Acta Ichthyologica et Piscatoria 56, 2026, 63–75 | DOI 10.3897/aiep.56.175000

PENSOFT

ACTA ICHTHYOLOGICA ET PISCATORIA

Reproductive and growth parameters of *Chelon auratus* (Actinopterygii, Mugiliformes, Mugilidae) in Bizerte Lagoon, Tunisia

Wafa HAJLAOUI[1,2], Sami MILI[3], Rym ENNOURI[2,4], Hadil SASSI[2], Ezzeddine MAHMOUDI[5], Amor HEDFI[6], Manel BEN ALI[6], Hechmi MISSAOUI[7]

1 *Aquaculture Laboratory, National Institute of Marine Sciences and Technologies (INSTM), Salammbô, Tunis, Tunisia*
2 *University of Carthage, Higher Institute of Marine Sciences of Bizerte (ISSMB), Errimel, Bizerte, Tunisia*
3 *Laboratory of Fisheries Sciences, National Institute of Marine Sciences and Technologies (INSTM), Salammbô, Tunis, Tunisia*
4 *Laboratory of Ecology, Biology and Physiology of Aquatic Organisms, Faculty of Sciences of Tunis, University of Tunis El Manar, Tunis, Tunisia*
5 *Laboratory of Environment Biomonitoring, Faculty of Sciences of Bizerte, University of Carthage, Zarzouna, Tunisia*
6 *Department of Biology, College of Sciences, Taif University, Taif, Saudi Arabia*
7 *National Institute of Marine Sciences and Technologies, Salammbô, Tunis, Tunisia*

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Corresponding author: Wafa Hajlaoui (wafahajlaoui@yahoo.fr)

Academic editor: Adnan Tokaç ♦ **Received** 15 October 2025 ♦ **Accepted** 4 January 2026 ♦ **Published** 19 February 2026

Citation: Hajlaoui W, Mili S, Ennouri R, Sessi H, Mahmoudi E, Hedfi A, Ben Ali M, Missaoui H (2026) Reproductive and growth parameters of *Chelon auratus* (Actinopterygii, Mugiliformes, Mugilidae) in Bizerte Lagoon, Tunisia. Acta Ichthyologica et Piscatoria 56: 63–75. https://doi.org/10.3897/aiep.56.175000

Abstract

Effective management of the golden grey mullet, *Chelon auratus* (Risso, 1810), in Mediterranean coastal ecosystems, including the Bizerte Lagoon, requires a comprehensive understanding of its biological and growth characteristics. This study aimed to assess the biological and growth parameters of *Chelon auratus* in the Bizerte Lagoon. Sampling was conducted from January to December 2022. A total of 576 specimens, ranging from 15 to 38 cm in length (TL), were caught. Our results indicated that the size at first maturity was 23.46 ± 0.2 cm TL for females and 22.5 ± 0.18 cm TL for males, corresponding to an age of two years. The gonadosomatic index indicated that the spawning season of *C. auratus* extends from October to December. The mean fecundity of *C. auratus* was 1233 oocytes per gram of body weight. The total length–weight (W) relationship was estimated at $W = 0.0235 \times TL^{2.6875}$. The monthly percentage of specimens exhibiting a terminal translucent zone indicated that growth rings, or circuli, formed once a year during the cold season in January. The back-calculation method confirmed the effectiveness of using scales to estimate age and growth. Based on the analysis of scales from 576 specimens, the parameters of the von Bertalanffy growth model were estimated as follows: $L_\infty = 44.25$ cm, $K = 0.179a^{-1}$, $t_0 = -1.8$. A total of six age groups were identified. This study presents the first comprehensive assessment of the reproductive biology, age, and growth of *C. auratus* in the Bizerte Lagoon, based on year-round sampling. The findings offer valuable insights into the development and reproductive patterns of *C. auratus*, which will inform the sustainable management of this species in the Bizerte Lagoon.

Keywords

age, Bizerte Lagoon, fecundity, growth, length–weight relationship, reproduction

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Introduction

Mullets (family Mugilidae) constitute an ecologically and economically important group of coastal fishes widely distributed throughout the Mediterranean Sea. In this region, the family Mugilidae are represented by seven species: *Mugil cephalus* Linnaeus, 1758; *Chelon labrosus* (Risso, 1827); *Chelon auratus* (Risso, 1810); *Chelon saliens* (Risso, 1810); *Planiliza carinata* (Valenciennes, 1836); *Chelon ramada* (Risso, 1827); and *Oedalechilus labeo* (Cuvier, 1829) (see Bauchot and Pras 1980; Fischer et al. 1987; Blel et al. 2008). These euryhaline fish, live in schools in the coastal waters and perform trophic migrations from the sea to lagoons. However, gonadal maturation and spawning occur exclusively at sea (Chauvet and Mkaouar 1977; Chauvet 1979; Crosetti and Blaber 2016). Their wide distribution exposes them to fishing activity using various types of fishing gear (nets, seines, bordigue, hook-and-line gear, traps, etc.).

In Tunisia, mullet fishing—except for *Planiliza carinata*—is of considerable socioeconomic importance and contributes significantly to local economies. Sustainable exploitation of these resources depends on a comprehensive understanding of key biological parameters such as growth, reproduction, and population structure, which are essential for stock assessment and management. Research on Mugilidae biology has a long history, beginning with the pioneering work of Heldt (1948) and followed by numerous studies addressing growth, reproduction, fisheries and migratory behavior (Farrugio and Quignard 1974; Farrugio 1975; Bruslé and Bruslé 1977; Chauvet and Mkaouar 1977; Chauvet 1979; Kraïem et al. 2001; Fehri-Bedoui and Gharbi 2005; Abdallah et al. 2012; Mili et al. 2015; Hajlaoui unpublished[1]). However, these studies demonstrate considerable spatial variability in life-history traits, largely driven by local environmental conditions and fishing pressure.

The golden grey mullet, *Chelon auratus*, is a major commercial species in the family Mugilidae found in Tunisian waters. This fish is widely distributed throughout the Mediterranean and the Black Sea, as well as along the Atlantic coasts from the Azores and Madeira, extending northward to the British Isles and the southern coasts of Norway and Sweden (Ilkyaz et al. 2006).

Although the biology of *C. auratus* has been investigated in several aquatic systems (Arruda et al. 1991; Hotos et al. 2000; Hoşsucu 2001; Fehri-Bedoui and Gharbi 2005; Fazli et al. 2008; Kraljević et al. 2011; Abdallah et al. 2012; Saoudi and Aoun 2014; Tulkani 2017; Panda et al. 2018; Hotos 2019), information on lagoonal populations remains limited, particularly under conditions of declining catches and environmental degradation.

Bizerte Lagoon holds considerable socio-economic importance at both regional and national levels. The lagoon serves as an area for spawner maturation and provides a preferred feeding habitat for migratory species (Ennouri et al. 2022). In recent years, catch volumes have drastically declined from 160 tonnes in 2006 to 31 tonnes in 2014 (Mili et al. 2023).

This decline may result from overexploitation and increased pollution, which disrupt reproductive cycles in some species and lead to low recruitment in others (DGEQV 2003). Despite this alarming trend, updated biological data on *C. auratus* in the Bizerte Lagoon remain scarce.

Therefore, the presently reported study aims to address this knowledge gap by providing updated information on the reproductive biology and population dynamics of *C. auratus* in the Bizerte Lagoon. Specifically, we investigate the reproductive cycle, size at first sexual maturity, sex ratio, age structure, and growth patterns. These data are essential for improving our understanding of the species' life history in lagoonal environments and for supporting evidence-based management and conservation strategies for this economically valuable fishery.

Materials and methods

Study area. The Bizerte Lagoon is located on the northern coast of Tunisia, on the southern coast of the Mediterranean Sea (37°08′–37°14′N, 9°46′–9°56′E) (Fig. 1). It covers an area of 128 km^2 and has a mean depth of 7 m (Bejaoui et al. 2008). The lagoon communicates with the Mediterranean Sea by a long navigation channel of about 6 km. It is connected in its western part to a large lake (Ichkeul Lake), with which it communicates via Wadi Tinja. The total amount of freshwater discharged into the lagoon is 125 million m^3 · y^{-1} and the salinity ranges from 33‰ to 35‰ (Zaaboub et al. 2014). Various human activities, such as the discharge of domestic sewage, industrial waste, atmospheric pollution, agricultural practices, and bivalve aquaculture, affect this ecosystem (Hamdaoui et al. 2022).

Sampling. A total of 576 samples of *Chelon auratus* were collected monthly from January through December 2022, in Bizerte Lagoon (Menzel Abderrahmane harbor) using a trammel net of 26 to 60 mm diamond mesh (Table 1). At the laboratory, total length (TL) was measured to the nearest 1 mm. The total weight and eviscerated body weight were measured to the nearest 0.1 g. The gonads and liver were weighed to the nearest 0.01 g. The biological analyses were performed using fresh specimens.

Table 1. The number of studied samples of *Chelon auratus* from in Bizerte Lagoon, Tunisia.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Number	31	65	80	54	63	34	37	26	40	30	57	59

[1] Hajlaoui W (2017) Etude écobiologique et dynamique des populations de la carpe commune *Cyprinus carpio communis* et le mulet *Liza ramada* dans la retenue du barrage Sidi Saâd (Centre de la Tunisie). PhD thesis, Institut National Agronomique de Tunisie, Tunis, 213 pp.

Figure 1. Satellite image of the Bizerte Lagoon, Tunisia (Map data 2025 (C) Google.).

Gonadosomatic index. The gonadosomatic index (GSI) was calculated monthly to determine spawning periods according to the equation (Lahaye 1980):

$$\mathrm{GSI} = \left(W_\mathrm{G} \times W_\mathrm{E}^{-1}\right) \times 100$$

where W_G is the gonad weight and W_E is the eviscerated body weight, both in grams.

Hepatosomatic index. The hepatosomatic index (HSI) was calculated based on the formula suggested by Lagler (1971), which is expressed as:

$$\mathrm{HSI} = \left(W_\mathrm{L} \times W_\mathrm{E}^{-1}\right) \times 100$$

where W_L is the liver weight and W_E is the eviscerated body weight, both in grams.

Relative growth condition factor. Relative growth condition factor (K) was estimated using the formula proposed by Tesch (1971):

$$K = \left(W_\mathrm{E} \times \mathrm{TL}^{-3}\right) \times 100$$

The degree of maturity of the gonads was determined for females and males according to the six-stage maturity scale (Holden and Raitt 1974; Brown-Peterson et al. 2011).

Sex ratio. The sex ratio was determined monthly as males: females (M:F), estimated using the formula:

$$\mathrm{SR} = 100F \times (F + M)^{-1}$$

where F is the number of females, while M is the number of males.

The chi-square (χ^2) was used to verify the existence of significant differences between the sex ratio of males and females (Vazzoler 1996).

Length at maturity. The length at maturity (L_{m50}), is the size at which 50% of individuals are mature, were estimated from the logistic curve parameters (King 1995):

$$\mathrm{Pm} = 1 \times \left[1 + \exp^{[-b(L - L\mathrm{m50})]}\right]^{-1}$$

where Pm is the proportion of mature individuals at a given length (L), b is the slope of the maturity curve and L_{m50} is the total length at which 50% of the fish are mature.

Fecundity. The fecundity analysis was performed on 45 ripe females (stage IV and V). For the fecundity estimation, Simpson's method was used (Bagenal and Tesch 1978). Three sub-samples each were taken from the anterior, middle and posterior parts of the ovary and were weighed and counted carefully in each sub-sample. Maturity stages IV and V were identified through a macroscopic examination of the ovaries. Each sub-sample of oocytes was counted twice using a stereomicroscope to ensure accuracy. The total number of eggs per gonad was obtained as the absolute fish fecundity. Relative fecundity (F) was determined by calculating the ratio of the total number of eggs to the unit weight or length of the fish. The relative fecundity (F) was estimated using the equation:

$$F = n\left(W_\mathrm{G} \times W_\mathrm{S}^{-1}\right)$$

where n is the number of eggs in the sub-sample, WG is the weight of gonad, and WS is the weight of sub-sample.

Length–weight relationship. The length–weight relationship was calculated for both sexes using the exponential equation of Ricker (1975):

$$W = a\mathrm{TL}^b$$

where W is the total weight [g], TL is the total length of the fish [cm], and parameters a and b are estimated, defining b as the coefficient of allometry. The degree of association between the variables was assessed using the coefficient of determination r^2. Student's t-test was used to determine if the coefficient b differed significantly from 3 (Teissier 1948).

Age estimation. For age estimation, scales were taken from the lateral line, behind the pectoral fin, from 576 individuals. They were cleaned with water and examined under the stereo binocular microscope. The periodicity of ring formation in scales was then checked by calculating the increase between the last and penultimate ring (or marginal increment (MI)) using the equation:

$$\mathrm{MI} = (R - R_n) \times (R_n - R_{n-1})^{-1}$$

where R, R_n, and R_{n-1} are, respectively, the radius of the scale, the radius of the last and the next-to-last growth rings. Monthly values of MI were compared using a one-way ANOVA test.

Linear regression analysis was conducted to determine the equation between total length and scale radius (Francis 1990). The total length was then back-calculated for each ring using the formula of Lee (1920):

$$\mathrm{TL}_i = a + \left[(\mathrm{TL} - a)R_i \times R^{-1}\right]$$

where: TL_i is the predicted total length of the fish corresponding to age or ring i, a is the intercept of the equation $R = a + b \times \mathrm{TL}$, TL is the total length of fish at capture, R_i is the scale radius at age i, R is the scale radius at capture in mm.

The von Bertalanffy growth curve was designed using the age–length key results using Marquardt's algorithm for non-linear least-squares parameter estimation (Saila et al. 1988). The FSAS program was used to estimate the parameters of the von Bertalanffy growth equation (von Bertalanffy 1938):

$$\mathrm{TL}_t = \mathrm{TL}_\infty \left[1 - e^{-K(t-t0)}\right]$$

$$W_t = W_\infty \left[1 - e^{-K(t-t0)}\right]^b$$

where TL_t is the total length [mm] at age t, TL_∞ is the asymptotic length, K is the growth coefficient, t is age, t_0 is hypothetical age at which length is zero, W_t is the weight of the fish at age t and W_∞ is the asymptotic weight (Le Cren 1951).

The index of growth performance (Φ'), which allows comparison of the growth of the same species in different environments, was calculated with the equation of Pauly and Munro (1984):

$$\Phi' = \log(K) + 2\log(L_\infty)$$

where K and $L\infty$ are the von Bertalanffy growth parameters.

The value of the maximum theoretical age (T_{max}), which expresses the longevity of the fish, was determined according to the formula cited by Pauly (1983):

$$T_{\max} = t_0 + 3K^{-1}$$

where t_0 and K are the parameters of the von Bertalanffy equation.

Results

Length-frequency distribution. Length distribution of *Chelon auratus* samples range between 15 and 38 mm (Fig. 2). The length for most captured fish in this lagoon fluctuated between 22 and 32 cm (92%).

Sex ratio. From the 576 specimens studied, 290 were female and 286 were male. Although equality between sexes was recorded most of the year. Females were found to outnumber males in January, April and November (Fig. 3).

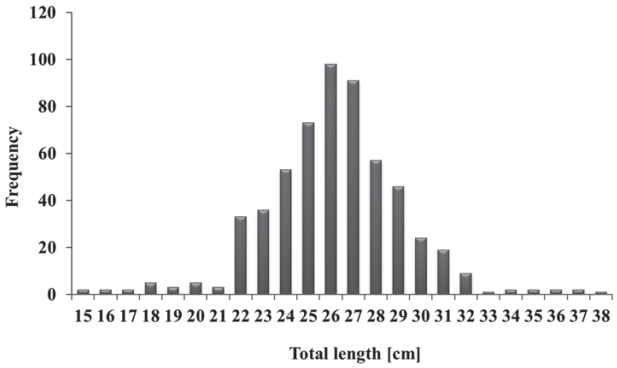

Figure 2. Total length frequency distribution of *Chelon auratus* from the Bizerte Lagoon, Tunisia.

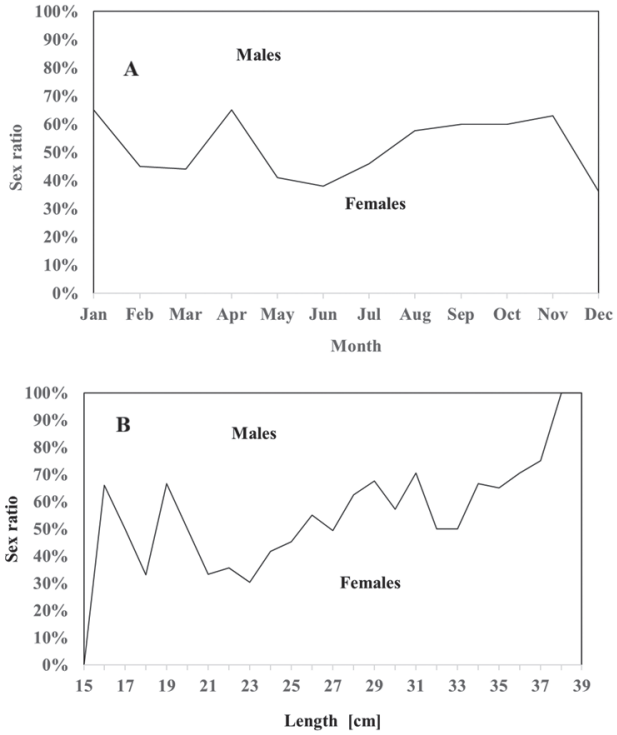

Figure 3. Sex ratio of *Chelon auratus* in the Bizerte Lagoon, Tunisia: monthly variation (A) and variation by size class (B).

The overall sex-ratio value estimated was 1.01, biased towards females (Fig. 3). The chi-square test showed no significant difference (χ^2 = 1.25; df = 1; $P > 0.05$). Further, females were predominant at lengths larger than 26 cm except at sizes 32 and 33 cm (Fig. 3).

Length at maturity. The estimated mean size at which 50% of females of *C. auratus* were mature was 23.46 ± 0.2 cm (Fig. 4), whereas the estimated mean size for males was 22.5 ± 0.18 cm (Fig. 4). Females and males attain sexual maturity during the second year of life. For this species, males are mature at relatively smaller sizes than the females.

Sexual cycle and spawning period. The mean monthly GSI values for *C. auratus* were low from January to August. After August, the gonads began their development and the GSI started increasing gradually.

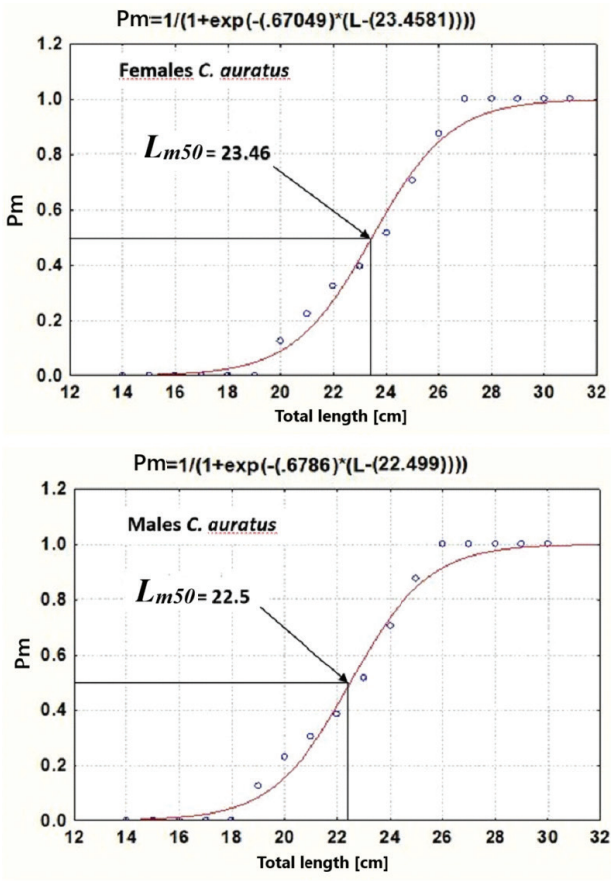

Figure 4. Size at first sexual maturity of female (Pm is the proportion of mature individuals); (**A**) and male (**B**) *Chelon auratus* in the Bizerte Lagoon, Tunisia.

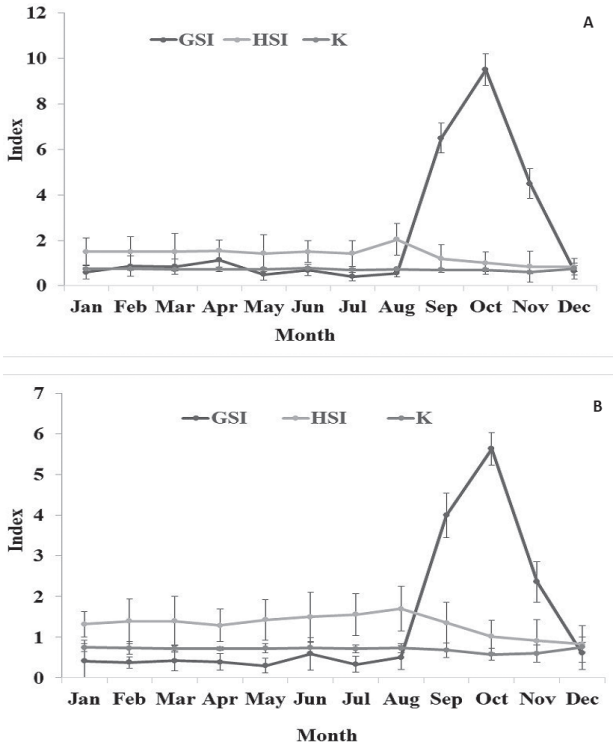

Figure 5. Monthly variation of gonadosomatic Index (GSI), hepatosomatic Index (HSI) and condition factor for females (**A**) and males (**B**) of *Chelon auratus* in the Bizerte Lagoon, Tunisia.

The maximum GSI value was 9.5 ± 0.7 for females and 5.64 ± 0.58 for males in October (Fig. 5). In December, the GSI value decreased. Our findings suggest that the reproductive period of this species occurs regularly between October and December.

Hepatosomatic index (HIS) and Gonadosomatic index (GSI). Analysis of the monthly evolution of the HSI for both sexes (Fig. 5) reveals a decrease, while the gonadosomatic index (GSI) increases. This suggests that *C. auratus* draws the reserves necessary for its maturation in the liver.

Condition factor. The monthly condition factor *K* values show non-significant ($P > 0.05$) variation for both females and males (Fig. 5).

Fecundity. Absolute fecundity was determined on 45 ripe females caught in September, October, and November. Absolute fecundity varied between 115 000 and 500 000 oocytes, with a mean of 256 867 ± 98 134 oocytes (mean ± SE; 95% confidence interval: 220 000–293 700) for specimens with a total length between 23.5 and 37 cm and a weight ranging from 106 to 439 g.

Relative fecundity varied between 967 and 1577 eggs · g^{-1} of body weight, with a mean of 1233 ± 143 eggs · g^{-1} (mean ± SE; 95% confidence interval: 1150–1316 eggs · g^{-1}).

The relationship between absolute fecundity (F_A), total length (TL), total weight (W_T), and gonad weight is shown in Fig. 6.

Length–weight relationships. Length–weight relationships were calculated separately for females, males and for both sexes. The equation for females was $W = 0.0306 \times TL^{2.6071}$; for males, $W = 0.0221 \times TL^{2.707,}$ and for combined sexes, $W = 0.0235 \times TL^{2.6875}$. The *b* value was significantly lower than the theoretical value (3) for males ($t = 9.47$, $P < 0.05$), females ($t = 41.78$, $P < 0.05$), and combined sexes ($t = 54.62$, $P < 0.05$), indicating a negative allometric growth pattern.

Marginal increment. Age estimation was made using scales from 576 fish samples (290 females and 286 males). The monthly change in the marginal increment (MI), using the scales, was used to determine the circulus growth (Fig. 7), suggesting that the single annulus was formed in January (MI = 0.23 ± 0.02). The maximal mean of marginal increment ratio (MIR) was found in October (MI = 0.84 ± 0.03). The maximum age estimated for both sexes was six years. The age range of the sampled fish was between 1 and 6 years, with most individuals belonging to the 3–4-year age class (Table 2).

Scale radius–body total length relationships. The relationships between the total fish length (TL) and the radius of the scale (*R*) in females, males and combined sexes are presented via the following equations:

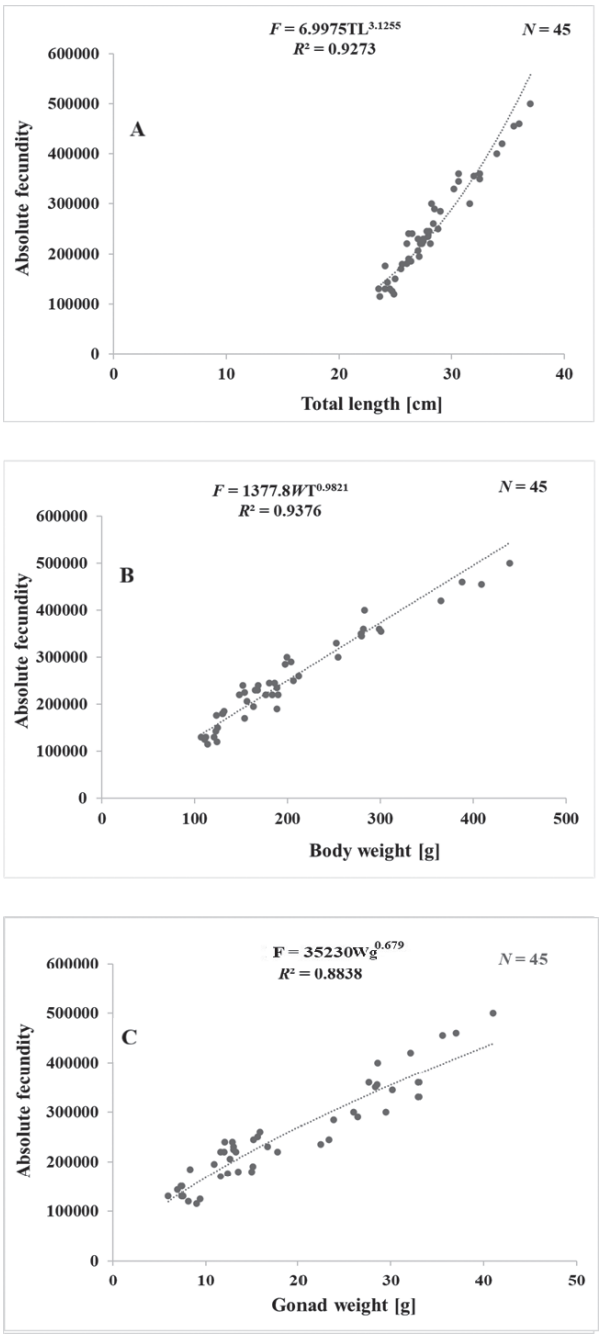

Figure 6. Relationships between absolute fecundity and total length (**A**), body weight (**B**), and gonad weight (**C**) of *Chelon auratus* in the Bizerte Lagoon, Tunisia. Regression lines were fitted to the data.

- Females: $R = 0.0403\text{TL} - 4.9709$; $R^2 = 0.966$ ($P < 0.01$),
- Males: $R = 0.0405\text{TL} - 4.8528$; $R^2 = 0.9443$ ($P < 0.01$),
- Combined sexes: $R = 0.0402\text{TL} - 4.86$; $R^2 = 0.9513$ ($P < 0.01$)

Back-calculations. Given the strong linear correlation between the radius of the scale and the total length of the specimen, we used the scale measurement to back-calculate the total length at previous ages. The observed lengths were similar to the back-calculated length for individual age groups. The mean back-calculated length-at-age for 1 to 6-year-old specimens is listed in Table 2. The growth rate was high during the first year of life for both sexes, while it slowed down after that (Fig. 8).

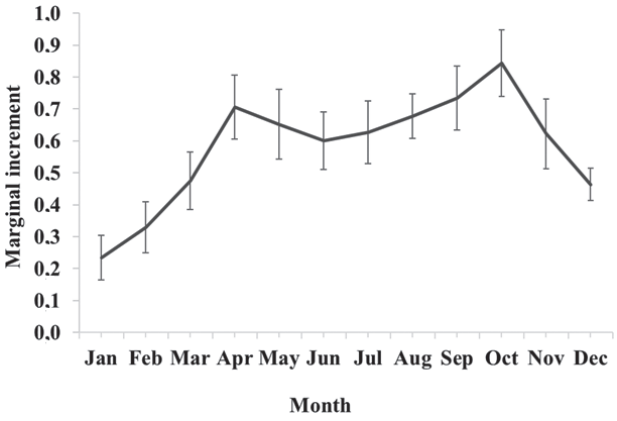

Figure 7. Monthly mean values of marginal increment of scales of both sexes of *Chelon auratus* from the Bizerte Lagoon, Tunisia, collected between January and December 2022.

Table 2. Back-calculated total lengths by age group of *Chelon auratus* from in Bizerte Lagoon, Tunisia.

Age class [years]	Observed mean TL	Mean back-calculated TL (both sexes)					
		1	2	3	4	5	6
1	17.51	16.65					
2	21.68	16.62	21.04				
3	25.81	16.79	22.50	25.20			
4	28.51	15.65	20.57	24.94	27.96		
5	31.08	16.76	21.81	26.29	29.67	30.51	
6	33.38	15.81	20.20	25.10	27.43	31.31	32.86
Total mean		**16.38**	**21.23**	**25.38**	**28.35**	**30.91**	**32.86**
Growth increment [%]		**25.78**	**17.84**	**11.06**	**8.63**	**6.11**	

TL, total length.

Von Bertalanffy growth estimation. The von Bertalanffy growth equations were fitted to fish length and age data using two approaches: directly from observed length-at-age data and from back-calculated lengths based on scale measurements.

For the observed data, the equations are:

- Females: $\text{TL} = 45.11(1 - e^{-0.176(t + 1.82)})$
- Males: $\text{TL} = 43.39(1 - e^{-0.18(t + 1.78)})$
- Combined sexes: $\text{TL} = 44.25(1 - e^{-0.179(t + 1.8)})$

For the back-calculated data, the equations are:

- Females: $\text{TL} = 41.39(1 - e^{-0.2263(t + 1.187)})$
- Males: $\text{TL} = 39.63(1 - e^{-0.2388(t + 1.191)})$
- Combined sexes: $\text{TL} = 40.485(1 - e^{-0.2306(t + 1.2434)})$

The growth rate was not significantly different between sexes ($\chi^2 = 0.03$, $P > 0.05$). The von Bertalanffy growth curve was fitted by length-at-age data for all individuals, as shown in Fig. 8.

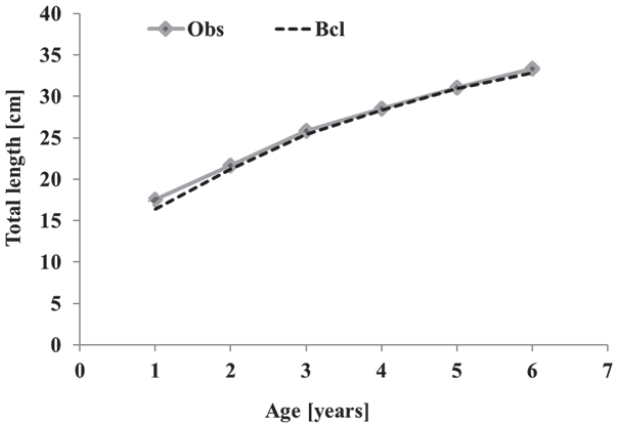

Figure 8. Von Bertalanffy growth curves for combined sexes of *Chelon auratus* from Bizerte Lagoon, Tunisia. Obs, observed length; Bcl, back-calculated length.

The observed and the back-calculated growths have similar curves which means that the index of performance for females ($\Phi' = 2.55$ cm · year^{-1}) is similar to males ($\Phi' = 2.53$ cm · year^{-1}).

Both methods are presented because the back-calculation method allows for the reconstruction of individual growth histories from scales. This helps validate the observed length-at-age data and detect any potential sampling bias in age classes.

The growth in weight described by the von Bertalanffy equation for females, males and combined sexes is presented respectively below:

- $W = 628.89(1 - e^{-0,18(t + 1.78)})^{2.6071}$; ($P < 0.05$)
- $W = 595.44(1 - e^{-0.179(t + 1.8)})^{2.707}$; ($P < 0.05$)
- $W = 618.72(1 - e^{-0.1542(t + 0.9732)})^{2.6875}$; ($P < 0.05$)

The annual growth rate in weight was slightly higher for females with a pronounced difference with age. The growth rate reached its maximum during the first year of life of the specimens.

Longevity. The maximum longevity that *C. auratus* can reach, in Bizerte Lagoon, is estimated at 15.23 years for females and 14.89 years for males.

Discussion

The analysis of the sex proportion showed no significant differences between the proportions of males and females, according to month. Relatively similar values in sex ratio are observed in the Golden Horn Estuary, Istanbul (Kesiktaş et al. 2020).

In contrast, significant female dominance in the *Chelon auratus* populations was reported in Izmir Bay (Aegean Sea) (Ilkyaz et al. 2006), in the Caspian (Fazli et al. 2008), in the Gulf of Gabes (Abdallah et al. 2013), and in Bardawil Lagoon, Egypt (Gaber et al. 2021). This variability is strongly affected by the sampling methodology (time and space, catchability, fishing gear, meteorological conditions, and competence of fishermen) (Bartulović et al. 2011).

Furthermore, the gender based on the total length shows that females dominate in high-length classes. Our results agree with those of Abdallah et al. (2013) in the Gulf of Gabes (Tunisia) and Gaber et al. (2021) in Bardawil Lagoon (Egypt).

The predominance of females at the old age group has been documented for mullet species, as well as in other species (Quignard and Farrugio 1981; Ghaninejad et al. 2010). It is probably attributed to selective fishing practices, to the morphological and behavioral differences between the sexes (Wenner 1972), where mature females, being heavier, are more vulnerable, or to different longevity that might affect sampling (Keverkidis et al. 1990). The predominance of females in the larger length classes could be attributed to faster growth in females, combined with higher natural mortality of males at smaller sizes/ages (Albaret and Legendre 1985).

L_{m50} of *C. auratus* fish occurs at 23.46 and 22.5 cm (TL) for females and males, respectively, which corresponds to their second year of age (presently reported study). Abdallah et al. (2013) confirmed that specimens of 23.73 and 23.84 cm (TL), respectively for females and males, mature at age 5+ in the Gulf of Gabes. On the other hand, Campillo (1993) reported that *C. auratus* was mature at size 27cm (age 3^+) and 34 cm (age 4^+), respectively, for males and females in the Gulf of Lion. Fehri-Bedoui and Gharbi (2005) affirmed that specimens of 21.95 cm and 21.41 cm reached maturity, respectively, for females and males, corresponding to age 3^+ in the Tunisian waters. Hotos et al. (2000) estimated that the first maturation in the Klisova Lagoon (Greece) occurs at age 1^+ for both sexes. While Ghaninejad et al. (2010) indicated that maturity occurred at 28.4 cm (FL) for golden grey mullet in the Caspian Sea. Moreover, Fazli et al. (2008) recorded maturity at a length of 26 cm (FL) in the Iranian waters. In Syrian waters (Eastern Mediterranean), Saad and Hamoud (2001) found that the maturity of this species occurred at a size of 34 cm (TL) for both sexes. The study conducted by Gaber et (2021) indicated that the species was mature at 19.5 cm and for both sexes in Bardawil Lagoon (Egypt). Kesiktaş et al. (2020) assert that the maturation of the golden grey mullet in the Golden Horn Estuary (Istanbul, Turkey) occurs at 26.2 cm and 24.1cm (TL) for females and males, respectively, corresponding to 3-year-old for females and 4-year-old for males. These differences in maturation were due to the variability of the environmental conditions in different regions. Low temperature and photoperiod are probably the main factors of variability (Nash and Koningsberger 1981; Crosetti and Blaber 2016; Bruslé unpublished[2]).

[2] Bruslé J (1982) Contribution à la connaissance de la sexualité des poisons téléostéens marins gonochoriques (Mugilidés) et hermaphrodites (Serranidés). PhD thesis, University of Perpignan, 360 pp.

The reproductive cycles for males and females are synchronized. GSI values for females are higher than those of males. Females' GSI values are around 9.5, while lower values have been recorded for males (5). The difference between male and female GSI values suggests that the energy invested by males for gamete production is probably less than that of females. This could be due to physiological and hormonal effects on the development of fish (Abdallah et al. 2013).

In this study, the reproductive period of *C. auratus* is short. The maturation of the gonads takes place from August to October. At the end of this period, the laying occurs, which ends in December. In the Mediterranean, the breeding period of the golden grey mullet is very brief and takes place nearly simultaneously across various localities. In Italy, the breeding period was spread out from September to November (Gondolfi and Orsini 1968; Ghittino 1983). However, Hotos et al. (2000), noted an earlier and much longer spanning period, from August to November in western Greece. Cambrony (unpublished[3]), focusing on golden grey mullet in the Languedoc region, observed a reproductive cycle extended from August to October. In Tunisian waters, Fehri-Bedoui et al. (2002) reported a brief breeding season in October–November and Abdallah et al. (2013) in October–December in the Gulf of Gabes (southeastern Tunisian waters). Kesiktaş et al. (2020) suggest that the major spawning period was between August and November, and the minor spawning peak was between March and April in the Golden Horn Estuary (Istanbul, Turkey). Reis and Ateş (2020), in the Köyceğiz Lagoon (estuary) (Mediterranean) based on the GSI temporal variation, suggests a shorter spawning period (October to January). In Bardawil Lagoon (Egypt), the spawning season of this species is extended from November to January (Gaber et al. 2021). These spatial differences in GSI could be caused by differences in food resources, living temperature, and the adaptation of different populations to the specific ecological properties of ecosystems (Bartulovic et al. 2011). Such variability highlights the need for fisheries management measures, including seasonal fishing closures and minimum catch sizes, to be adapted to local reproductive cycles rather than applied uniformly, to ensure successful recruitment and the sustainability of golden grey mullet stocks, particularly in lagoon and estuarine ecosystems (Kesiktaş et al. 2020; Gaber et al. 2021; Kartal et al. 2025). In the Bizerte Lagoon, our findings of a short spawning period emphasize the urgency of setting species-specific regulations. The dominance of 3-year-olds in the population further indicates vulnerability to recruitment failure if fishing pressure is not controlled. Broader conservation strategies should also include habitat protection and socio-economic considerations, given the reliance of small-scale fisheries on this species.

The monthly progress of HSI showed that both sexes of the golden grey mullet use the liver for the storage and mobilization of reserves to develop gametes and ensure spawning. This strategy of fat storage in the liver during reproduction is adopted by many species (Bailey 1952; Smith 1957; Bertin 1958; Crosetti and Blaber 2016).

In our study, the mean absolute fecundity of the golden grey mullet was 256 876 eggs/year. In previous research conducted by Abdallah et al. (2013), the absolute fecundity was 2865 64 eggs/year in the Gulf of Gabes (Tunisia). Askerov et al. (2003) noted that this fecundity has an average of 500 000–600 000 eggs/year in the Caspian Sea. Whereas Abdolmalaki et al. (1998) found a fecundity of 102 6920 eggs/year for the golden grey mullet along the Gilan Province coastal waters. Ghaninejad et al. (2010) testified a fecundity with a mean value of 700 881 eggs/year in the Iranian coastal waters.Pillay (1972) stated that absolute fecundity ranges from 157 000 to 926 000 eggs/year. On the other hand, Hotos et al. (2000) reported a fecundity range of 80 000 to 1 410 000 eggs/year in the lagoon of Klisova (Greece). The mean relative fecundity of the golden grey mullet observed in this study is 1233 eggs per gram of body weight. Ghaninejad et al. (2010) found a mean number of 1363 eggs This variability was due to environmental conditions, particularly the lengths of the sampled females.

The exponents of length–weight relationships for males (b = 2.707), females (b = 2.6071) and combined sexes (b = 2.6071), estimated in the Bizerte Lagoon, showed that the growth of the golden grey mullet was hypoallometric, slightly faster in length than in weight. Besides, no significant difference in b among the sexes was observed (ANCOVA, $P > 0.01$).

These results are congruent with previous findings where negative allometric growth was noted by Abdallah et al. (2012) in the south of Tunisia (b = 2.845), Kesiktaş et al. (2020), in the Golden Horn Estuary, Istanbul (b = 2.83) and Arruda et al. (1991) in the Ria de Aveiro (Atlantic) (b = 2.397). While isometric allometric growth of this species (b = 2.93) was recorded in the Homa Lagoon (Izmir Bay, Aegean Sea) (Ilkyaz et al. 2005) and in Bardawil Lagoon (Egypt) (b = 3.053) Marizek et al. (2021).

The pattern of weight growth fluctuates over the year depending on several factors such as season, habitat, gonad maturity, sex, diet, stomach fullness, health, preservation techniques, and length variability of specimens (Reis and Ateş 2019).

The relationship between fish length and scale radius suggests that the golden grey mullet scales continue to grow throughout life, making them a suitable structure to estimate age and investigate growth (Crosetti and Blaber 2016). Indeed, this structure was frequently used for the age estimation of Mugilidae (Arruda 1991; Kraljević and Dulcic 1996; Ilkyaz et al. 2005; Fehri-Bedoui and Gharbi

[3] Cambrony M (1983) Recrutement et biologie des stades juvéniles de Mugilidae (Poissons Téléostéens) dans trois milieux lagunaires du Roussillon et du Narbonnais (Salses-Leucate, Lapalme, Bourdigou). PhD thesis, Université de Perpignan, France, 285 pp.

2005; Hotos and Katselis 2011; Marizek et al. 2021). The observed lengths were similar to the back-calculated lengths for individual age groups. The results achieved through the back-calculation method are up to standard and provide the validity of using scales to estimate the golden grey mullet age and growth in the Bizerte Lagoon.

Validating age and estimating growth are crucial parameters in age-structured population dynamic models. As a result, the use of verification and validation methods in fish growth studies has increased, including marginal increment analysis, centrum-edge analysis, and size model analysis (Panfili et al. 2002).

To validate the periodicity of bend formation, we used MI. Most works on golden grey mullet age and growth estimation are congruent with our results, showing the formation of one annulus a year in winter. This period of slow growth is associated with times of low water temperature, as recorded in our study area, in winter (10°C) (Barhoumi 2014). Similar findings have been reported for the population of *C. auratus* on southern Tunisian waters due to unfavorable environmental conditions (Abdallah et al. 2012). The majority of references support the formation of only one annulus per year during cold months for the Mugilidae species of temperate and subtropical regions (Farrugio and Quignard 1974; Libosvarsky 1976; Cambrony 1984; Koutrakis and Sinis 1994).

The asymptotic length of the golden grey mullet from Bizerte Lagoon (Tunisia) is 45.11 cm for females and 43.39 cm for males. These findings are incompatible with other studies (Fazli et al. 2008; Hotos and Katselis 2011). For combined sexes, many studies reported similar asymptotic total length (Albertini-Berhaut 1978; İlkyaz et al. 2006; Abdallah et al. 2012). Other studies have achieved different results (Modrušan et al. 1988; Arruda et al. 1991; Arruda et al. 1991; Kraljević and Dulčić 1996; Buhan 1998; Fehri-Bedoui and Gharbi 2005; Hotos and Katselis 2011; Kraljević et al. 2011; Hotos 2019; Reis and Ateş 2020; Kesiktaş et al. 2020; Ezzat unpublished[4]) (Table 3).

We also noted that the difference in the growth estimation may be related to the heterogeneity of the age estimation methods, the calcified part selection and the method used to adjust the data in the growth model. Collected data on the golden grey mullet age show inconsistent growth rates among specimens of different areas (France, Croatia, Portugal, Turkey, Tunisia, Greece, and USA) (Crosetti and Blaber 2016). Moreover, studies conducted in various regions have reported that growth variability in the Mugilidae can result from diverse environmental conditions, misinterpretation of scales, population density, and migration, which promotes mixing between migrant and local populations (Fehri-Bedoui and Gharbi 2005; Gautier and Hussenot 2005).

This variability is probably due to local differences in many factors influencing growth, like water temperature. This is because grey mullets spend most of their time in shallow inshore waters, where the temperature is influenced more by local conditions than by the temperature of the open sea, which is more stable (Kennedy and Fitzmaurice 1969). However, the variability of the golden grey mullet growth rates in different locations may be attributed to other factors such as food availability and/or density-dependent relations (El Zarka et al. 1970; Drake et al. 1984)

Table 3. Growth parameters of von Bertalanffy equation for *Chelon auratus* in different areas.

Country	Sex	L_∞	K	t_0	Φ'	Reference
Étang de Berre, France	M	57.8	0.16	–0.5	2.73	Ezzat (unpublished[4])
	F	68.6	0.14	–0.5	2.82	
Bay of Marseille	M + F	45	0.2	–0.49	—	Albertini-Berhaut 1978
Krka Estuary, middle Adriatic	M + F	51.0	0.3	–0.4	2.89	Modrusan et al. 1988
Ria de Aveiro Lagoon, Portugal	M + F	68.5	0.11	–0.51	2.71	Arruda et al. 1991
Luka Mirna, Croatia	M + F	39.8	0.21	–0.51	2.52	Kraljević and Dulčić 1996
Köyceğiz Lagoon, Turkey	M + F	37.6	0.519	–0.152	2.865	Buhan 1998
Tunisian coasts	M + F	36.4	0.180	–1.810	—	Fehri-Bedoui et al. 2005
Homa Lagoon, Izmir, Turkey	M + F	43.2	0.33	–0.3	2.79	İlkyaz et al. 2006
Caspian Sea	M	62.7	0.15	–0.23	2.77	Fazli et al. 2008
	F	59.4	0.18	–0.61	2.8	
Messolonghi-Etoliko Lagoon, Greece	M + F	64.1	0.152	–1.14	2.80	Hotos 2011
	M	64.9	0.152	–1.14	2.81	
	F	63.1	0.159	–1.09	2.80	
Mirna Estuary	M + F	40.0	0.163	–1.15	5.817	Kraljevic et al. 2011
Tunisian south coast	M + F	43.51	0.11	–2.211	—	Abdallah et al. 2012
Lagoon of Klisova-Messolonghi	M + F	70.78	0.129	–1.345	6.47	Hotos 2019
Köyceğiz Lagoon, Turkey	M + F	58.78	0.163	–0.0195	2.750	Reis and Ates 2020
Bizerte Lagoon, Tunisia	M + F	44.25	0.179	–1.8	2.54	Presently reported study
	M	43.39	0.18	–1.78	2.53	
	F	45.11	0.176	–1.82	2.55	

[4] Ezzat A (1965) Contribution à l'étude de la biologie de quelques Mugilidae de la région de l'étang de Berre et de Port-de-Bouc. Thèse de doctorat, Université Aix-Marseille II, France, 255 pp.

Chelon auratus found an ideal environment in lagoons and lakes, which offer better trophic conditions conducive to growth than those found at sea (Losse et al. 1991; Kraïem et al. 2001; Fehri-Bedoui et al. 2001).

In our study, the growth performance index of the golden grey mullet estimated ($\Phi' = 2.54$) is in line with other research studies (Table 3). In both sexes, during the first two years of life, the young golden grey mullet grows rapidly in length and weight. Growth rates slow down during the transition from the second to the third year of life. These results agree with those of Hotos and Katselis (2011), who worked on the same species in the Messolonghi-Etoliko Lagoon (Western Greece).

The longevity of *Chelon auratus* in the Bizerte Lagoon was estimated at 15.2 years for females and 14.9 years for males. These values are comparable to those reported for other Tunisian populations, particularly in Tunisian coastal waters, where Fehri-Bedoui and Gharbi (2005) reported a maximum longevity of 16.8 years.

However, the estimated longevity in Bizerte Lagoon is lower than that reported for the Messolonghi–Etoliko Lagoon in Greece (19 years; Hotos and Katselis 2011), but higher than values observed in Bardawil Lagoon (11 years; Marizek et al. 2021) and Homa Lagoon (8.8 years; Ilkyas et al. 2006). These inter-lagoon differences in longevity likely reflect the combined effects of environmental limiting factors such as lagoon productivity, salinity fluctuations, temperature regime, and fishing pressure.

This study offers important insights into the growth and reproductive biology of *Chelon auratus* in the Bizerte Lagoon, a species that is commercially significant in Tunisia. The findings are essential for supporting sustainable fisheries management and enhancing our understanding of population dynamics within lagoon ecosystems. While the research was limited to a single year and one lagoon, it establishes a valuable baseline for future studies conducted over multiple years and in various locations. To gain a more comprehensive understanding of the factors affecting growth and reproduction, it would be beneficial to incorporate broader spatial and temporal monitoring, as well as environmental and genetic data. These findings are not only applicable to the Bizerte Lagoon but can also guide fisheries management and conservation strategies in other Mediterranean lagoons.

Conclusion

The current study highlights the importance of investigating fish populations within specific ecosystems, such as lagoons. Our findings offer new insights into the biological and growth characteristics of the commercial species *Chelon auratus* found in Bizerte Lagoon. This research opens up exciting possibilities for future stock assessments, management, and conservation of this resource.

Acknowledgments

The authors would like to acknowledge the Deanship of Graduate Studies and Scientific Research, Taif University for funding this work.

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