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Spatial and seasonal variations in the growth of the populations of tongue sole fish (*Cynoglossus quadrilineatus* Bleeker, 1851) along four different stations of Makran coast by using the von Bertalanffy model

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A R T I C L E I N F O

Keywords:
Cynoglossus quadrilineatus
Length-frequency data
von Bertalanffy growth model (VBGF)
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A B S T R A C T

Background: Growth is a most important life-history trait that defines the maximum size and age, maturation stage, and mortality of any fish species and is also involved in stock assessment models commonly used in fisheries conservation or management.
Objectives: The present study focused on assessing the growth patterns and related parameters to the population of tongue sole (*Cynoglossus quadrilineatus*) along different sites of the Makran coast in temperate regions.
Methodology: A total of 987 tongue sole fishes were collected seasonally from four different sites along the Makran coast (Gwadar, Pasni, Ormara, and Sur Bandar). Growth parameters i.e., length-weight relationships, length-frequency distribution, von Bertalanffy (VBGF) growth model, and stock status were analyzed.
Results: The overall results of the length-weight relationship (LWRs) of this species showed only a significantly positive allometric growth pattern ($b < 3.0$; $p < 0.05$) observed during three seasons along the four selected sites of Makran Coast. The estimated von Bertalanffy (VBGF) growth parameters of *C. quadrilineatus* at four stations were described as; maximum observed length (L_{max}) = 31.65 cm, asymptotic length (L_{∞}) = 33.32 cm, size at sexual maturity (L_m) = 17.98 cm, L_{opt} = 20.55 cm, growth coefficient per year (k) = 0.55 year $^{-1}$, t_0 = 0.04 year $^{-1}$, f = 2.79, T_{max} = 2.80 years, t_m = 0.78 year, M = 1.64 per year, t_{opt} = 1.30 years. The present study also noted seasonal variations in the length frequency distribution (LFD) data between the four selected sites.
Conclusions: Thus, our study concluded that the von Bertalanffy growth model (VBGF) is the best-fitted model for analyzing the growth patterns of *C. quadrilineatus* at different sites and during various seasons along the Makran Coast. This model demonstrated superior predictive ability and effectively described changes in growth patterns or body size across sub-populations of *C. quadrilineatus* at the four study sites. Thus, our research provides valuable insights into the population dynamics and life history traits of this tongue sole population in the Makran coast. Moreover, as the first study on the growth of this species, our findings offer essential information for informing sustainable exploitation, conservation, and fishery management strategies.

1. Introduction

Makran is one of the administrative divisions of Province Balochistan, Pakistan. It is a semi-desert southern coastal strip that extends over 750 km, and is characterized by a generally rocky seabed. Its notable productive zones include Sonmiani Bay, Kund Malir, Ormara, Kalmat, Pasni, Gwadar, and Jiwani. Makran coastal areas are characterized by irregular bays, mangrove forests, islands, lagoons, estuaries, and submerged rocks (FAO, 2009; Kalhoro et al., 2014; Mangroves for the Future (MFF), 2016).

Cynoglossus quadrilineatus belongs to the family Cynoglossidae commonly known as "tongue sole fishes", which are small to medium-sized bottom-dwelling marine flatfishes, which feed on benthivores and small crustaceans. Tongue sole mostly inhabits shallow habitats of

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temperate and warm waters at a depth of 1500 m. This species has now pronounced economic and ecological importance all over the world (Ali et al., 2021; Nag et al., 2022).

The length-weight relationship (LWRs) is a crucial tool that can be employed for various purposes, such as collecting assessment data, distinguishing between different biological stock models, and acknowledging the variations in LWRs for the same species observed across different geographic locations with varying environmental conditions. It also helps in estimating the health and life history traits of fish species found in different regions (Dagtekin et al., 2022; Mughul et al., 2022). Length-Frequency (LF) data is another significant tool that helps in identifying different length/size groups of fish, which is valuable for stock assessment models and studying morphological similarities among fish populations collected from different locations (Raza et al., 2022). Both LWRs and LFD hold significant positions in the fields of fish biology, physiology, ecology, and fishery stock assessment (Karna et al., 2018; Majeed et al., 2021).

Growth in fish, defined as the increase in size or weight over time, is a crucial biological process linked to reproduction, fecundity, and natural mortality. Accurate growth modeling is essential for understanding fish population dynamics, setting sustainable harvest levels, and conserving stocks. Growth models, such as the von Bertalanffy Growth Model (VBGM), Gompertz Growth Model (GGM), Logistic Growth Model (LGM), Schnute–Richards Growth Model (SRGM), and simple linear regression models, help assess the growth condition of fish species and inform management decisions (Renner-Martin et al., 2018). Models like GGM and LGM are often used for larval and juvenile fish growth. The primary output of these models is an equation describing growth, providing parameter estimates for comparing growth within and between populations (Zhang et al., 2020). Fisheries biologists have used these models for over a century, particularly for marine fish, to assess daily growth and apply fisheries data effectively.

Choosing the appropriate growth model for fish populations depends on factors such as species, available data, intended use of the model, and management objectives. Mathematical growth models that relate age to size (length or weight) are crucial for monitoring fish populations and making management decisions, like setting size limits for harvesting. The von Bertalanffy growth model, widely used for vertebrates, is commonly applied in fisheries biology to estimate fish population growth parameters (Flinn and Midway, 2021). Therefore, this study uses the von Bertalanffy model to compare growth variations in populations of the tongue sole fish species (*Cynoglossus quadrilineatus*) collected from four sites (Gwadar, Pasni, Ormara, and Sur Bandar) along the Makran coast.

2. Materials and methods

2.1. Study area and fish sampling

In this study, the population parameters of tongue soles, *C. quadrilineatus* were studied seasonally (i.e., pre-monsoon, Monsoon, and post-monsoon seasons) at four selected sites of Makran's coast during July 2021 to July 2022. These four different sites includes i.e., Pasni, Gwadar, Ormara, and Surbandar (Fig. 1).

2.2. Analysis of length-frequency (LF) data

The LF data were collected at seasonal intervals from the four selected fish landing centers of Makran coast, which later used to assess the population parameters i.e., the growth performance index and stock assessment status as the method described by Raza et al. (2022).

2.3. Analysis of growth performance of sole fish

2.3.1. Analysis of length-weight relationship (LWRs)

The following linear regression equation of LWRs was used as equation (1) given by Le Cren (1951), and Masood et al. (2022);

$$Wt = aL^b \tag{1}$$

Whereas; Wt = weight of fish in grams (g); L = total length (TL) of fish in (cm); a = constant (intercept) used to determine the body shape of species (if a = 0.001 = eel like shape; if a = 0.008 = elongated shape, if a = 0.01 = fusiform shape, a = 0.018 = short and deepen); b = regression coefficient (slope) shows growth pattern either allometric or isometric; $r^2 =$coefficient of determination, which shows the strength of the relationship between length-weight was also calculated. If the $r^2 \geq$ 0.70 then the correlation is strong between the length and weight of fish, but $r^2 = 0.60$ shows a moderate relationship; whereas, $r^2 \leq 0.60$ shows weak relationship (Froese, 2006).

2.3.2. Fulton's condition factor (CF)

The following equation of Fulton's was used to calculate the condition factor (CF) as described in equation (2) followed by Masood et al. (2022) below;

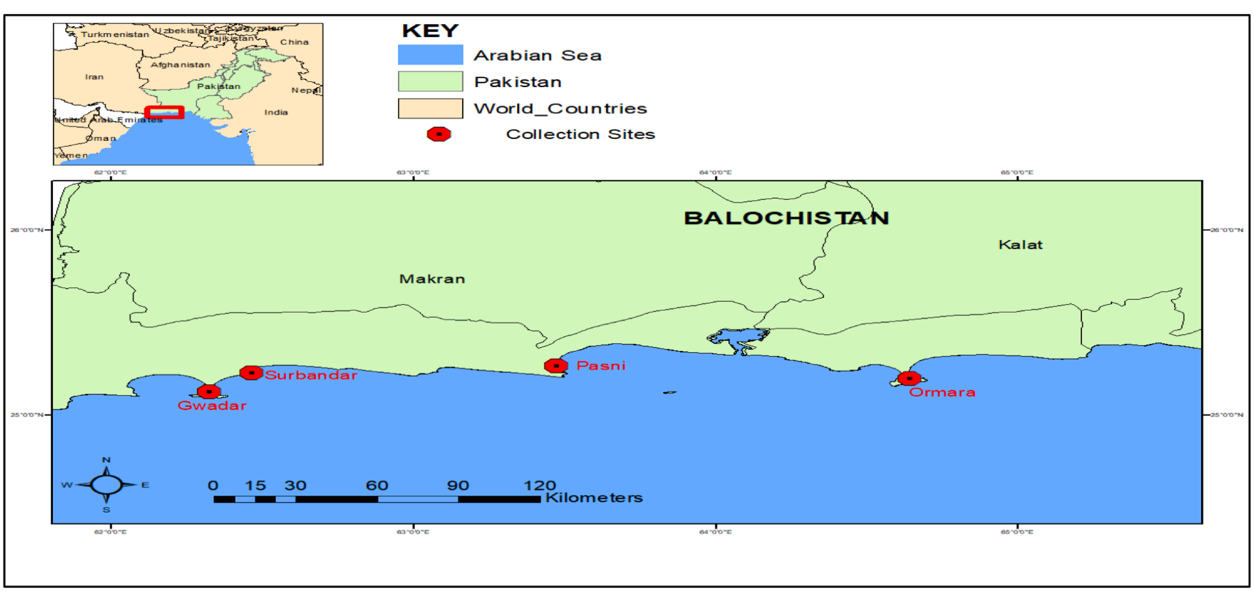

Fig. 1. Map of four selected stations of Makran coast.

$$CF = W\,x\,100/L3 \quad (2)$$

But if CF $\geq$ 1.0 then the environmental condition will be suitable for the fish growth, but if less than ideal value, CF $<$ 1.0, then habitat condition will be unsuitable.

2.3.3. Choice of growth model

Selecting an appropriate growth model is crucial and complex in fishery research. Our study aims to identify the best-fitting model, such as the von Bertalanffy Growth Model (VBGF), to describe growth variations among inter-populations of *C. quadrilineatus* along the Makran Coast. This VBGF model was used to compare growth performance across four populations collected from Gwadar, Pasni, Ormara, and Sur Bandar. This model, deemed the best fit using the methods outlined by Kalhoro et al. (2014), facilitated differentiation in growth rates by calculating VBGF parameters (Ogle & Isermann, 2017). A comprehensive evaluation of the VBGF for this species considered both its statistical presentation and biological applicability, focusing on its ability to accurately describe and predict growth during three different seasons at the four sites of Makran coast.

2.3.3.1. Calculation of von Bertalanffy growth method (VBGF). The growth dimensions were calculated by using VBGF parameters as mentioned below to describe the discrimination between the growth of four sub-populations of tongue soles in different fishing sites during different seasons with the help of equation (3) used by Panda et al. (2018) as follows;

$$L_t = L_\infty(1 - Exp(-K(t - t_0))) \quad (3)$$

where L_t is the length at the predicted time t,L_∞ is the asymptotic length, K is the growth coefficient and t_0 is the hypothetical age or time where length was equal to zero. An additional estimated value of t_0 was obtained by the following empirical equation (4) of Panda et al. (2018) as follows;

$$log_{10}\ \ (-t_0) = -0.3922 - 0.275 log_{10}\ L_\infty - 1.038 log_{10} K \quad (4)$$

The estimated growth parameters values of L∞ (asymptotic length) and K (growth constant) were used to compute the growth performance index (f) by following equations (5) & (6) of Pauly and Munro (1984) were used as follows;

$$f = log10K + 2log10L\infty \quad (5)$$

$$and\, f\ =\ log10\,K\ +\ 2/3\,log10\,W\infty \quad (6)$$

2.3.3.2. Model evaluation criteria of von Bertalanffy growth model. When evaluating the von Bertalanffy Growth Model (VBGF) in fish biology, several criteria is typically considered as below;

(a) *Fit to the database:* The model's performance can be compared against empirical data to assess how well it describes the growth pattern of the fish species under study.

(b) *Statistical measures:* Various statistical measures, such as the coefficient of determination (r^2) and root mean square error (RMSE), can quantify the goodness of fit between the model calculation and observed data.

(c) *Biological acceptability:* The model's biological realism is evaluated to ensure its assumptions align with known biological processes. For example, VBGF assumes that growth rate decreases as the animal approaches a maximum size, which should align with the biology of the species being studied.

(d) *Parameter estimation:* Precision, accuracy, and uncertainty associated with estimating VBGF parameters are evaluated during the study.

(e) *Predictive ability:* The model's utility for predicting growth patterns under different conditions is assessed to determine its reliability in practical applications.

(f) *Sensitivity analysis:* This analysis helps identify which parameters have the greatest influence on model outcomes and assesses the model's robustness to parameter uncertainty.

2.4. Collection of stock status data of sole fishes

The average annual landing data of *C. quadrilineatus* during the past five periods from 2015 to 2019 was collected from the Gwadar Port Authority, District Gwadar of Balochistan to observed that whether the average landings of the fisheries stock of this species either increasing or decreasing in past five years.

2.5. Statistical analyses

Statistical data were calculated by using MS Excel version 10, and Graph Pad Prism 8.0 computer software.

3. Results

A total of 987 individuals of the fish *Cynoglossus quadrilineatus* (Bleeker, 1851) were collected from the Makran Coast of Balochistan from July 2021 to July 2022 during three different seasons (pre-monsoon, monsoon, and post-monsoon, as shown in Table 1 and Fig. 2.

3.1. Length-frequency (LF) data

The results of LF data *C. quadrilineatus* at four different stations of Makran Coast were recorded in Fig. 3A-3D, which indicate the most frequent length or size of fish (in centimeters) found along these four different sites.

3.2. Spatial and seasonal variations in the growth performance of tongue sole fishes

3.2.1. Length-weight relationship (LWRs) data

Fig. 4A-4D show LWRs data for fish *C. quadrilineatus* gathered throughout the entire year from July 2020 to June 2021. The overall *b*-values (regression coefficient) recorded from all stations were close to 2, indicating a positive allometric growth pattern (b $<$ 3.0) during all three seasons. In this study, the coefficient of determination '$r^{2\prime}$ showed a strong and significant correlation for Ormara ($r^2 > 0.70$) and Gwadar, while moderate ($r^2 = 0.60$ to 0.69) for Pasni and Surbandar, which represents a better adaptation to length and weight among all three seasons at the four sites.

3.2.2. Condition factor (CF)

Fig. 5 displays the highest CF mean values in the different seasons along the Ormara coast. The overall mean CF values observed during the three seasons at the four different sites was less than one (CF $<$ 1.0), which indicates that the environmental conditions of Makran Coast were unfavorable for the growth of this species. Therefore, proper management is essential for the conservation of this species.

3.2.3. Von Bertalanffy growth model (VBGF) of C. quadrilineatus

Table 2 presents an analysis of growth parameters in *C. quadrilineatus* fish using the VBGF model. The maximum observed length (Lmax) was recorded at 32.50 cm in Ormara, 31.10 cm in Gwadar, 31.50 cm in Pasni, and 31.50 cm in Surbandar. The asymptotic lengths in centimeters (L∞) were determined to be 31.21 cm in Ormara, 32.74 cm in Gwadar, 33.16 cm in Pasni, and 33.16 cm in Surbandar. Additionally, the growth coefficient per year (k) was consistent at 0.55 across all sites, including Ormara, Gwadar, Pasni, and Surbandar. The age at zero length in years (t_0) was measured as 0.041 in Ormara, 0.042 in Gwadar, 0.04 in Pasni, and 0.04 in Surbandar. The growth performance indexes (f) were observed to be 2.81 in Ormara, 2.77 in Gwadar, 2.78 in Pasni, and 2.78 in Surbandar. The lifespan or longevity in years (Tmax) was calculated as 2.80 in Ormara, Gwadar, Pasni, and Surbandar. The size at sexual

Table 1
Descriptive statistics of mean length and mean weight of *Cynoglossus quadrilineatus* populations collected during three seasons along four sites of Makran coast.

Sites name	Seasons	N	Mean length (cm)	Mean weight (g)	Median		Standard Derivation		Mode	
					Length	Weight	Length	Weight	Length	Weight
Pasni	Moon soon	59	28.04	134.52	29.50	141.00	1.54	9.28	30.00	148.00
	Pre-Moon soon	95	28.04	134.52	28.00	135.00	1.27	7.29	28.00	134.00
	Post Moon soon	93	29.21	140.51	29.20	143.00	1.40	8.32	28.50	146.00
	Moon soon	72	27.93	141.54	28.50	144.00	3.05	15.52	31.00	144.00
Gwadar	Pre-Moon soon	98	27.31	137.48	27.200	136.00	1.056	6.41	28.200	134.00
	Post Moon soon	90	27.60	139.67	27.40	138.00	1.20	6.53	27.00	136.00
	Moon soon	60	28.83	138.85	29.10	140.00	1.53	10.19	30.00	140.00
Ormara	Pre-Moon soon	110	28.90	139.71	29.10	140.00	2.42	12.98	28.50	134.00
	Post Moon soon	79	28.95	139.17	29.00	140.50	1.22	9.39	29.50	150.00
	Moon soon	45	28.13	135.07	28.50	135.50	2.10	13.49	28.80	150.00
Surbandar	Pre-Moon soon	111	27.71	135.68	28.00	136.00	2.53	14.85	31.00	126.00
	Post Moon soon	76	28.13	135.07	28.50	135.50	2.10	13.49	28.80	150.00

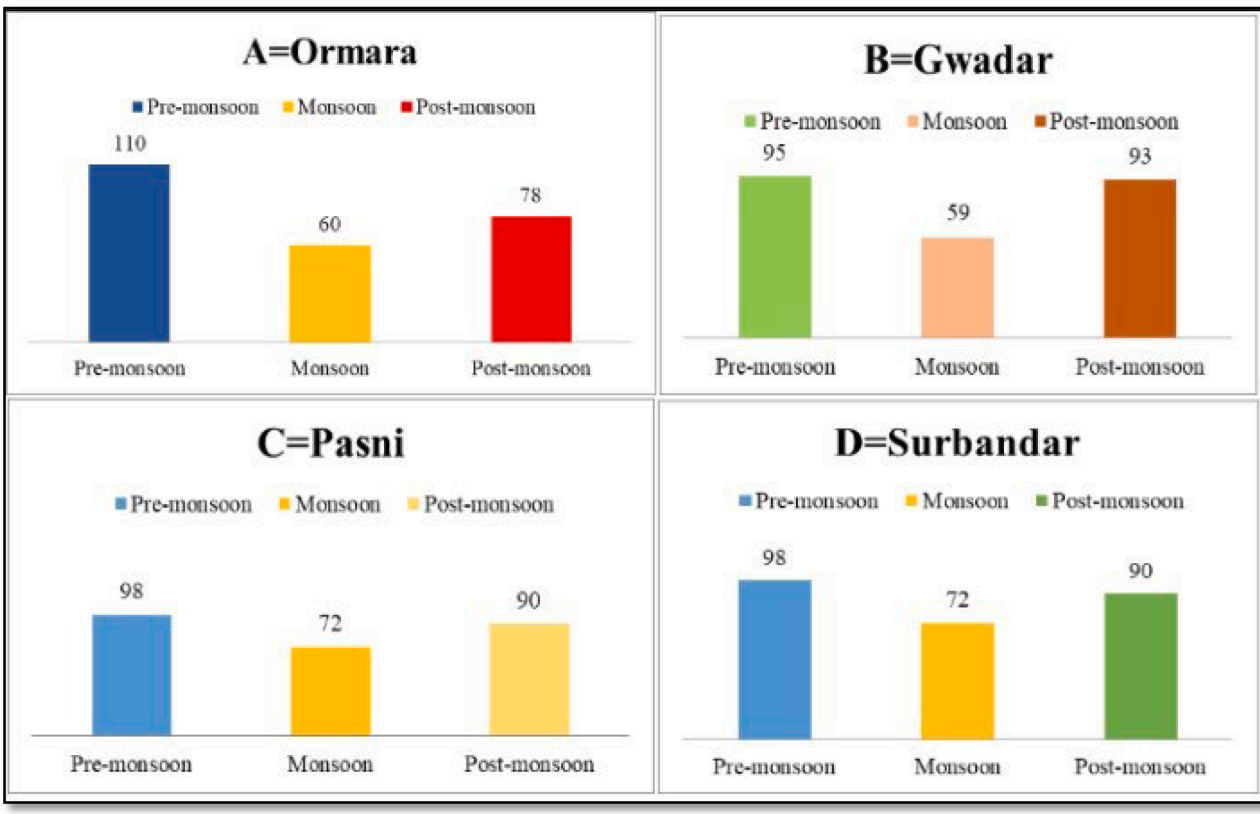

Fig. 2. Collection of fish samples of *Cynoglossus quadrilineatus* during pre-monsoon, monsoon and post-monsoon seasons from four different sites of Makran Coast.

maturity in centimeters (Lm) was measured at 18.43 in Ormara, 17.70 in Gwadar, 17.90 in Pasni, and 17.90 in Surbandar, while the age at sexual maturity in years (tm) was determined to be 0.78 in Ormara, Gwadar, Pasni, and Surbandar. The natural mortality rate per year (M) was found to be 1.64 across all sites. Lengths at maximum yield per recruit in centimeters (Lopt) were recorded at 21.10 in Ormara, 20.20 in Gwadar, 20.45 in Pasni, and 20.45 in Surbandar. The age at maximum yield per recruit in years (topt) was consistent at 1.30 across all sites. Dunn's multiple comparison tests in Table 3 were applied among the four sites denoted as A (Ormara), B (Gwadar), C (Pasni), and D (Surbandar), which revealed a significant correlation ($p < 0.05$) among all four different sites, which indicates a meaningful relationship between parameters of VBGF growth model.

3.3. *Sole fish stock status data*

Fig. 6 illustrates the sole fish stock data in metric tons for *C. quadrilineatus* reported during the years from 2015 to 2019 at four selected stations along the Makran Coast. The total catch in 2017 increased significantly along the Ormara and Gwadar sites, however decreasing again from 2018 to 2019. However, the total catch in 2018–2019 was found to increase significantly along the Pasni and Surbandar sites.

4. Discussion

4.1. *Length-weight relationship (LWRs) data of C. quadrilineatus*

Though various species of the family Cynoglossidae are highly abundant on the Pakistan coast and throughout the world, but still previously published literature related to analyzing the growth pattern of *C. quadrilineatus* along the Balochistan coast was unavailable. Therefore, this study builds upon prior investigations of various species of genus *Cynoglossus* of this family, as reported by previous researchers

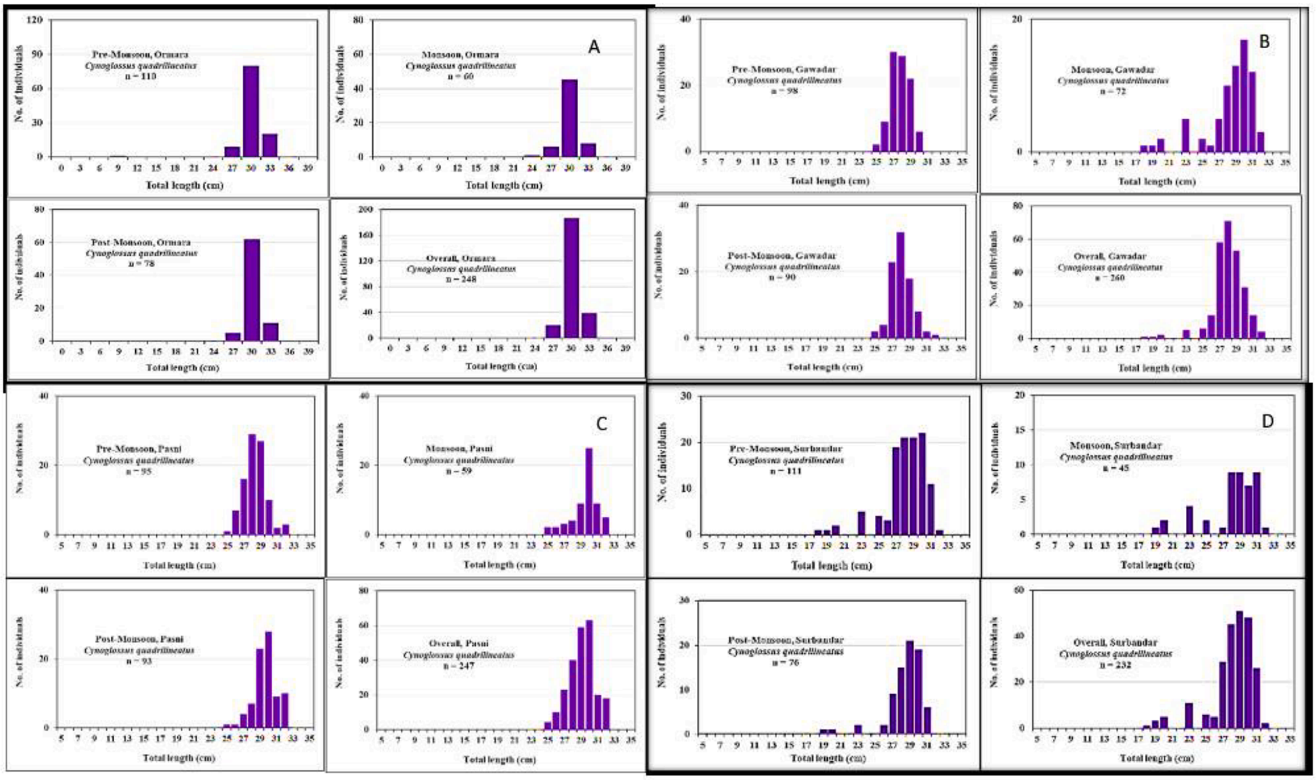

Fig. 3. Shows Length frequency distribution data of *Cynoglossus quadrilineatus* were collected in three seasons from Ormara (A), Gwadar (B), Pasni (C) and Surbandar (D) sites of Makran coast.

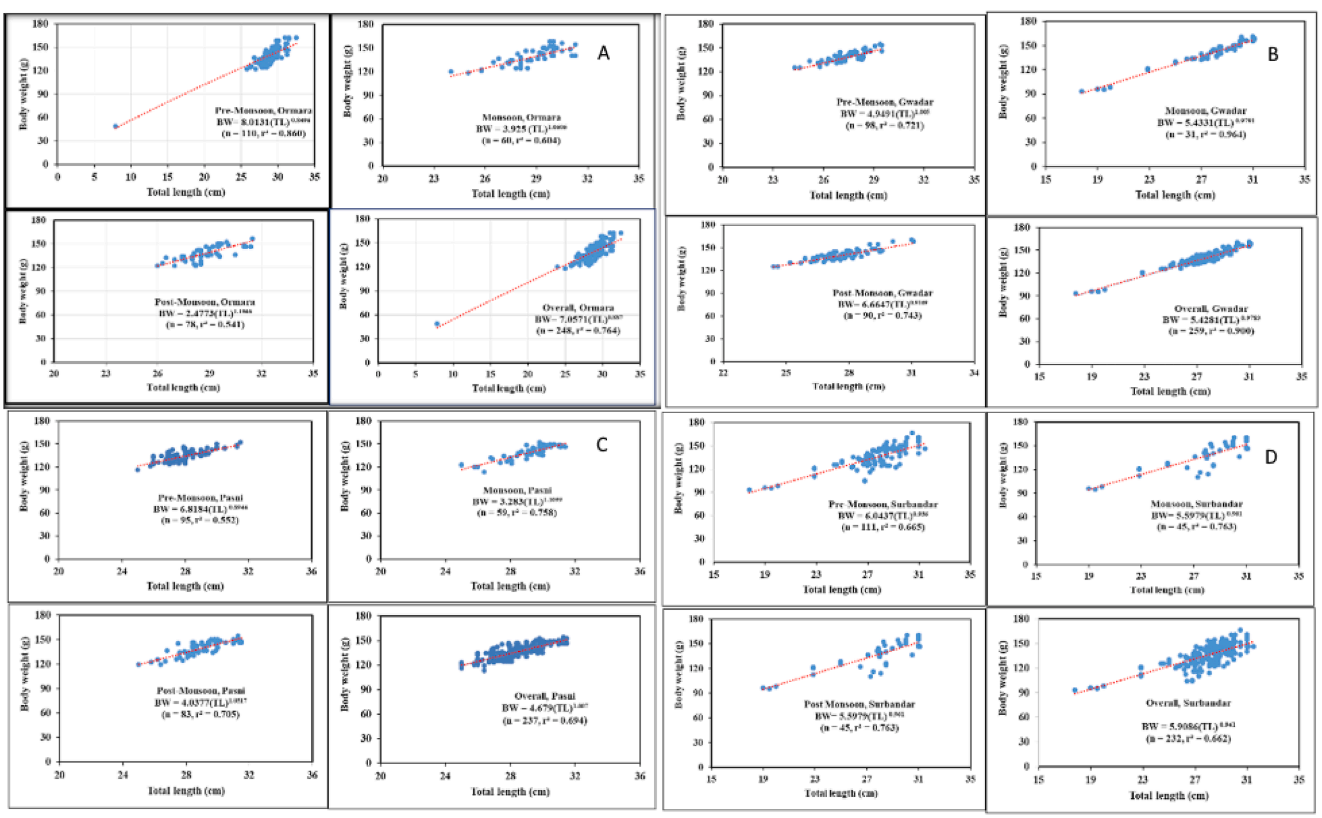

Fig. 4. Shows length-weight relationship (lwrs) data of *Cynoglossus quadrilineatus* collected from Ormara (A), Gwadar (B), Pasni (C) and Surbandar (D) sites of Makran coast during three different seasons.

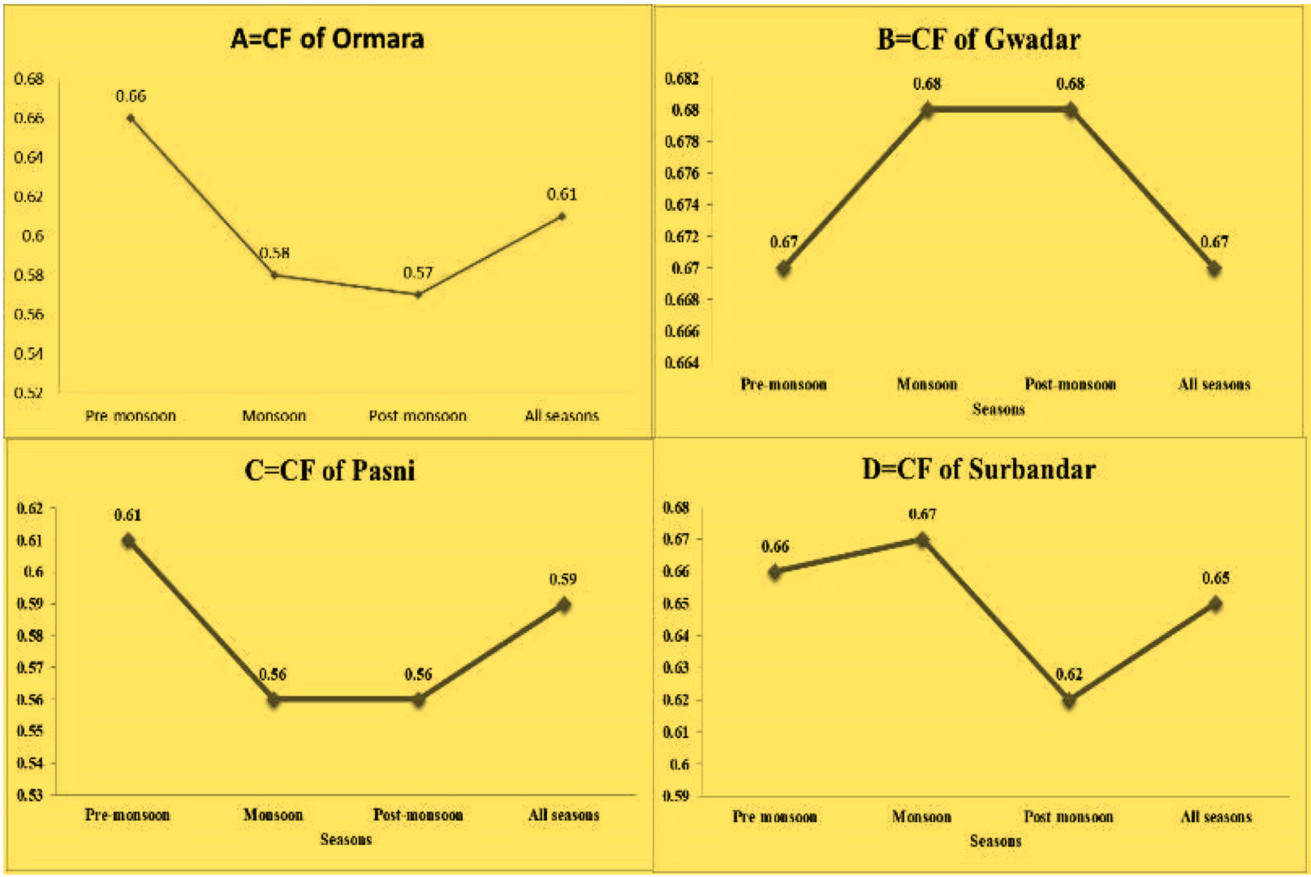

Fig. 5. Shows mean condition factor (CF) values for *Cynoglossus quadrilineatus* collected from four different sites of Makran coast in three different seasons.

in Asia and other countries of the world. Across all seasons and sites, we found only an allometric growth pattern ($b < 3.0$) in our present study, which was consistent with Ali et al. (2021), who also reported allometric growth pattern with *b*-values observed as 2.85 for *C. quadrilineatus*, 2.859 for *C. arel,* and 2.02 for *C. puncticeps* along the Sindh coast of Pakistan. This indicates that the environmental conditions of Pakistan's coasts are not completely suitable for the growth of this species. In contrast, Aghajanpour et al. (2015) reported an isometric growth pattern ($b > 3.0$) for *C. quadrilineatus* along the Iranian coast, representing better environmental conditions for the growth of this species. Similarly, Jayaprakash (2001a) observed isometric growth patterns ($b > 3.0$) in *C. macrostomus* and *C. arel*, found along the southwest coast of India. Katayama and Yamamoto (2012) observed an isometric growth pattern ($b = 3.44$) in *C. robustus* along the Seto Inland Sea of Japan. Yuquan (2014) also observed an allometric growth pattern ($b = 2.99$) in females of *C. semilaevis,* cultured at the Shandong Peninsula of China. Bhalekar et al. (2018) reported an isometric growth pattern ($b > 3.0$) in *C. macrostomus* along the Ratnagiri coast of Maharashtra, India. Karna et al. (2018) investigated the LWRs of *C. puncticeps, C. lingua,* and *C. lida* from Chillida Lagoon in India and found both allometric and isometric growth patterns in them.

Moreover, Jayaprakash (2001b) reported a strong and significant correlation ($r^2 > 0.70$; $p < 0.05$) between LWRs for *C. macrostomus* and *C. arel* along the Indian Coast. Likewise, Ali et al. (2021) also had a strong and significant correlation ($r2 > 0.70$; $p < 0.05$) between LWRs for *C. quadrilineatus* along the Sindh coast of Pakistan, which were in consistent with our present study. Thus, growth of any fish species can also be influenced by some factors, including habitat variation in different regions, water temperature, food availability, spawning periods, stomach condition, maturity, gonad status, overall fish health, conservation methods, and variations in fish morphology within the sample, as previously reported by Yilmaz et al. (2010), Ali et al. (2021), and Masood et al. (2022).

4.2. Fulton's condition factor (CF)

In this study, the condition factor (CF) values for *C. quadrilineatus* across three seasons and four sites were below 1.0, indicating poor growth conditions, resulting in elongated and thin bodies. This suggests that the growth condition of tongue sole along the Makran coast is suboptimal. Similar findings were reported by Ali et al. (2021) for *C. quadrilineatus* along the Sindh coast of Pakistan (CF = 0.6345) and by Abowei et al. (2009) for *C. senegalensis* in the Niger Delta of Nigeria. Tanjin et al. (2021) also observed low CF values (CF = 0.6469) for *C. cynoglossus* in the Bay of Bengal, indicating unstable physiological conditions. These variations in CF values may result from factors such as food availability, climatic changes, pollution, overexploitation, spawning periods, foraging behavior, and energy accumulation (Tanjin et al., 2021). Our results provide valuable information for fisheries biologists to manage the growth conditions of this species effectively.

4.3. Length-frequency (LF) data of C. quadrilineatus

In this study, the mean length of *C. quadrilineatus* ranged from 27.31 to 29.21 cm across four sites during three seasons. Variations in mean length were observed, with the highest mean length at Pasni, Ormara, and Sur Bandar during the post-monsoon season, and the lowest at Gwadar. Similar seasonal variations in fish length were noted by Elahi and Tabassum (2013) for *Sardinella gibbosa* at Makran Coast and by Akanse and Eyo (2018) for *C. senegalensis* in Nigeria. Ali et al. (2021) reported a mean length of 32.77 cm for *C. quadrilineatus* along the Sindh coast of Pakistan. These consistent findings suggest shared

Table 2
Analysis of von Bertalanffy growth model parameters of fish *Cynoglossus quadrilineatus* were collected from four sites (Ormara, Gwadar, Pasni and Surbandar) of Makran coast, Balochistan.

Serial No.	Parameter	Ormara	Gwadar	Pasni	Surbandar	Mean
1	Observed maximum length in cm (L_{max})	32.50	31.10	31.50	31.50	31.65
2	Asymptotic length in cm (L_{∞})	34.21	32.74	33.16	33.16	33.32
3	Growth co-efficient per year (k)	0.55	0.55	0.55	0.55	0.55
4	Age at zero length in year (t_0)	0.041	0.042	0.04	0.04	0.04
5	Growth performance index (f)	2.81	2.77	2.78	2.78	2.79
6	Life-span / Longevity in year (T_{max})	2.80	2.80	2.80	2.80	2.80
7	Size at sexual maturity in cm (L_m)	18.43	17.70	17.90	17.90	17.98
8	Age at sexual maturity in year (t_m)	0.78	0.78	0.78	0.78	0.78
9	Natural mortality per year (M)	1.64	1.64	1.64	1.64	1.64
10	Length at maximum yield per recruit in cm (L_{opt})	21.10	20.20	20.45	20.45	20.55
11	Age at maximum yield per recruit in year (t_{opt})	1.30	1.30	1.30	1.30	1.30

environmental factors influencing fish length. Thus, the LF data is essential for calculating fish yields and understanding variations in LWRs over time.

4.4. Von Bertalanffy growth model (VBGF) of C. quadrilineatus

In this study, the average estimated von Bertalanffy growth function (VBGF) parameters for *C. quadrilineatus* at four sites on the Makran coast were: asymptotic length (L∞) of 33.32 cm, growth coefficient (k) of 0.55 year-[1], and age at zero length (tof 0.04 years. No previous literature on VBGF for sole fish species in Pakistan, specifically the Makran coast, exists. This study builds on prior research of various species in Asia and other countries, as shown in Table 4. Khalhoro et al. (2014) estimated VBGF parameters for *Saurida undosquamis* on Pakistan's coasts: L∞ = 39.90 cm, k = 0.270 year-1, and t = -0.572 years. Bhalekar et al. (2016) studied *C. macrostomus* along India's Ratnagiri coast using VBGF, while Amponsah et al. (2023) examined *C. senegalensis* growth on Ghana's coast. Gabr (2015) analyzed *Solea aegyptiaca* in Egypt's Bardawil Lagoon, and Mehanna et al. (2015) along with Cerim and Ateş (2020), studied *Solea solea* in the Mediterranean and Aegean Sea. Majeed et al. (2021) used VBGF for *Alepes djedaba* from Pakistan's Balochistan coast, estimating L∞ = 39.9 cm and k = 1.6 year-1. Kahraman et al. (2021) examined *Solea solea* in Turkey's Marmara Sea. These studies indicated high fishing pressure on these stocks. Given the economic importance of *C. quadrilineatus* to local communities along the Makran coast, understanding their growth and age/size at maturity is essential for effective management and exploitation.

Table 3
Dunn's multiple comparison test in between four (Ormara, Gwadar, Pasni and Surbandar) Makran coast, Balochistan.

Dunn's multiple comparisons test	Mean rank diff.	Significance (P < 0.05)	Summary		
Column A vs. Column B	233.3	Yes	****		
Column A vs. Column C	44.98	No	ns		
Column A vs. Column D	133	Yes	****		
Column B vs. Column C	−188.3	Yes	****		
Column B vs. Column D	−100.3	Yes	***		
Column C vs. Column D	88.03	Yes	**		
Test details	**Mean rank 1**	**Mean rank 2**	**Mean rank diff.**	**n1**	**n2**
Column A vs. Column B	593.6	360.3	233.3	248	260
Column A vs. Column C	593.6	548.6	44.98	248	237
Column A vs. Column D	593.6	460.6	133	248	232
Column B vs. Column C	360.3	548.6	−188.3	260	237
Column B vs. Column D	360.3	460.6	−100.3	260	232
Column C vs. Column D	548.6	460.6	88.03	237	232

Environmental changes can significantly impact the growth and maturity of fish, making the accurate estimation of growth patterns crucial in fisheries science. Determining the best-fitting growth model is challenging due to the variety of models available (Flinn and Midway, 2021). However, many fisheries biologists prioritize the von Bertalanffy Growth Model (VBGF) for its extensive use in describing the growth of exploited fish populations based on length/weight data from mature individuals. The VBGF is recognized for effectively studying growth patterns among intra- and inter-populations across different sites or seasons (Pagalay and Anisyah, 2016; Zhang et al., 2020). It represents fish growth as a balance between catabolism and anabolism (Pagalay and Anisyah, 2016). Our length/size data for *C. quadrilineatus* suggest that growth is linear and allometric or isometric in the early years, increasing significantly in later years, consistent with the VBGF model. This indicates the model's effectiveness in describing somatic growth in adult sole fishes, where growth tends to be linear. The VBGF model is widely applied, as post-maturation growth phases dominate length-at-age data due to their longer duration compared to pre-maturation phases. This dominance can be by sampling protocols that target adult fishes, often excluding immature specimens necessary for characterizing pre-maturation growth (Lester et al., 2004). Of the approximately 7,000 fish species consumed worldwide, sustainable use data is available for only about 1,200 species. Estimating fish mortality rates and maximum sustainable yields using key population parameters is crucial for conservation. Differences in growth parameters are indicators for more detailed studies on fish growth. While some attempts have been made to provide growth models for Makran fisheries, ecological models that demonstrate predator–prey relationships and provide essential information for fisheries regulation and management are still lacking.

4.5. Stock status of sole fish

Marine fisheries resources in Pakistan have been significantly impacted by overfishing, juvenile capture, unsustainable fishing practices, and marine pollution. As a result, numerous studies have assessed the stock of various marine fish species along the Pakistan coast,

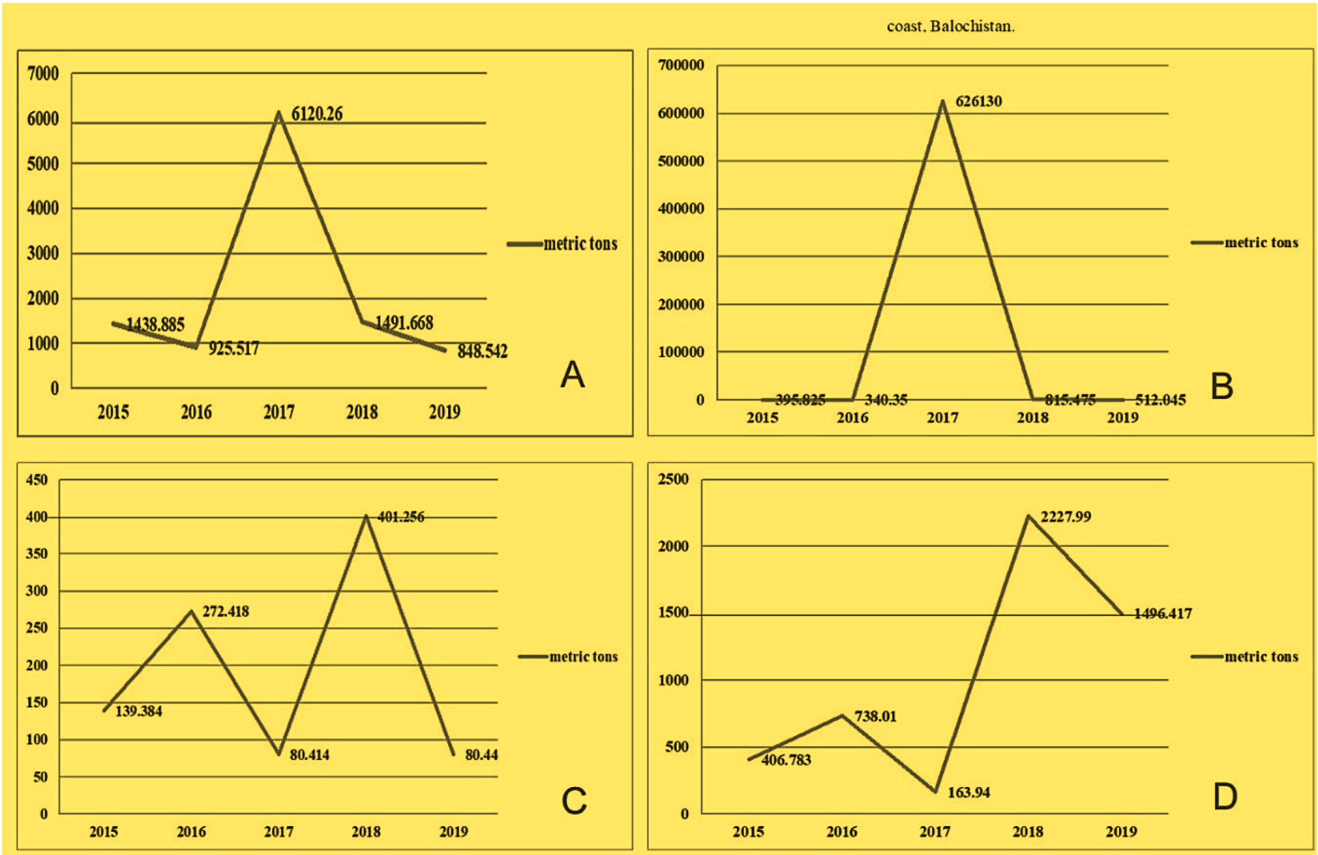

Fig. 6. Shows the average annual landings or stock status data in (metric tons) of *Cynoglossus quadrilineatus* landing at Makran coast during the past five years from 2015 to 2019 (data sources: Gwadar Port Authority, District Gwadar, Balochistan).

Table 4
Previous published records for comparison of some growth parameters of different Sole fish species from various regions of world with present study.

Species	Family	Region	Asymptotic lengths in cm (L∞)	Growth coefficient per year (k)	Age at zero length in years (t_0)	Reference
Cynoglossus quadrilineatus	Cynoglossidae	Makran coast, Pakistan	33.32	0.55	0.04	Present study
Cynoglossus macrostomus	Cynoglossidae	Ratnagiri coast of Maharashtra, India	19.2	0.9	−0.0022	Bhalekar et al. (2016)
Cynoglossus senegalensis	Cynoglossidae	Coastal water of Ghana	57.2	0.40	0.37	Amponsah et al. (2023)
Solea solea	Soleidae	Alexandria waters	34.77	0.55	−0.07	Mehanna et al. (2015)
Solea aegyptiaca	Soleidae	Bardawil Lagoon, Egypt	37.52	0.42	−0.04	Gabr (2015)
Solea solea	Soleidae	Southern Aegean Sea of Turkey	29.11	0.324	−0.030	Cerim and Ateş (2020)
Solea solea	Soleidae	Marmara Sea of Turkey	33.7	0.48	−0.18	Kahraman et al. (2021)

consistently reporting that poor growth conditions and overfishing adversely affect these stocks. Issues such as misreporting, incomplete data, and limited catch data highlight the importance of studies focusing on length-frequency data and stock assessment tools to understand the exploitation status of these species (Raza et al., 2022). A substantial body of research exists on length-weight relationships (LWRs), length-frequency (LF) data, and population parameters of various marine fish species globally, including those in Pakistan's waters (Bhendarkar et al., 2014). Numerous studies on LWRs, population parameters, and stock status or yield have recommended management measures to ensure fish stock sustainability along the Pakistan coast (Majeed et al., 2021). Our current study on the LWRs, LF data, stock status, and growth parameters of tongue sole fish along the Balochistan coast highlights the high economic demand for this species, which constitutes a substantial portion of by-catch exported globally (Mughul et al., 2022).

5. Conclusion

The analysis of growth patterns, length-frequency data, and declining stock status of *C. quadrilineatus* along the Makran coast indicates overexploitation. This study underscores the need for immediate management measures to sustain this fish species for future generations. We recommend increasing the mesh size of fishing nets to reduce overexploitation. Additionally, our study, which utilizes the VBGF model to analyze the growth dynamics of tongue sole fish, provides critical insights that were previously unavailable. Our findings are crucial for fisheries biologists and managers in developing strategies for sustainable exploitation and improving environmental conditions along the Makran coast. Measures such as reducing aquatic pollution, controlling mining activities, and curbing illegal fishing are essential until this fish species is well-preserved. We also suggest reducing the number of fishing boats to mitigate overfishing and fish mortality, thereby restoring sustainable population levels.

CRediT authorship contribution statement

Masooma Eido: Methodology, Investigation, Conceptualization. **Zubia Masood:** Writing – original draft, Supervision, Conceptualization. **Wajid Ali:** Visualization. **Quratulan Ahmed:** Writing – review & editing. **Ashekur Rahman:** Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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