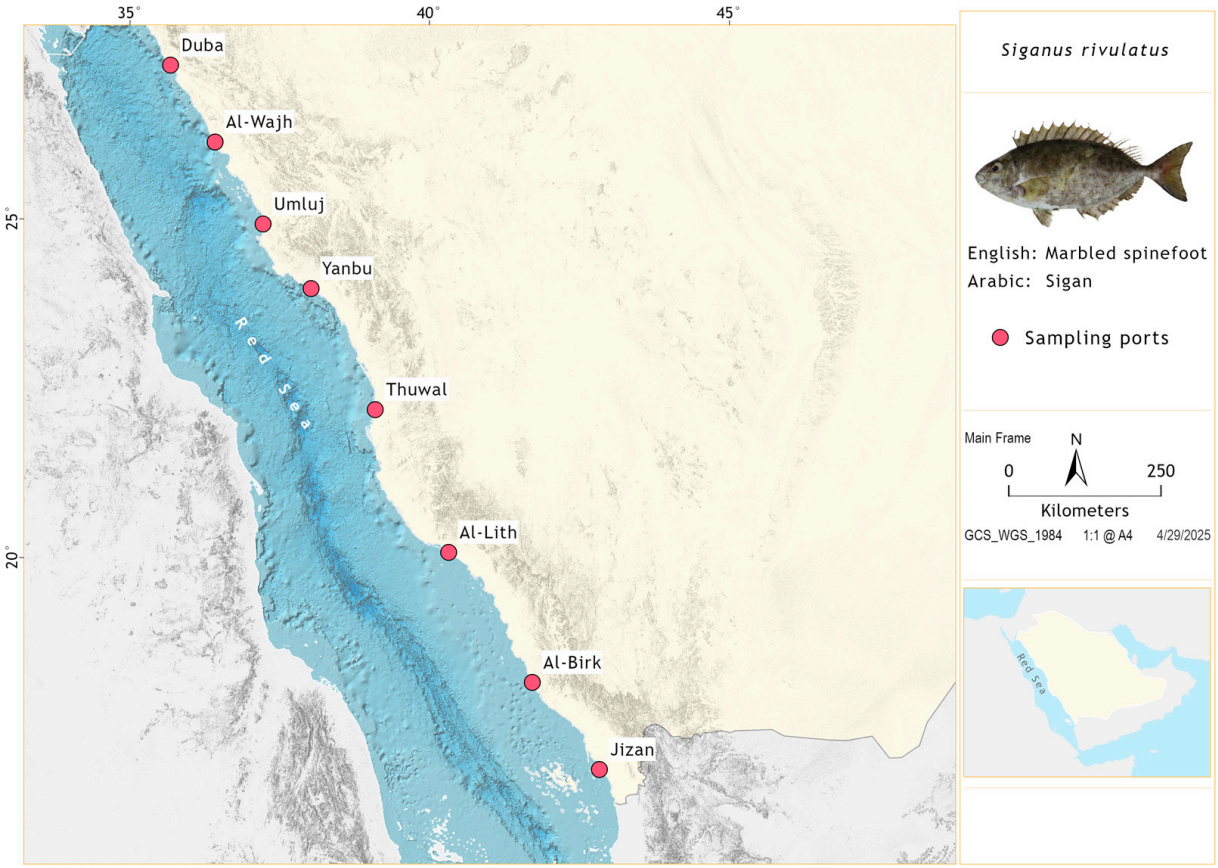


Figure 1. Map showing the ports where *S. rivulatus* specimens were collected between 2022 and 2024.

2.2. Otolith Extraction and Reading

Age determination of the specimens was conducted via direct reading of the otoliths, following the FAO protocol outlined by Carbonara and Follesa [18]. This method is based on counting annual growth rings on the sagittal otoliths, characterized by alternating opaque and hyaline zones. One pair of hyaline and opaque rings was interpreted as representing one year of age (Figure 2). Age was read from polished otoliths observed under the reflective light of a Leica M205 C stereomicroscope at 40x magnification. A total of 156 sagittal otoliths were examined from the specimens, ranging from 10 to 30 cm *TL*. To ensure accuracy, otolith images were enhanced digitally, and readings were performed independently by two experienced readers.

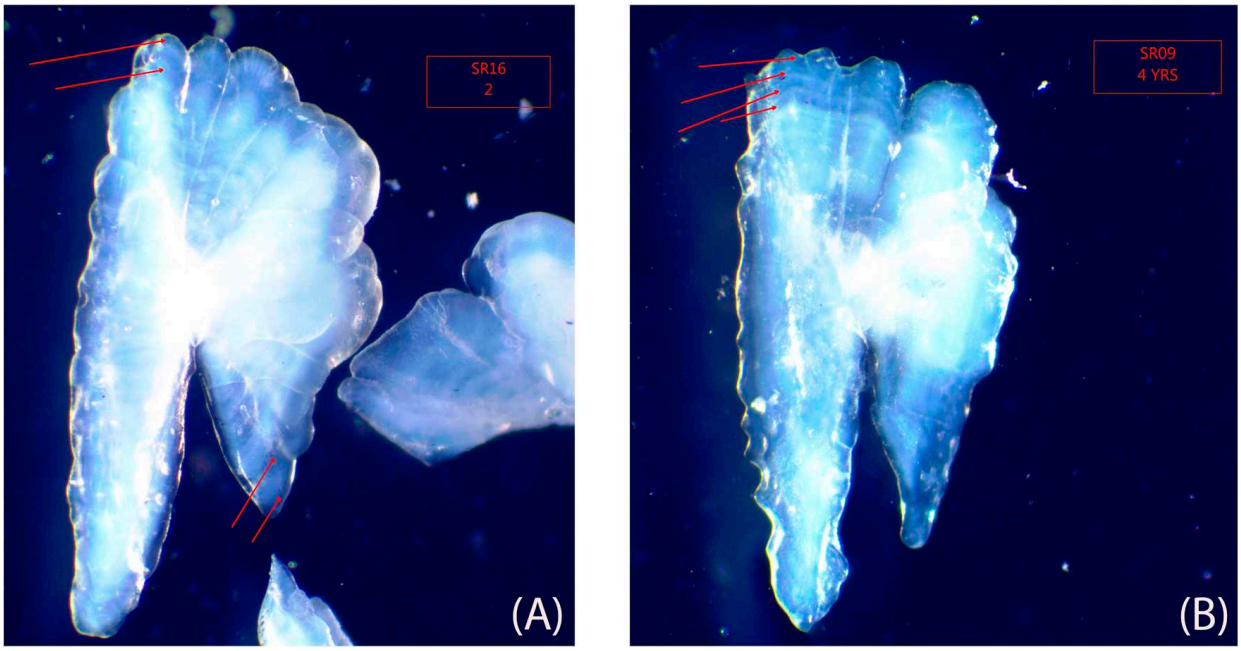


Figure 2. Otolith shapes of (**A**) age group 2 and (**B**) age group 4 of *S. rivulatus* in the Red Sea. Red arrows refer to the hyaline growth bands of the annuli.

2.3. Data Analysis

The relationship between W and TL was established using the equation $W = a \times TL^b$ [19]. Coefficients a and b were determined through linear regression analysis on logarithmically transformed data.

Length-at-age data, derived from otolith readings, were analyzed using the von Bertalanffy Growth Model (VBGM), following the equation

$$TL_t = TL_\infty \times \left(1 - e^{-K \times (t - t_0)}\right)$$

where TL_∞ represents the asymptotic length, K is the growth coefficient, and t_0 is the theoretical age at which fish have zero TL [19,20]. The model was applied separately for each sex and combined sexes using nonlinear regression analysis.

The gonads were examined macroscopically, and maturity stages were classified according to the criteria outlined by Gunderson [17] and Abdelhak [13]. The median size at first maturity (TL_{50}) was estimated using logistic regression to model the relationship between TL and the binomial maturity state (0 = immature, 1 = mature), as described by Aydın and Tıraşın [21]. A nonparametric confidence interval (CI) for TL_{50} was generated using the bias-corrected and accelerated bootstrap (BCa) method [22].

Natural mortality (M) was estimated using multiple approaches to ensure robustness. Three empirical formulas, as suggested by Hamel and Cope [23] and Then et al. [24], were applied:

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

$$M = 1.55 \times K$$

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

where t_{max} represents the maximum age, or longevity, of a species, and K and TL_∞ are the VBGM parameters. The mean of these estimates provided an initial overall M. Additionally, M for each age class was calculated using the PRODBIOM method [25], following the

approach described by Martiradonna [26]. A new mean M for each age class was derived by integrating the initial mean with PRODBIOM-based estimates.

The exploitation rate (E) represents the fraction of a fish stock harvested through fishing activities within a specific period. It is a vital metric for evaluating the intensity of fishing pressure on a fish stock and assessing the sustainability of such practices. The exploitation rate is calculated using the following formula:

$$E = \frac{F}{F + M} = \frac{F}{Z}$$

Virtual Population Analysis (VPA) was used to reconstruct historical population dynamics and evaluate the status of the stock [19]. This approach estimates the number of fish alive in each age group by retrospectively solving the Baranov catch equation, starting from the oldest cohort. The analysis incorporated age-specific M estimates, an initial estimate of terminal fishing mortality (F_t = 0.4), and the time interval between age groups. The VPA relies on the following two formulas:

$$N_t = C_t \times \frac{(M_t + F_t)}{F_t}$$

$$C_i = N_i \times \frac{F_i \times (1 - \exp(-(F_i + M_i)))}{F_i + M}$$

where N is the stock size in numbers, C is the catch, F is the fishing mortality, and M is the natural mortality. VPA was conducted to examine the contribution of individual age groups to the total catch, integrating fishery statistics and age-sampling data to estimate recruitment and age-specific F.

The data analysis was conducted using R software (version 4.4.2) [27], utilizing the ggplot2 package (version 3.5.2) [28] along with base R functions for visualization.

3. Results

The *TL* of *S. rivulatus* (N = 6192) collected from eight landing sites along the Red Sea, from Duba to Jizan during 2022–2024, ranged from 10 to 33.5 cm, with corresponding W between 17 and 470 g (Table 1). The *TL*-*W* relationship for all specimens is described by the equation $W = 0.0175 \times TL^{2.92}$ (Table 1, Figure 3).

Table 1. Summary statistics for total length (*TL*) and total weight (W), and parameters of the *TL*-*W* relationship with their 95% confidence intervals (CIs).

***TL* (cm)**		***W* (g)**	
Mean	18.8	Mean	98.8
Max.	33.5	Max.	470.0
Min.	10.0	Min.	17.0
Median	19.0	Median	87.0
Sd	3.4	Sd	64.9
TL-*W* relationship parameters		95% CI	
a	0.0175	0.0163–0.0187	
b	2.92	2.90–2.95	

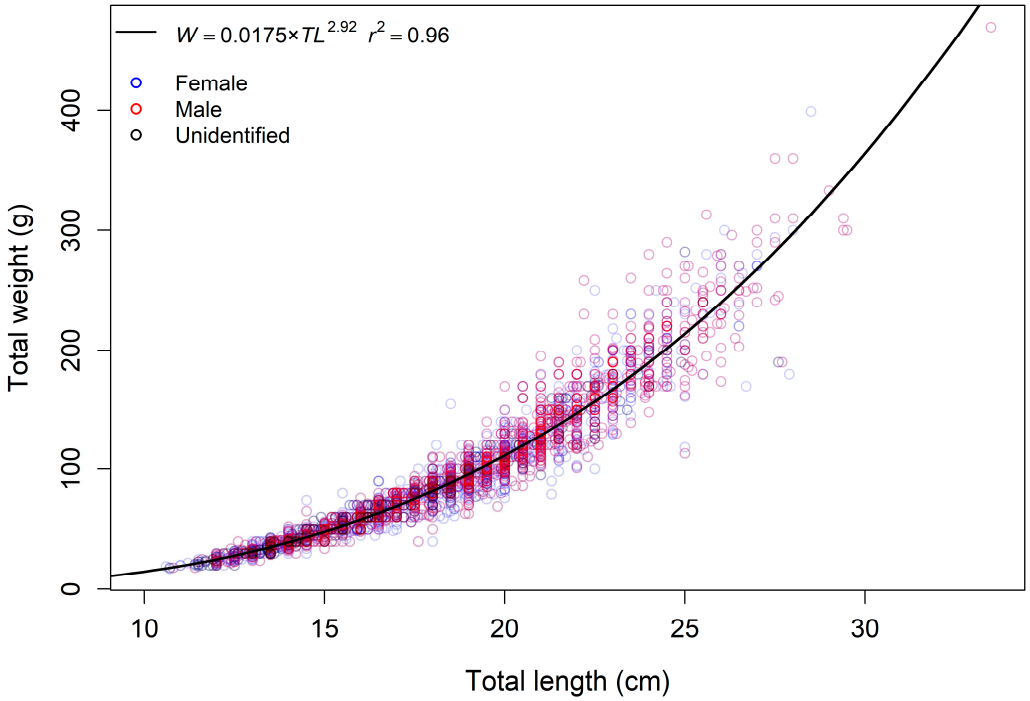


Figure 3. *TL-W* relationship of 2904 of *S. rivulatus* sampled between 2022 and 2024.

3.1. Maturity

The *TL* at which 50% of the population was considered mature (TL_{50}) was estimated to be 14.83 cm, with a 95% CI of 14.64–15.31 cm (Figure 4). Both males (N = 1154) and females (N = 1467) were classified as mature at stage II of the defined maturity stages.

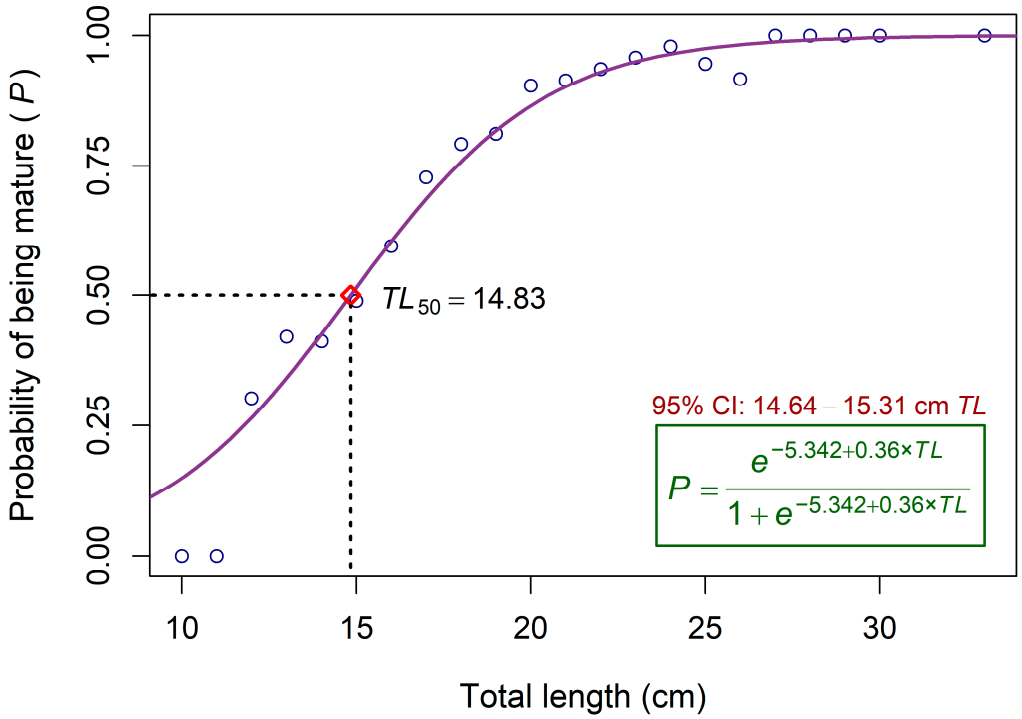


Figure 4. The estimated median *TL* at first maturity (TL_{50}) of *S. rivulatus* sampled between 2022 and 2024. The curve shows the logistic model fitted to the binomial maturity data of female and male fish. Circles represent the observed proportions of mature specimens to the total sampled fish. The red diamond square marks the estimated TL_{50} on the logistic curve. CI denotes the confidence interval.

3.2. Age and Growth

The maximum age recorded during the study period was 5 years, corresponding to a *TL* of 30.0 cm in a female individual (Table 2). However, as this observation was based on a single individual, it was excluded from the growth analysis but was still plotted on the growth curve in Figure 5 to illustrate its alignment with the fitted model. The estimated VBGM parameters and their standard errors (SE) were TL_∞ = 43.5 (±7.79) cm, K = 0.18 (±0.058) year^{-1}, and t_0 = −1.12 (±0.265) years.

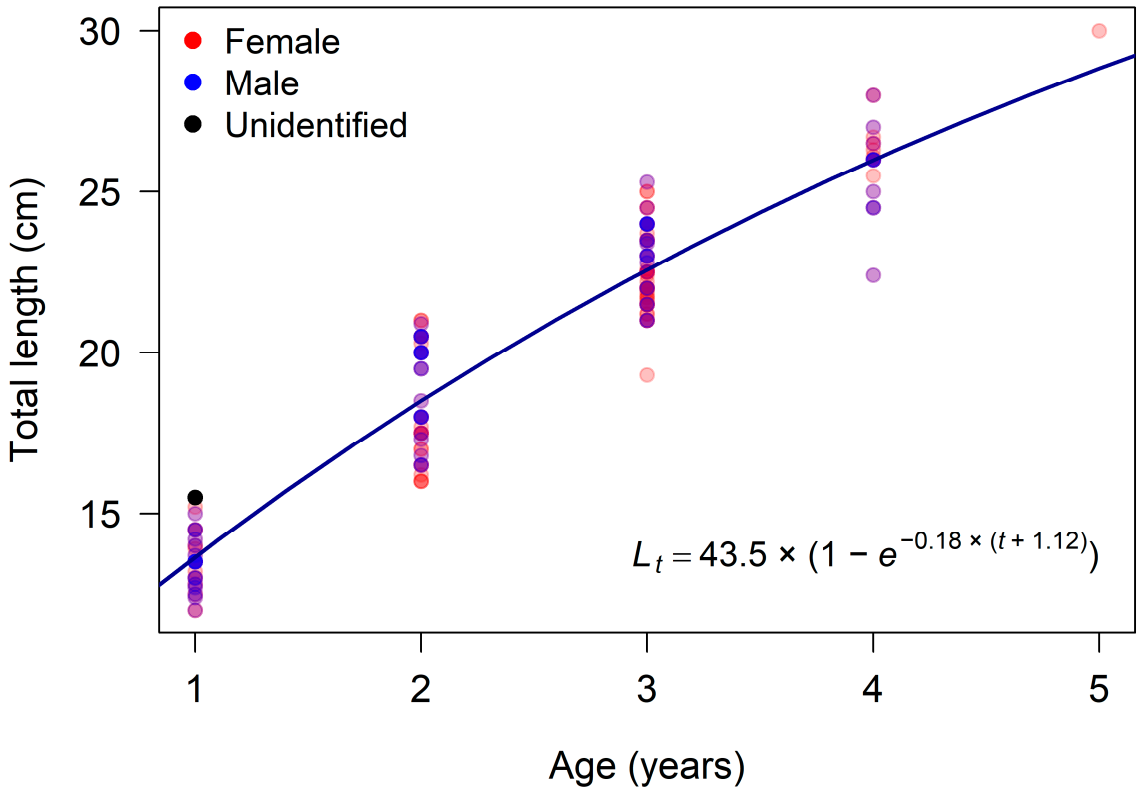


Figure 5. Observed *TL*-at-age for *S. rivulatus* curve sampled between 2022 and 2024, with the VBGM curve superimposed.

Table 2. Age length key for *S. rivulatus*.

TL Class (cm)	Age (Year)				
	1	**2**	**3**	**4**	**5**
12	8				
13	14				
14	7				
15	5				
16		9			
17		9			
18		6			
19		3			
20		13			
21		2	18		
22			19		
23			11		
24			12		
25			4	1	

Table 2. *Cont.*

TL Class (cm)	Age (Year)				
	1	**2**	**3**	**4**	**5**
26				11	
27				1	
28				2	
30					1

3.3. Natural Mortality

The estimates of M obtained from the three empirical methods showed considerable variation. The formula based on t_{max} [23] estimated M at 1.08 year^{-1}, while the calculation using only K [23] yielded an M of 0.28 year^{-1}. The modified Pauly's formula [24] provided an M estimate of 0.33 year^{-1}. The average of these three estimates was 0.57 year^{-1}, with a median value of 0.33 year^{-1}.

Using the PRODBIOM method, M values were calculated for each age class as 0.68, 0.61, 0.59, 0.58, and 0.57 year^{-1}. The highest M value (0.68 year^{-1}) was observed at age 1, with M decreasing as age increased, reaching the lowest value of 0.57 year^{-1} at age 5. The average M across all age classes derived from the PRODBIOM method was 0.62 year^{-1}.

3.4. Stock Assessment

The VPA estimated F values ranging from 0.01 year^{-1} at age 1 to 0.89 year^{-1} at age 3 (Table 3, Figure 6). The E was calculated as 0.60 for age classes 3 and 4. The terminal F was estimated at 0.57 year^{-1}, while individuals in age class 0 were not subjected to F, indicating selective fishing practices for this species. The majority of fishing pressure was concentrated on individuals aged 3–4 years (Figure 6, Table 3).

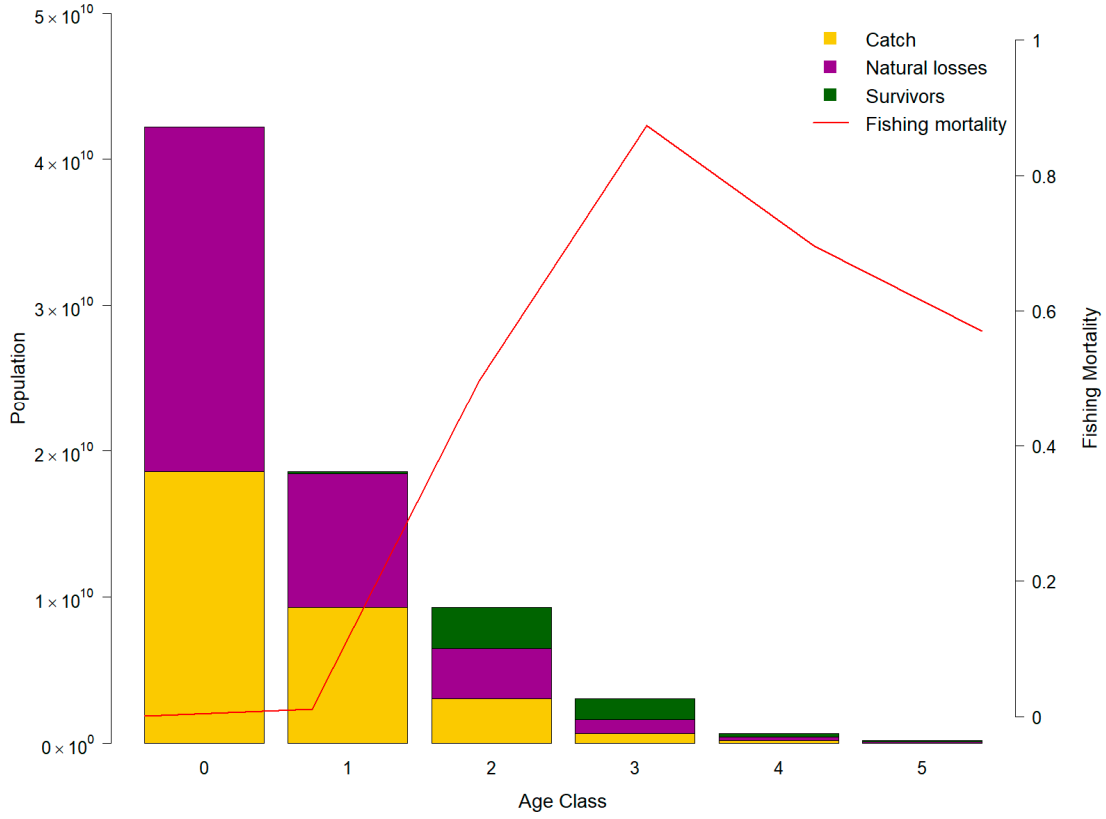


Figure 6. Age-structured VPA results of *S. rivulatus* sampled between 2022 and 2024.

Table 3. The VPA estimates for *S. rivulatus*.

VPA Outputs	Age Classes					
	0	**1**	**2**	**3**	**4**	**5**
Survivors (10^8)	193.8	97.2	32.1	7.2	1.9	0
Natural losses (10^8)	246.2	95.2	36.9	10.7	2.5	1.0
Catch × 1000	6.0	142.5	2806.8	1411.3	279.7	99.3
Catch (tonnes)	0.6	14.4	283.9	142.7	28.3	10.1
Fishing mortality (*F*)	0.0002	0.01	0.49	0.89	0.72	0.57
Total mortality (*Z*)	0.82	0.69	1.10	1.48	1.29	1.14

3.5. Fishery Characteristics

Gillnets and handlines were identified as the primary fishing gears used to capture *S. rivulatus* (Figure 7). The age class 2 group comprised the largest proportion of landings during the study period. In 2022, gillnet catches were higher than in 2023 and 2024, while trap fisheries predominantly targeted fish aged 3 years, resulting in comparatively higher yields for this age group (Figure 7).

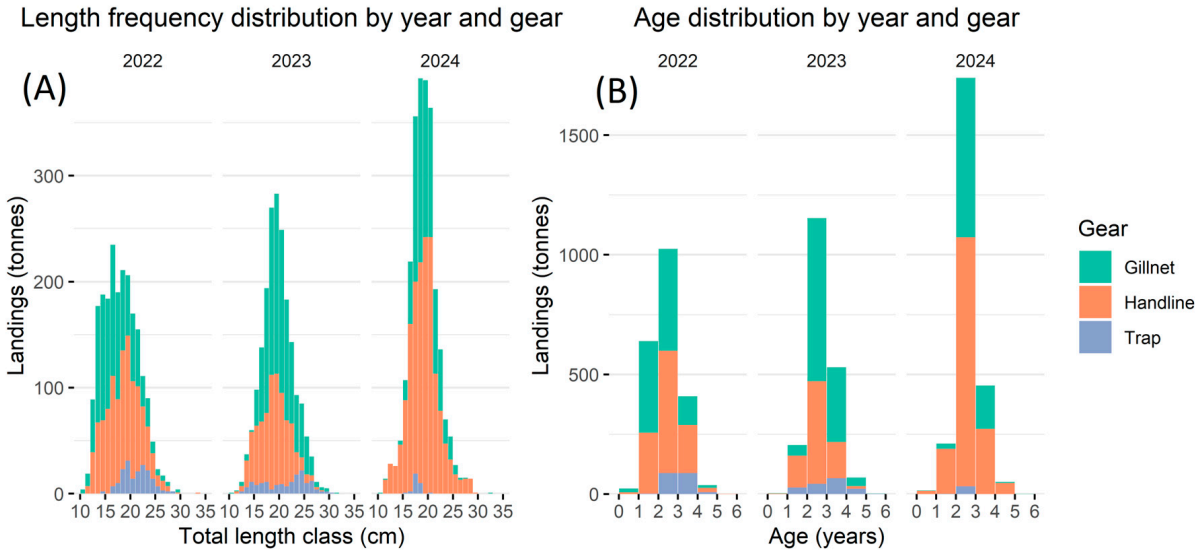


Figure 7. (**A**) Length frequency distribution and (**B**) age distribution of landings of *S. rivulatus* per gear type between 2022 and 2024.

4. Discussion

S. rivulatus is a commercially important herbivorous fish species with significant ecological roles in the Red Sea, particularly in controlling macroalgae growth and maintaining the balance of coral reef ecosystems. This study provides comprehensive insights into the life history traits, growth dynamics, and exploitation status of *S. rivulatus* along the Saudi Red Sea coast.

The *TL-W* relationship aligns closely with previous findings (Table 4), confirming a negative allometric growth pattern (b = 2.92) [29–31]. The VBGM parameter estimates for *S. rivulatus* from previous studies in the Red Sea and the Mediterranean Sea are summarized in Table 4. As shown, the growth parameters reported across studies exhibit considerable variability. The estimates obtained in the present study, based on age groups 1–4, differ notably from earlier Red Sea studies (Table 4). The point estimates for TL_∞ (43.5 ± 7.79 cm) and K (0.18 ± 0.058 year^{-1}) represent, respectively, among the highest and lowest values documented for this species, except for a slightly lower K value of 0.16 year^{-1} previously recorded along the Mediterranean coast of Libya by Shakman et al. [32]. However, when ac-

counting for the uncertainty indicated by standard errors, the present TL_∞ and K estimates become more comparable to values reported in the literature. According to the findings presented in Table 4, *S. rivulatus* generally appears to attain a larger asymptotic size in the Red Sea compared to the Mediterranean Sea. Interestingly, the elevated K values reported from the Red Sea by El-Gammal [29] and Mehanna and Abdallah [5] also suggest a faster growth rate for the Red Sea population compared to Mediterranean populations [30,32,33]. While these two parameters are often considered to be negatively correlated [19,34], this expected relationship is not consistently observed across the studies reviewed (Table 4). The regional differences in growth dynamics are likely influenced by environmental variability, including sea temperature, primary productivity, and fishing pressure. However, beyond geographic and temporal variation, the observed discrepancies among growth parameter estimates may also result from methodological differences. Some earlier studies relied on back-calculated mean lengths, used scales rather than otoliths for age determination, or employed less precise analytical techniques, such as the Ford–Walford or Gulland and Holt plots [34], instead of fitting observed length-at-age data through nonlinear regression. Such methodological choices can introduce bias or reduce estimation accuracy, contributing further to the observed variability across studies.

The TL_{50} estimate of 14.83 (95% CI: 14.64–15.31) cm is comparable to values reported for the Red Sea populations but significantly higher than the Mediterranean record of 13.65 cm [30]. This discrepancy likely reflects actual regional differences rather than random variability, highlighting the influence of local environmental conditions and fishing pressures on growth dynamics. The observed variation in life history traits between Red Sea and Mediterranean populations may also be explained by the species' invasive status in the Mediterranean. As a Lessepsian migrant outside its native Indo-Pacific and Red Sea range, *S. rivulatus* has demonstrated ecological and physiological plasticity in adapting to novel environments [35]. Such adaptability often results in altered growth rates, reproductive timing, and size-at-maturity in response to different ecological conditions across invaded regions and over time [36]. Nevertheless, differences among studies may also stem from methodological inconsistencies and sampling biases, which should be considered in cross-regional comparisons.

Three empirical formulas proposed by Hamel and Cope [23] and Then et al. [24] were applied, as recommended by Quinn and Deriso [19], to provide robust estimates of M. Additionally, the PRODBIOM method [25] was used to generate age-specific M estimates. When combined with these M values, the VPA revealed high F rates, particularly for age classes 3 and 4, which were estimated at 0.89 and 0.72 year^{-1}, respectively (Table 3). Consequently, the E estimates for these age classes were calculated at 0.60 and 0.56, well exceeding the limit reference point of 0.5 [37,38]. This indicates overfishing and raises significant concerns about the sustainability of current fishing practices. These findings are consistent with earlier studies that have documented overexploitation of this species in the Red Sea [5,8]. The selective nature of fishing methods, as evidenced by the absence of fishing mortality in age class 0, highlights a reliance on gear targeting larger individuals. However, the intense pressure on mature age classes underscores the urgent need for management interventions to mitigate overfishing and promote stock sustainability, such as implementing temporal fishing bans.

Gillnets and handlines were identified as the dominant fishing methods for *S. rivulatus* along the Saudi Red Sea coast, with trap fisheries showing a preference for age class 3 individuals. The age composition of landings varied annually, with gillnet catches peaking in 2022 and decreasing in subsequent years. This trend may reflect changes in fishing effort or stock availability. The predominance of age class 2 in landings highlights a reliance on younger cohorts, which, when combined with high exploitation rates, poses a

significant threat to the sustainability of the fishery. Similar trends have been reported in earlier studies, underscoring the importance of diversifying fishing methods and adopting targeted strategies to reduce pressure on younger age classes.

Table 4. Summary of growth and mortality parameters of *S. rivulatus* from the literature and the present study. In the present study, *Z*, *F*, and *M* values were obtained by averaging the estimates from respective methods for fish age class 2. All values represent combined sexes, with no separate estimates for males or females. "y" denotes year.

Growth					
N	TL_∞ **(cm)**	K **(y^{-1})**	t_0 **(y)**	**Region**	**Reference**
781	31.89	0.23	−1.31	Mediterranean, Lebanon	[30]
2176	38.10	0.28	−0.24	Red Sea, Saudi Arabia	[31]
251	32.85	0.47	−0.09	Red Sea, Egypt	[29]
521	22.30	0.28	−0.50	Mediterranean, Türkiye	[33]
1672	35.0	0.16	−1.04	Mediterranean, Libya	[32]
425	37.1	0.397	−0.186	Red Sea, Egypt	[5]
2000	34.44	0.38	−0.41	Red Sea, Egypt	[8]
1116	22.8	0.341	−1.376	Mediterranean, Egypt	[39]
2904	43.50	0.18	−1.22	Red Sea, Saudi Arabia	Present study
Mortality					
Dates	Z **(y^{-1})**	M **(y^{-1})**	F **(y^{-1})**	***E***	**Region**	**Reference**
2013–2014	2.04	0.41	1.63	0.80	Red Sea, Saudi Arabia	[31]
2017–2018	2.46	0.64	1.82	0.74	Red Sea, Egypt	[8]
2000–2001	1.27	0.26	1.01	0.80	Red Sea, Egypt	[5]
2022–2024	1.29	0.62	0.67	0.52	Red Sea, Saudi Arabia	Present study

The main findings of this study indicate that the *S. rivulatus* stock is presently experiencing slight overfishing, with the current *F* requiring a reduction of at least approximately 5%, and ideally more, to align with the precautionary approach. This situation places the stock at an elevated risk of future overexploitation, particularly given its low population resilience to both anthropogenic pressures (e.g., fishing) and environmental stressors such as climate change. In order to mitigate the overexploitation of *S. rivulatus* and ensure the long-term sustainability of its fishery, immediate management interventions are essential. Key recommendations include implementing size limits to protect juveniles, introducing seasonal fishing bans during peak reproductive periods, and enhancing compliance with existing fishing regulations. These measures would help reduce fishing mortality, improve recruitment, and facilitate stock recovery. Additionally, future research should explore the impacts of climate change on the species' spatial distribution and population dynamics, as well as assess the socio-economic implications of proposed management interventions.

5. Conclusions

Using the rigorous age-based VPA, applied for the first time to this species in the Red Sea, the findings of this study support our hypothesis that *S. rivulatus* in the region is experiencing unsustainable fishing pressure, with evidence indicating that the stock is slightly overfished. In addition to assessing exploitation status, the study provides new information regarding the life history traits and growth dynamics of *S. rivulatus*, a species that remains relatively understudied. The findings reveal that the species exhibits slower growth yet attains a larger asymptotic size than previously reported. A significant concern is that a considerable proportion of individuals are being harvested before reaching sexual maturity, with the *TL* at first capture (12 cm) falling below the estimated TL_{50}. The estimated

exploitation ratios further indicate unsustainably high fishing pressure, particularly in age classes 3 and 4. These findings highlight the urgent need for targeted management interventions, such as the implementation of minimum size limits, temporal fishing bans, and stricter enforcement of existing regulations. To ensure the long-term sustainability of this fishery, further research should explore the effects of environmental variability and climate change on the species' population dynamics, as well as the socio-economic dimensions of fishing practices and their implications for effective resource management.

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Institutional Review Board Statement: This study was based on fish specimens obtained from commercial catches and purchased at local fish markets. All measurements and analyses were conducted on these samples post-capture. No live specimens were involved in this research, and no experiments were conducted on animals.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on reasonable request from the corresponding author.

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