Acta Ichthyologica et Piscatoria 55, 2025, 317–331 | DOI 10.3897/aiep.55.160771

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ACTA ICHTHYOLOGICA ET PISCATORIA

Seasonal variations in the biological characteristics and biochemical composition of bluemouth rockfish, *Helicolenus dactylopterus* (Actinopterygii, Perciformes, Sebastidae), in the central Mediterranean Sea

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Academic editor: Adnan Tokaç ♦ **Received** 31 May 2025 ♦ **Accepted** 10 September 2025 ♦ **Published** 7 November 2025

Citation: Helali A, Ghribi F, Bejaoui S, Ben Ali M, Hedfi A, Hassan M, Hajlaoui W, Belhassen D, Chetoui I, Ennouri R, Agrebi S, Mili S (2025) Seasonal variations in the biological characteristics and biochemical composition of bluemouth rockfish, *Helicolenus dactylopterus* (Actinopterygii, Perciformes, Sebastidae), in the central Mediterranean Sea. Acta Ichthyologica et Piscatoria 55: 317–331. https://doi.org/10.3897/aiep.55.160771

Abstract

This study provides a comprehensive analysis of the annual biological cycle and biochemical composition of the bluemouth rockfish, *Helicolenus dactylopterus* (Delaroche, 1809), collected in 2022, from the northern Tunisian coast. We investigated seasonal variations in biological indices (condition, gonadosomatic, and relative growth) and biochemical constituents (lipids, proteins, glycogen, and fatty acids). Our key finding is a defined cold-season (winter) spawning period, evidenced by a significant peak in the gonadosomatic index (GSI) coinciding with a depletion of somatic condition, hepatic glycogen, and lipid reserves. Spawning was associated with a pronounced shift in energy allocation, with lipid and glycogen levels in muscle tissue decreasing by up to 92% and 88%, respectively, in winter. Biochemically, the species exhibited high protein content (41–77 mg · g^{-1}) and was rich in omega-3 fatty acids, particularly in warm seasons (PUFA n-3 = 28%). The fatty acid profile (FA) was dominated by PUFA > MUFA > SFA year-round, with notable differences in energy reserves between sexes, as females showed higher energy mobilization for reproduction. These results provide crucial insights into the reproductive biology and energy allocation strategy of *H. dactylopterus*, underscoring its vulnerability to fishing pressure during spawning and its consistent nutritional value, which is vital for sustainable management in the Mediterranean.

Keywords

benthic fish, periodic change, metabolism, morphometric

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Introduction

Fish have long been recognized as a vital component of a healthy human diet, offering a wide range of health benefits. Sourced from both marine and freshwater environments, their exceptional nutritional value has secured them a prominent place in global cuisines (Tidwell and Allan 2001). Fish are rich in essential nutrients, including lipids, proteins, minerals, vitamins, and bioactive fatty acids, making them an excellent dietary choice for all age groups. As a natural reservoir of these compounds, regular consumption of fish supports optimal bodily function and overall health (Sarojnalini and Hei 2019; Mili et al. 2023; Hajlaoui et al. 2025).

The consumption of fish and their derivatives, such as oils and dietary supplements rich in bioactive lipids, has surged notably in recent decades. This trend is largely driven by the recognition of fish's exceptional nutritional value, which provides high-quality nutrients (Kiczorowska et al. 2019). Fish are a rich source of bioactive lipid compounds, including omega-3 (n-3) polyunsaturated fatty acids (PUFAs) (Gormley 2006), polar lipids (PLs), marine carotenoids, and fat-soluble vitamins A, E, and D (Lordan et al. 2020).

These nutrients, particularly omega-3 PUFAs like docosahexaenoic acid (DHA), are critically important for human health. They contribute to cardiovascular health by reducing triglycerides, inflammation, and the risk of heart disease and stroke (Barber 2004). Furthermore, DHA is essential for brain development in infants and helps maintain cognitive function, potentially reducing the risk of cognitive decline in older adults (Jacqueline and Calder 2020). Omega-3 fatty acids also support ocular health, helping to prevent age-related macular degeneration (AMD) and dry eye syndrome (Lawrenson and Evans 2015).

Beyond these specific benefits, extensive research substantiates the pivotal role of fish lipids in organ development, biochemical and physiological functions, and overall protection against various diseases (Mohanty and Nayak 2018; Grabner et al. 2021; Ashraf et al. 2022). The bluemouth rockfish, *Helicolenus dactylopterus* (Delaroche, 1809), is a bathydemersal scorpionfish with a robust and moderately compressed body, large eyes, and a wide-opening grey-black mouth bearing villiform teeth along both the jaws and the palate (Heemstra and Heemstra 2004; Berge et al. 2023). This fish is otherwise known as blackbelly rosefish or bluemouth seaperch. Its coloration ranges from light yellowish orange to vibrant red, often with darker dorso-ventral bars on the head and body. This species inhabits continental shelf and upper slope soft-bottom habitats, typically between 150 and 600 m depth, though it can occur from 50 to 1100 m (Sion et al. 2024). It is widely distributed across the eastern and western Atlantic, from Nova Scotia to Venezuela in the west, and from Iceland and Norway to the Mediterranean in the east (Pirrera et al. 2009; Sion et al. 2024), including the western and central basins of the Mediterranean (Pirrera et al. 2009).

Ecologically, *H. dactylopterus* functions as a mesopredator, feeding on benthic and pelagic crustaceans, fishes, cephalopods, and occasionally echinoderms and polychaetes, with ontogenetic and habitat-related dietary shifts (Capezzuto et al. 2020; Sion et al. 2024). Its life-history traits include slow growth, long lifespan (up to 43 years), and late maturity (around 32 cm total length), making populations particularly vulnerable to fishing pressure (Consoli et al. 2010; Mili et al. 2016). Regional growth studies estimated von Bertalanffy parameters at $L_\infty = 37$ cm, $k = 0.142 \cdot \text{year}^{-1}$ in Tunisian waters (Mili et al. 2016) and $L_\infty = 26.1$ cm, $k = 0.14 \cdot \text{year}^{-1}$ in the central Mediterranean (Consoli et al. 2010).

Reproductively, the species exhibits a zygoparous form of oviparity, with internal fertilization and embryo development inside a gelatinous ovarian matrix before release as pelagic larvae (Muñoz et al. 2000; Sion et al. 2024). Females are multiple-batch spawners, producing asynchronous oocyte batches with up to 37 000 embryos per spawning event (Muñoz et al. 2000).

Population structure and distribution vary with depth and latitude: juveniles generally occur at lower depths (<500 m), while adults dominate deeper habitats (>500 m), with higher abundances in the western Mediterranean and southern latitudes (Massutí et al. 2000; Pirrera et al. 2009). Morphometric analyses further support the existence of discrete stocks across the Northeast Atlantic and Mediterranean, particularly between the Alboran Sea, Balearic Sea, and adjacent Atlantic regions (Rodríguez-Mendoza et al. 2011). Despite the growing body of research, significant knowledge gaps persist, particularly regarding stock structure validation, reproductive dynamics under fishing pressure, and standardized growth–age assessments across regions (Rodríguez-Mendoza et al. 2011; Sion et al. 2024). Given its increasing commercial importance, as it is regularly targeted by long-lines and gillnets in Mediterranean fisheries (Mili et al. 2016), the present study aims to address these gaps by examining the biochemical composition (lipids, proteins, glycogen, and fatty acids) and various biological aspects, including relative growth, condition index, and gonadosomatic index of *H. dactylopterus* harvested from the northern Tunisian coasts throughout an annual cycle. These analyses provide valuable insights into the species' growth patterns, physiological condition, and nutritional value, thereby offering relevant information for both fisheries management and human consumption.

Material and methods

Sampling area. The northern coast of Tunisia, designated as GFCM-GSA12, extends approximately 400 km (Fig. 1) and comprises two distinct zones. The first section, extending from the Tunisian–Algerian border to Cap Blanc, is characterized by a dense hydrographic network, turbulent waters, and frequent strong winds. The second zone is defined by high-energy wave action that drives ongoing cliff erosion and topographic alteration. This distinct morphology results from high exposure to the deep sea and a narrow, rocky, and steep

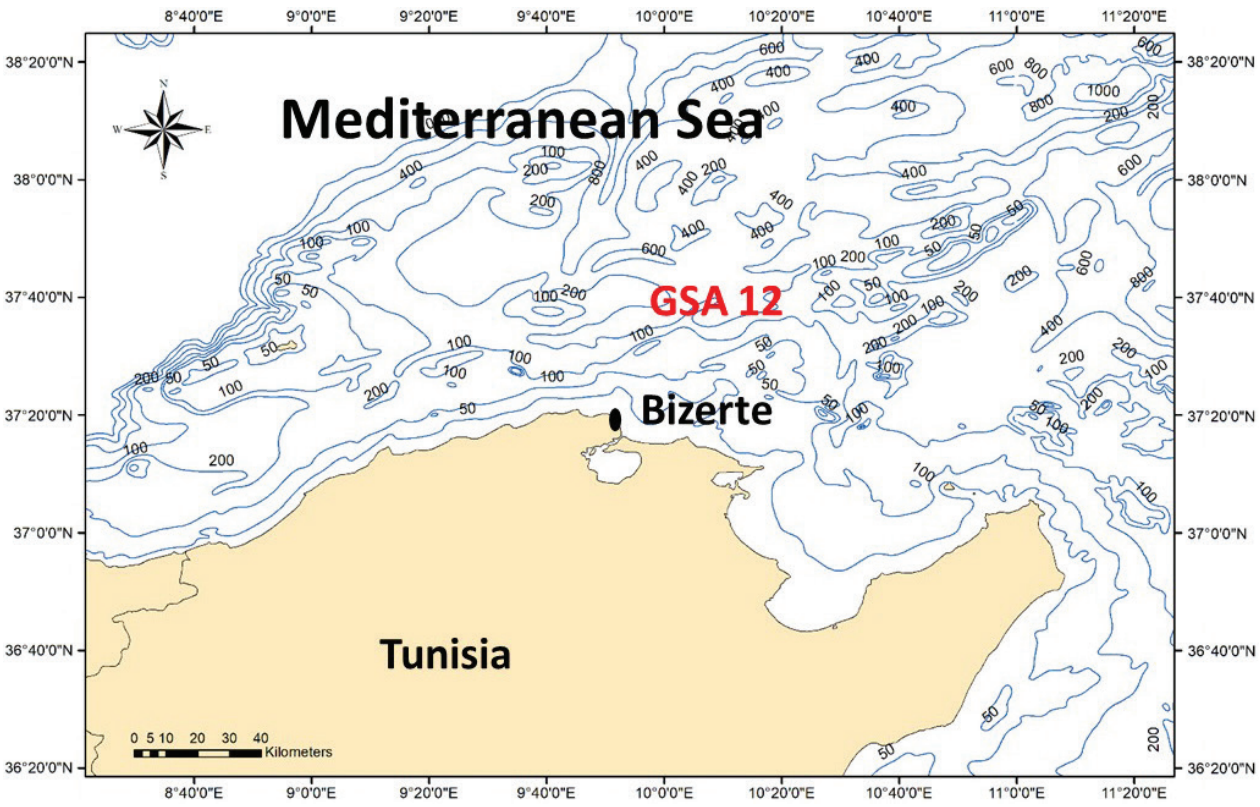

Figure 1. Sampling location, northern Tunisia GFCM-GSA 12 (central Mediterranean Sea).

continental shelf (Ben Ismail et al. 2010; Amrouni et al. 2014; Ben Ismail 2014; Khoufi 2015). Characterized by a dry Mediterranean climate, the northern Tunisian coast (GFCM-GSA12) experiences hot, dry summers and winters with brief, heavy rainfall. This climate is significantly influenced by storm systems originating from the Balearic Islands and the Gulf of Genoa (Ben Ismail 2014; Khoufi 2015; Rjeibi unpublished*).

The northern part of Tunisia exhibits considerable temperature variations, which are influenced by seasonal factors and depth. During the winter and spring seasons, temperatures oscillate between 14.3°C at the surface and 50 m depth, 14.4°C at 100 m, and 13.5°C at 150 m. In contrast, during the summer, a thermocline emerges at depths ranging from 20 to 50 m (Ben Ismail 2014; Rjeibi unpublished).

During the winter season in the Galite, the Atlantic surface waters are at a salinity of 36.73‰, where Salinity can rise to 37.5‰ at a depth of 50 to 150 m. Deeper waters have higher salt levels with more water flowing westward, with salinities ranging from 38‰ to 38.5‰ (Würtz 2010; Ben Ismail 2014).

Sampling fish and dissection. A total of 931 *Helicolenus dactylopterus* specimens (538 males and 393 females) were collected every month in 2022 from northern Tunisia (GFCM-GSA 12) and subsequently transferred to the biological laboratory at the Higher Institute of Marine Sciences of Bizerte. Five morphometric characters were measured for each fish including the total length (L_T) measured to the nearest millimeter using a ruler, the total weight (W_T), eviscerated weight (W_E), gonad weight (W_G) and liver weight (W_L) using a top loading digital scale (precision of 0.001 g) (Table 1). The biological analyses were performed utilizing fresh specimens, while damaged individuals were systematically discarded. Also, the muscular tissues of 24 fish per sex and per season were kept at –80°C for biomarker assays.

Weight–length relationship analysis. Weight–length relationships (WLR) were established to assess the growth pattern and body condition of *H. dactylopterus*. This analysis is fundamental in fisheries science for converting length data to weight, estimating biomass, and understanding the species' life history, as it reveals whether growth is isometric or allometric (Ricker 1973). The relationships between the measured parameters, specifically between total length (L_T) and total weight (W_T), and between total length (L_T) and eviscerated weight (W_E), were determined using the power-law equation:

$$W = aL^b$$

* Rjeibi O (2012) Biologie et dynamique des populations de la langouste rouge *Palinurus elephas* pêchée sur les côtes Nord de la Tunisie. [Biology and population dynamics of the red lobster *Palinurus elephas* caught on the northern coast of Tunisia.] Doctoral thesis, National Agronomic Institute of Tunisia.

This equation was linearized by applying logarithmic transformations to both sides to calculate the parameters *a* and *b* via linear regression:

$$\log(W) = \log(a) + b \times \log(L)$$

where W is the weight (either total weight, W_T, or eviscerated weight, W_E) in grams, L is the total length (L_T) in centimeters, a is the scaling constant (intercept), which reflects the condition factor, and b is the allometric exponent (slope), which describes the type of growth.

The value of the allometric exponent b indicates the growth pattern of the species, defining the proportionality of weight increase relative to length increase:

- Isometric growth ($b = 3$): Body shape remains constant as the fish grows; weight increases in direct proportion to the cube of its length.
- Negative allometry ($b < 3$): The fish becomes lighter for its length as it grows; weight increases at a slower rate than the cube of its length.
- Positive allometry ($b > 3$): The fish becomes stockier for its length as it grows; weight increases at a faster rate than the cube of its length.

We performed an ANCOVA analysis with interaction terms. The full model for each relationship (W_T–L_T and W_E–L_T) was specified as follows:

$$\log(W) \text{ and } \log(L_T) \times \text{Season} \times \text{Sex}$$

We then used model simplification via likelihood ratio tests (LRTs) to explicitly test the influence of season and sex on both the intercept (a) and the slope (b).

Hepatosomatic indices (HSI). The livers were carefully removed and weighed on the digital balance after removing the excess moisture, using blotting paper. The hepatosomatic index was calculated using the following formula:

$$\text{HSI} = \frac{W_L}{W_T - W_G} \times 100$$

Gonadosomatic indices (GSI). The gonadosomatic index (GSI), assessing the ratio between gonad weight and body weight, is frequently used to compare reproductive conditions across individuals or different groups of individuals (Devlaming et al. 1982). The gonadosomatic index was calculated based on the following equation:

$$\text{GSI} = \frac{W_G}{W_T - W_G} \times 100$$

Sex ratio determination. The seasonal sex ratio (SR) was calculated as the proportion of females to the total number of female (F) and male (M) individuals, using the formula

$$\text{SR} = (F \times 100) \times (F + \text{M})$$

Significant deviations from a 1:1 ratio were tested using the chi-square test (χ^2), according to Vazzoler (1996).

Biochemical analysis

Ash determination. To determine the ash content in *H. dactylopterus* muscles, the AOAC method (2005) was used. Briefly, approximately 0.5 g of the muscle was weighed and then dried at a temperature of 300°C for 24 h. The dry weight obtained allowed us to calculate the content of the ashes according to the formula below:

$$\text{Ash}\% = \frac{\text{Ash weight}}{\text{Sample weight}} \times 100$$

Moisture determination. Using an electric scale, 0.5g of *H. dactylopterus* muscle was weighed to determine the initial wet weight. After drying in an oven at a temperature of 105°C for 24 h, the samples were weighed again to determine the dry weight. The percentage of water is calculated according to the formula below (AOAC 2005):

$$\text{Moisture}\% = \frac{\text{Sample weight}}{\text{Fish weight}} \times 100$$

Isolation, hydrolysis, and dosage of glycogen. The glycogen isolation process consists of putting 1g of *H. dactylopterus* muscle, weighed using an electric balance, into centrifugation tubes containing 2 mL of potassium hydroxide KOH (Dubois et al. 1956). Then, the tubes underwent incubation in a boiling water bath at 100°C for 20 to 30 min, shaking from time to time. Then, 0.2 mL of saturated Na_2SO_4 sodium sulfate is added. To precipitate the glycogen, 1 mL of 95% ethanol is added. After centrifugation at 3500 RPM for 15 min, the supernatant is removed, and the pellet is dissolved in 10 mL of distilled water.

For glycogen hydrolysis a volume of 1 mL of the glycogen solution sample was transferred, using a graduated pipette, into test tubes containing 1 mL of hydrochloric acid HCl. Then the tubes were incubated in a water bath at 100°C for 2 h.

To determine the concentration of glucose (GLY) in the glycogen hydrolysate as per the colorimetric glucose oxidase method, 1 mL of the sample of the hydrolyzed glycogen solution was taken (2 h at 100°C) using a graduated pipette. This sample was then combined with 2 drops of phenolphthalein and 5 mL of sodium hydroxide NaOH to neutralize the hydrolyzate. Following this step, the resulting extract was diluted in 1400 mL of distilled water. Then, 1 mL of the glucose oxidase reagent was added, and the test tubes were incubated in a water bath at 37°C for 15 min. A standard range was prepared from a glucose solution to determine the slope and facilitate the calculation of the quantity of glycogen. Glycogen contents are expressed in mg · g^{-1} of fresh weight.

Proximate composition analysis. Fish were separated into male and female per season with soft tissues being excised, frozen in liquid nitrogen, and subsequently stored at –80° C until analysis. The extraction process consisted of weighing 0.5 g of fish muscles in Eppendorf Tris-HCl (20 mM; pH = 7.4), followed by a grinding step,

using a plastic grinding rod. Subsequently, the samples were centrifuged at 10 000 rpm for 20 minutes. After centrifugation, the upper supernatant phase was recovered using a Pasteur pipette.

For the protein analysis, the colorimetric method of Lowry et al. (1951) was established to determine the protein content in fish muscle using the reaction mixture and the Folin reagent, which reacts with both peptide bonds and tyrosine chains. A standard range was produced in parallel using bovine serum albumin (BSA). The hydrolyzate diluted to 20% (200 L final volume) was mixed with 2 mL of the reaction mixture, and then 0.2 mL of Folin reagent (1V/1V) was added. Afterwards, the obtained mixture was incubated in the dark at room temperature for 30 min before measuring the optical density by spectrophotometry at 500 nm. The results are expressed in mg $\cdot$ g^{-1} of fresh weight.

Lipid determination was carried out according to the method of Frings et al. (1972). To each 20 µL sample, 200 µL of sulfuric acid H_2SO_4 (95%) was added. After a ten-minute incubation in boiling water and a 5-min cooling, 1 mL of the vanillin solution was added (composed of 0.12 g of vanillin in 20 mL of distilled water and 100 mL of 85% ortho-phosphoric acid). Then, the mixture was incubated for 15 more minutes at 37°C, followed by 5 min of cooling. A standard range was produced in parallel using olive oil (Sigma, St. Louis, USA), and the optical density was measured at 540nm. The results are expressed in per mg $\cdot$ g^{-1} fresh weight.

Total lipid extraction, FA analysis, and nutritional index calculation. Total lipid (Lip) from fish muscle samples was extracted using a 2:1 (v/v) chloroform/methanol mixture using the procedure outlined by Folch et al. (1957). The extracted lipid samples were esterified following the method described by Cecchi et al. (1995). Before the analysis, the derived FA methyl ester (FAME) samples were dissolved in 0.5 mL of hexane and adequately mixed with a vortex mixer. An exact volume of 2 µL each of this solution was injected into a gas chromatograph (GC; Ceres 800 plus, Chemito Instruments Pvt. Ltd., Mumbai, India) equipped with a BP20 column (SGE Analytical Science; dimensions: 30 m × 0.25 mm; 0.25 µm film thickness of the stationary phase-polyethene glycol) and flame ionization detector (FID). The operating conditions were standardized, with the injector and detector temperatures set at 250°C and 280°C, respectively. The oven temperature was set initially at 60°C and then increased to 260°C after 3 min, which was maintained for 5 min for better peak separation. Nitrogen gas was used as a mobile phase with a flow rate of 0.75 mL $\cdot$ min^{-1}

FAs were identified by comparing their retention times to a mixture of FA methyl ester standards (37-component FAME mixture, C4–C24, SUPELCO Analytical, Bellefonte, PA, USA). Furthermore, confirmation of different FAs was achieved by spiking the samples with a standard. The composition of FAs was expressed in the relative percentage of the total FAs identified based on their peak areas. Essential fatty acid sum; PUFA/SFA; DHA/EPA, and n-3/n-6 PUFA ratios were also determined from fatty acid profiles (Bejaoui et al. 2017).

Statistical analysis. Two-way analyses of variance (Two-way ANOVAs for seasons and sexes) were conducted for growth, morphological, and biochemical parameters separately using R software. The FAs were significant in the Two-way ANOVA; therefore, male and female data were further analyzed separately using a one-way analysis of variance (One-way ANOVA) to assess the effect of season. Further, Principal Component Analysis (PCA) was used, using R software, to see the potential link between the analyzed parameters, sex, and seasons.

Results

Morphometric indices. The length of both males and females of *Helicolenus dactylopterus* was the same across the seasons (Table 1). The length for females and males varied similarly between 17 and 18 cm. The total and eviscerated weight ranges were 87.72–112.55 g and 80.63–92.19 g. However, the weight varied with the season (Table 1). Males and females were significantly heavier in autumn compared to all other seasons. Both sexes in autumn had the least eviscerated weight compared to the other seasons.

Sex ratio. Of the 849 specimens analyzed, 348 were females and 501 were males. The male samples predominated in all months (Fig. 2). The overall sex-ratio value estimated was 1.44, biased towards males. The Chi-square test showed a significant difference (χ^2 = 27.57; df = 1; $P < 0.05$).

Table 1. Morphometric characteristics of *Helicolenus dactylopterus* sampled from northern Tunisia during four seasons of 2022.

Season	Sex	*N*	Total length [cm]	Total weight [g]	Eviscerated weight [g]
Spring	♀	93	17.549 ± 3.407	95.348 ± 6.253	88.797 ± 6.099
	♂	144	17.282 ± 3.754	95.173 ± 5.959	88.859 ± 5.839
Summer	♀	144	17.295 ± 2.901	98.618 ± 6.852	90.196 ± 6.453
	♂	144	18.487 ± 3.467	99.674 ± 6.389	92.198 ± 6.302
Autumn	♀	77	17.031 ± 3.535	112.554 ± 5.951	82.514 ± 5.685
	♂	113	17.767 ± 3.885	106.004 ± 6.159	80.635 ± 4.322
Winter	♀	79	17.911 ± 3.767	87.722 ± 4.537	80.635 ± 4.432
	♂	137	17.424 ± 3.619	94.169 ± 5.211	87.961 ± 5.141

Results are presented as mean ± standard deviation. *N* = number of fish studied.

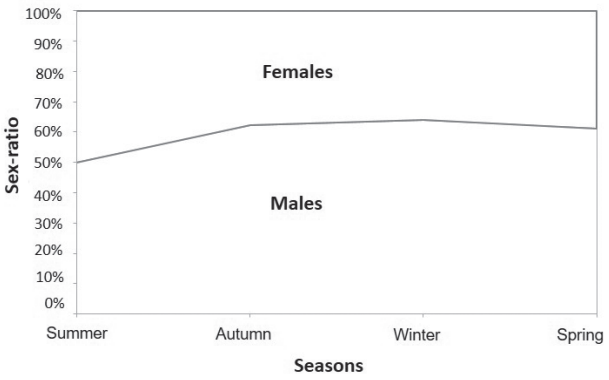

Figure 2. Sex ratio of *Helicolenus dactylopterus* (male and female) collected in northern Tunisia during four seasons of 2022.

Gonadosomatic and hepatosomatic indices. The seasonal patterns of GSI and HSI indices are shown in Fig. 3. For HSI, similar trends were observed in both females and males, with lower values during summer, autumn, and winter ($P < 0.01$), and higher values during spring. The GSI of males followed a similar pattern to HSI, showing a marked increase in spring compared to other seasons. In contrast, the GSI in females remained relatively stable, with no significant variation observed across the studied seasons.

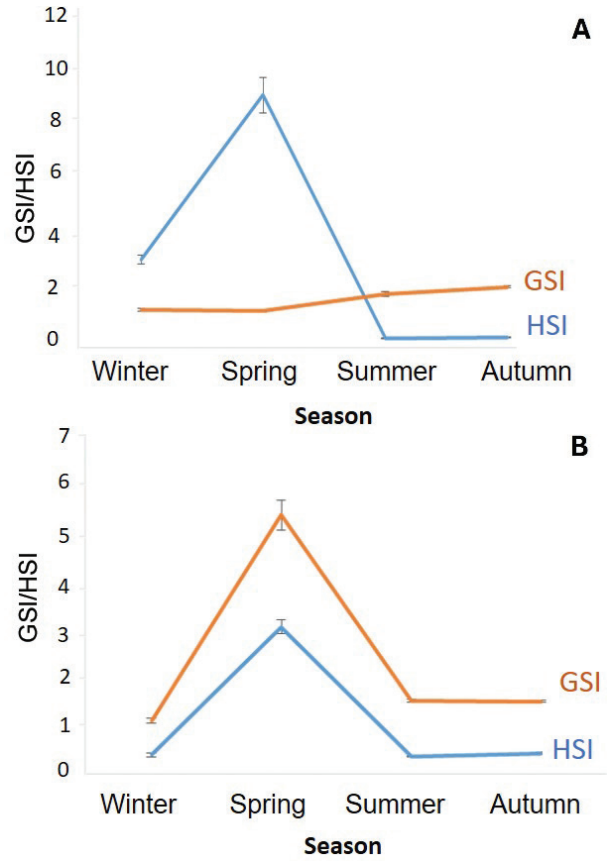

Figure 3. Gonadosomatic (GSI: orange line) and hepatosomatic (HSI: blue line) ratios of *Helicolenus dactylopterus* (**A**: female; **B**: male) collected in northern Tunisia during four seasons of 2022. Values are presented by mean and standard deviation.

Growth relationship. The seasonal variations in the relative growth of fish collected from northern Tunisian waters (GFCM-GSA 12) are recorded in Table 2. The allometry coefficients of weight growth relations ranged between 2.6 to 2.8 and 2.9 to 3.0, respectively, for total weight and eviscerated weight. Amongst the morphometric relationships, negative allometry was found to be significantly more abundant than positive allometry. This positive allometry between eviscerated weight and total length was observed during autumn for both males and females.

For the W_T–L_T relationship, the three-way interaction (log L_T × Season × Sex) was not significant ($\chi^2 = 8.51$, df = 9, $P = 0.483$). However, the two-way interaction log(L_T): Season was significant ($\chi^2 = 25.34$, df = 3, $P < 0.001$), indicating that the allometric slope (b) varies significantly across seasons regardless of sex. The effect of sex on the slope was not significant (log L_T: sex, $\chi^2 = 2.15$, df = 1, $P = 0.142$).

For the W_E–L_T relationship, the three-way interaction was also not significant ($\chi^2 = 7.62$, df = 9, $P = 0.571$). The two-way interaction log(L_T): Season was significant ($\chi^2 = 18.92$, df = 3, $P < 0.001$), confirming that season significantly influences the allometric slope again. The effect of sex on the slope was not significant (log L_T: sex, $\chi^2 = 0.87$, df = 1, $P = 0.351$).

Biochemical composition. The biochemical composition of male and female *H. dactylopterus* is presented in Table 2. Ash content varied similarly between sexes across seasons, ranging from 18.6% to 19.3% in males and 17.7% to 20.5% in females. Moisture content was high in both sexes (71.7%–89.7%) and exhibited parallel fluctuations, with no significant differences observed between males and females. However, seasonal variation was significant ($P < 0.01$), with lower moisture content recorded during warm seasons (spring and summer) and higher content during cold seasons (autumn and winter). Protein content varied seasonally, with similar levels between sexes in summer and autumn. Significant sexual dimorphism was observed in spring and winter ($P < 0.05$), with males exhibiting higher muscular protein content than females. The lowest protein levels were recorded in winter for both sexes, and females also showed significantly reduced protein content in spring ($P < 0.01$). Lipid content varied significantly across seasons in both sexes (Table 3). Females exhibited considerable variation, with a significant rise in lipids during summer and autumn, followed by a sharp decrease to minimal levels in winter ($P < 0.001$). In contrast, seasonal variation in males was less pronounced, though a significant decline was also observed during winter ($P < 0.01$). Similar to other biochemical constituents, glycogen levels varied significantly both seasonally and between sexes. Female *H. dactylopterus* exhibited the highest glycogen content during summer (1.19 mg · g^{-1}) and autumn (1.20 mg · g^{-1}), with levels declining sharply to minima in winter (0.11 mg · g^{-1}) and remaining low in spring (0.28 mg · g^{-1}) ($P < 0.001$). In males, glycogen levels were stable during warm seasons but showed significant variation during cold seasons ($P < 0.001$), characterized by moderate content in autumn and a minimum in winter.

Table 2. The length–weight relationship of *Helicolenus dactylopterus* sampled from northern Tunisia during four seasons of 2022.

Relation	Season	Sex	*a*	*b*	R^2	*t*	Type
W_T–L_T	Winter	♀	0.022	2.863	0.985	10.480	Negative allometry
		♂	0.034	2.734	0.983	17.203	Negative allometry
	Autumn	♀	0.029	2.793	0.986	11.979	Negative allometry
		♂	0.037	2.710	0.982	15.653	Negative allometry
	Summer	♀	0.029	2.783	0.975	18.521	Negative allometry
		♂	0.168	2.606	0.933	15.700	Negative allometry
	Spring	♀	0.030	2.777	0.988	10.858	Negative allometry
		♂	0.037	2.704	0.983	13.600	Negative allometry
W_E–L_T	Winter	♀	0.013	3.010	0.980	17.230	Positive allometry
		♂	0.012	3.047	0.984	16.026	Positive allometry
	Autumn	♀	0.018	2.919	0.986	11.247	Negative allometry
		♂	0.018	2.936	0.983	14.679	Negative allometry
	Summer	♀	0.015	2.969	0.977	17.052	Negative allometry
		♂	0.016	2.912	0.937	10.898	Negative allometry
	Spring	♀	0.017	2.936	0.990	10.086	Negative allometry
		♂	0.017	2.926	0.984	12.500	Negative allometry

W_T = total weight, L_T = total length, W_E = eviscerated weight, R^2 = coefficient of determination, *a* = scaling constant (intercept), *b* = allometry coefficient value, *t* = correlation test.

Table 3. Biochemical composition of *Helicolenus dactylopterus* sampled from northern Tunisia during four seasons of 2022.

Season	Sex	Ash [%]	Moisture [%]	Proteins [mg · g^{-1}]	Lipids [mg · g^{-1}]	Glycogen [mg · g^{-1}]
Spring	♀	18.673 ± 1.116	71.777 ± 9.000	50.848 ± 2.016	4.984 ± 0.344	0.288 ± 0.054
	♂	19.321 ± 4.654	71.888 ± 9.253	77.390 ± 0.380**	5.286 ± 0.513	0.480 ± 0.033**
Summer	♀	19.321 ± 1.844	81.944 ± 0.962	75.907 ± 5.317	11.083 ± 0.797	1.198 ± 0.208
	♂	18.965 ± 4.370	80.833 ± 1.666	76.880 ± 0.494	5.193 ± 0.284***	0.307 ± 0.036***
Autumn	♀	17.767 ± 2.210	86.666 ± 6.821	76.038 ± 1.407	15.006 ± 0.882	1.203 ± 0.230
	♂	19.270 ± 4.610	87.222 ± 5.912	75.969 ± 0.441	5.149 ± 0.318***	0.730 ± 0.069*
Winter	♀	20.519 ± 1.488	89.722 ± 2.405	41.325 ± 5.136	1.085 ± 0.382	0.110 ± 0.062
	♂	18.609 ± 3.390	88.722 ± 2.405	44.881 ± 3.437*	2.398 ± 0.635*	0.140 ± 0.024
♀ Seasons		ns	##	###	###	###
♂ Seasons		ns	##	###	##	#

Significant differences between sexes are reported at 0.5% with stars as follows: $P < 0.05$ *; $P < 0.01$**; $P < 0.001$***.
Significant differences between seasons are reported at 0.5% with sharp #: $P < 0.05$ #; $P < 0.01$##; $P < 0.001$###.

Fatty acid composition of females. Table 4 presents the seasonal variation in the muscle fatty acid (FA) composition of female *H. dactylopterus* from northern Tunisia (GFCM-GSA 12). Polyunsaturated fatty acids (PUFAs) were the dominant class year-round, followed by monounsaturated (MUFAs) and saturated (SFAs) fatty acids. SFA levels varied significantly among seasons ($P < 0.001$), with the highest content in winter and the lowest in spring. This trend was driven primarily by fluctuations in their major compounds, mainly C16:0, C18:0, and C20:0, as they increased significantly in winter (25.5%, 9.02%, and 8.05%, respectively) and decreased in spring (to 2.61%, 7.58%, and 0.34%, respectively). MUFA content peaked during autumn (48.16%), coinciding with high levels of its predominant components, C16:1 (32.59%) and C18:1 (14.78%). MUFA levels decreased significantly in other seasons, reaching a minimum in summer ($P < 0.001$), a trend associated with a pronounced depletion in these key compounds ($P < 0.001$). PUFA content also exhibited significant seasonal variation (Table 4), with the highest levels recorded in winter, spring, and summer, contrasting with lower levels in autumn ($P < 0.05$). The elevated PUFA content in autumn and winter was largely attributable to high levels of n-6 PUFAs, confirmed by a significant increase in C20:4n-6 and its precursors (C18:2n-6 and C20:2n-6; $P < 0.01$). Conversely, the warm seasons (spring and summer) were characterized by the dominance of n-3 PUFAs, which reached their highest levels (28%). This was linked to a significant rise in C20:5n-3 (EPA) and C22:6n-3 (DHA) compared to cold seasons ($P < 0.01$).

Fatty acid composition of males. The fatty acid (FA) profile of male *H. dactylopterus* comprised 14 identified FAs, categorized into three saturated (SFA), three monounsaturated (MUFA), and eight polyunsaturated (PUFA) species (Table 5). A significant seasonal effect was observed on the SFA profile ($P < 0.001$), with the highest composition occurring in spring. This peak was primarily driven by a maximum in palmitic acid (C16:0) content (26.31%). The MUFA profile was dominated by palmitoleic (C16:1) and oleic (C18:1) acids, which were most abundant in autumn. These values decreased significantly in other seasons, reaching a minimum in winter ($P < 0.001$). PUFA levels were significantly highest in summer ($P < 0.05$), primarily due to a rise in n-3 PUFAs, specifically eicosapentaenoic (C20:5n-3, EPA) and docosahexaenoic (C22:6n-3, DHA) acids ($P < 0.001$).

Table 4. Fluctuation of the fatty acid composition of *Helicolenus dactylopterus* females sampled from northern Tunisia during four seasons of 2022.

Fatty acid	Autumn	Winter	Spring	Summer	*P*
C16:0	3.49 ± 0.63	25.58 ± 0.94	2.61 ± 0.24	23.04 ± 0.06	***
C16:1	32.59 ± 2.68	4.22 ± 1.60	4.69 ± 0.27	1.52 ± 0.22	***
C18:0	7.95 ± 0.55	9.02 ± 2.48	7.58 ± 0.05	2.17 ± 0.03	*
C18:1	14.78 ± 1.5	2.77 ± 0.82	24.05 ± 0.70	4.67 ± 0.09	***
C18:2n-6	2.89 ± 0.19	7.88 ± 2.90	1.04 ± 0.04	3.59 ± 0.12	**
C18:3n-6	1.61 ± 0.17	6.56 ± 2.20	10.69 ± 0.41	1.35 ± 0.20	***
C18:3n-3	1.61 ± 0.08	2.9 ± 0.23	1.29 ± 0.01	12.92 ± 0.35	***
C20:0	1.47 ± 0.11	8.05 ± 0.58	0.34 ± 0.01	3.19 ± 0.31	***
C20:1	0.78 ± 0.05	3.19 ± 0.38	0.43 ± 0.04	2.88 ± 0.14	***
C20:2n-6	9.11 ± 0.57	5.39 ± 1.90	5.62 ± 0.05	3.14 ± 0.16	*
C20:4n-6	10.26 ± 0.10	14.2 ± 0.50	3.72 ± 0.18	5.11 ± 0.01	***
C20:5n-3	3.49 ± 0.34	4.52 ± 1.26	10.5 ± 0.14	6.18 ± 0.05	**
C22:5n-3	1.90 ± 0.47	2.64 ± 0.94	8.37 ± 0.05	3.05 ± 0.39	**
C22:6n-3	3.73 ± 0.14	3.59 ± 0.01	7.59 ± 0.20	6.67 ± 0.10	**
SFA	12.9 ± 0.03	42.65 ± 0.96	10.52 ± 0.21	28.41 ± 0.34	***
MUFA	48.16 ± 1.13	10.19 ± 1.16	29.17 ± 0.92	9.07 ± 0.02	***
PUFA	34.59 ± 0.73	47.67 ± 4.13	48.82 ± 0.24	42.02 ± 0.68	*
PUFA n-3	10.73 ± 1.03	13.64 ± 2.43	27.75 ± 0.39	28.83 ± 0.59	***
PUFA n-6	23.86 ± 0.31	34.03 ± 1.71	21.07 ± 0.15	13.19 ± 0.09	**

Fatty acids are the mean ± SD (n = 3 per season of 6 pooled samples per month).
Significant changes between seasons are presented at 5% as follows: * $P < 0.05$; ** $P < 0.01$, and *** $P < 0.001$ using ANOVA one-way followed by a Student's t-test.

Table 5. Fluctuation of the fatty acid composition of *Helicolenus dactylopterus* males sampled from northern Tunisia during four seasons of 2022.

Fatty acid	Autumn	Winter	Spring	Summer	*P*
C16:0	4.77 ± 0.58	20.51 ± 0.11	26.31 ± 0.15	1.38 ± 0.23	***
C16:1	28.71 ± 2.5	2.44 ± 0.28	1.39 ± 0.15	2.25 ± 0.14	***
C18:0	7.42 ± 0.33	6.86 ± 0.28	5.07 ± 0.36	7.66 ± 0.77	*
C18:1	10.05 ± 0.42	2.87 ± 0.11	13.29 ± 0.28	19.48 ± 0.23	***
C18:2n-6	5.22 ± 0.12	1.62 ± 0.13	1.31 ± 0.13	9.18 ± 0.22	***
C18:3n-6	4.86 ± 0.30	2.24 ± 0.09	3.16 ± 0.54	2.06 ± 0.06	*
C18:3n-3	4.07 ± 0.29	1.03 ± 0.09	3.21 ± 0.07	0.81 ± 0.04	***
C20:0	2.21 ± 0.26	1.76 ± 0.22	2.88 ± 0.38	0.76 ± 0.01	***
C20:1	2.98 ± 0.18	2.68 ± 0.10	1.49 ± 0.14	0.83 ± 0.01	***
C20:2n-6	3.38 ± 0.09	4.73 ± 0.57	4.09 ± 0.01	4.99 ± 0.10	ns
C20:4n-6	9.62 ± 0.46	17.62 ± 1.68	5.03 ± 0.10	3.71 ± 0.12	***
C20:5n-3	5.42 ± 0.25	3.52 ± 0.04	5.95 ± 0.04	10.35 ± 0.16	***
C22:5n-3	1.58 ± 0.14	1.42 ± 0.07	3.45 ± 0.27	6.17 ± 0.33	***
C22:6n-3	3.22 ± 0.32	3.20 ± 0.11	6.39 ± 0.31	6.31 ± 0.18	**
SFA	14.4 ± 1.17	29.14 ± 0.6	34.25 ± 0.89	9.79 ± 0.53	***
MUFA	41.73 ± 1.89	7.98 ± 0.49	16.17 ± 0.29	22.56 ± 0.38	***
PUFA	37.37 ± 1.72	35.38 ± 0.76	32.58 ± 0.60	43.57 ± 0.76	*
PUFA3	14.29 ± 1.00	9.17 ± 0.31	19.01 ± 0.08	23.63 ± 0.72	***
PUFA6	23.09 ± 0.73	26.21 ± 1.07	13.57 ± 0.52	19.93 ± 0.05	***

Fatty acids are the mean ± SD (n = 3 per season of 6 pooled samples per month).
Significant changes between seasons are presented at 5% as follows: * $P < 0.05$; ** $P < 0.01$, and *** $P < 0.001$ using ANOVA one-way followed by a Student's t-test.

In contrast, n-6 PUFA levels were elevated in winter and autumn. Among n-6 PUFAs, arachidonic acid (C20:4n-6) was predominant during these seasons, reaching 26.21% and 23.09%, respectively (Table 5).

Comparison of fatty acid composition between males and females. The principal component analysis, which explained 62% of the cumulative variance, was used to compare the fatty acid compositions between sexes and to better understand the specific FA of each season (Fig. 4). This analysis identifies three clusters corresponding to winter, autumn, and groups that overlap with spring and summer. The FA, responsible for distinguishing the winter season from the other ones, was mainly reported by SFA, PUFA-6, and arachidonic acid (C20:4n-6). However, group 2 showed almost complete overlap between males and females sampled in spring and summer. This group was characterized by a similar FA composition, including PUFA, PUFA-3; C22:6n-3, and C20:5n-3, etc. The last small group was characterized by the presence of C18:0, C16:1 and C20:2n-6 in both males and females.

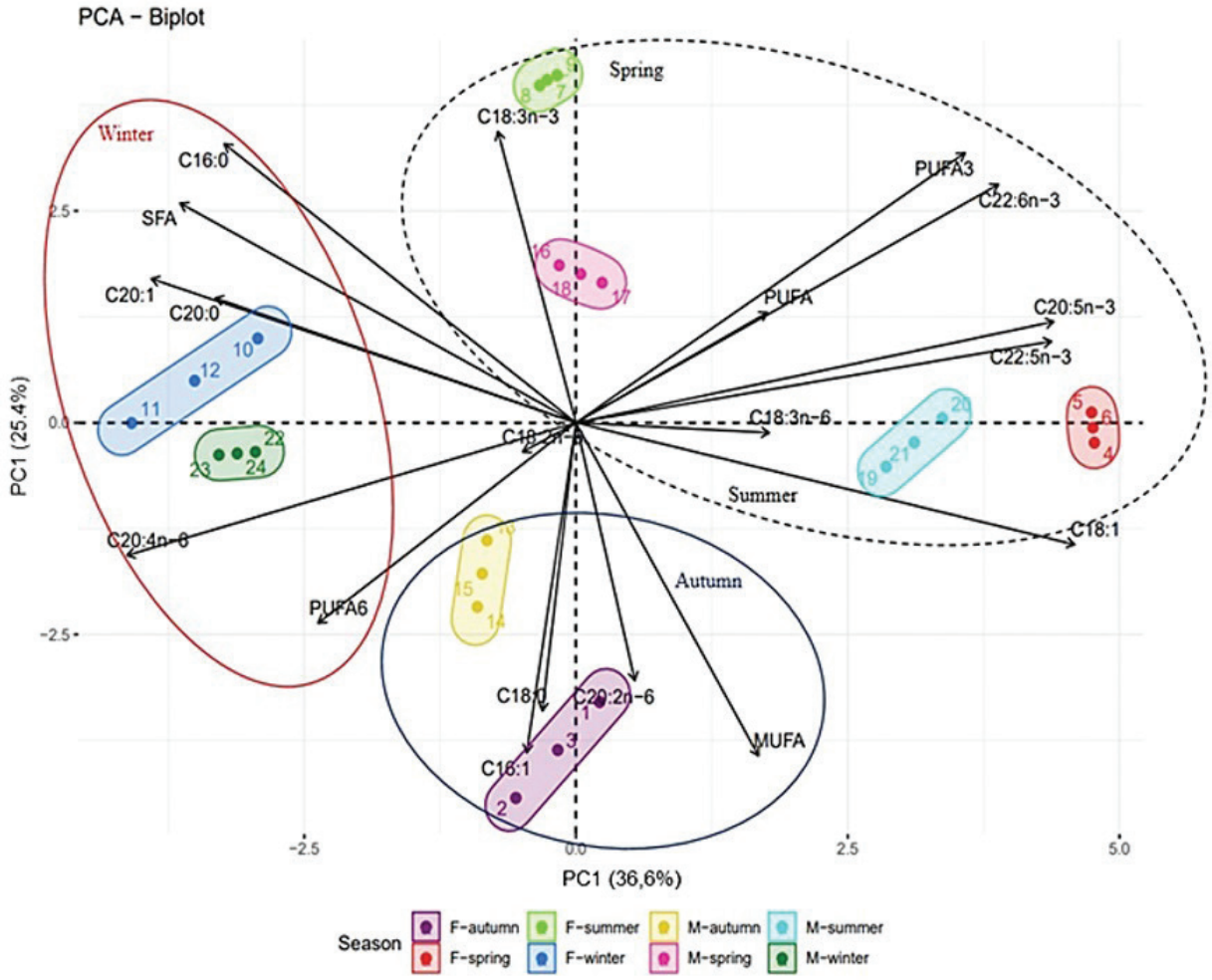

Figure 4. Principal Component Analysis (PCA) of fatty acid composition in males and females *Helicolenus dactylopterus* collected in northern Tunisia during four seasons of 2022.

Nutritional quality indices. The nutritional quality indices of male and female *H. dactylopterus* are presented in Fig. 5. Levels of essential n-3 PUFAs were significantly lower in both sexes during cold seasons compared to warm seasons ($P < 0.001$). Conversely, the relative proportion of n-6 PUFAs was lowest during spring compared to autumn and winter ($P < 0.01$). The PUFA/SFA and n-3/n-6 PUFA ratios also showed significant variation between sexes and across seasons, with the lowest values observed during winter.

Integration between biochemical and biological indices using PCA analysis. Principal Component Analysis (PCA) was used on biological and biochemical parameters across sexes and seasons. The biplot illustrates fish samples, which are colored according to sex and season, while ellipses indicate the clustering of groups. PCA 1 explains 31.5% of the total variance, and PCA 2 accounts for 22.1% (Total of 53.6% of the overall variation). The arrows on the biplot represent the direction and strength of the contribution of each variable, such as GSI, HSI, PUFA, GLY, and Lip, to the PCA axes (Fig. 6).

PCA 1 appears primarily associated with morphometric traits, including size and weight variables (L_T, W_T, W_E), as well as reproductive indices (GSI). Samples with higher PCA1 values correspond to larger and heavier individuals. In contrast, PCA2 is largely linked to biochemical and reproductive indices, such as PUFA, PUFA3, PUFA6, GSI, GLY, Lip, HSI, and GSI, where higher values indicate elevated biochemical content or reproductive condition.

Seasonal and sex-related patterns are evident in the PCA. Female samples from spring, represented in pink, are distributed along PCA1 and characterized by large size and weight, as well as moderate biochemical content, particularly Lipids. Summer females, shown in green, cluster near the center and are mainly influenced by PUFA3 and glycogen content. Winter females' group in the upper-left quadrant, associated with PUFA6 and RGS, whereas autumn females are located in the lower-left quadrant, linked to MUFA. Male samples also show distinct seasonal patterns. Spring males occupy the right quadrant and are associated with size and reproductive indices. Summer males are near the center, influenced by moderate PUFA3 and glycogen content. Autumn males cluster in the lower-left quadrant, related to HSI, while winter males are positioned in the upper-right quadrant, linked to protein and fatty acids.

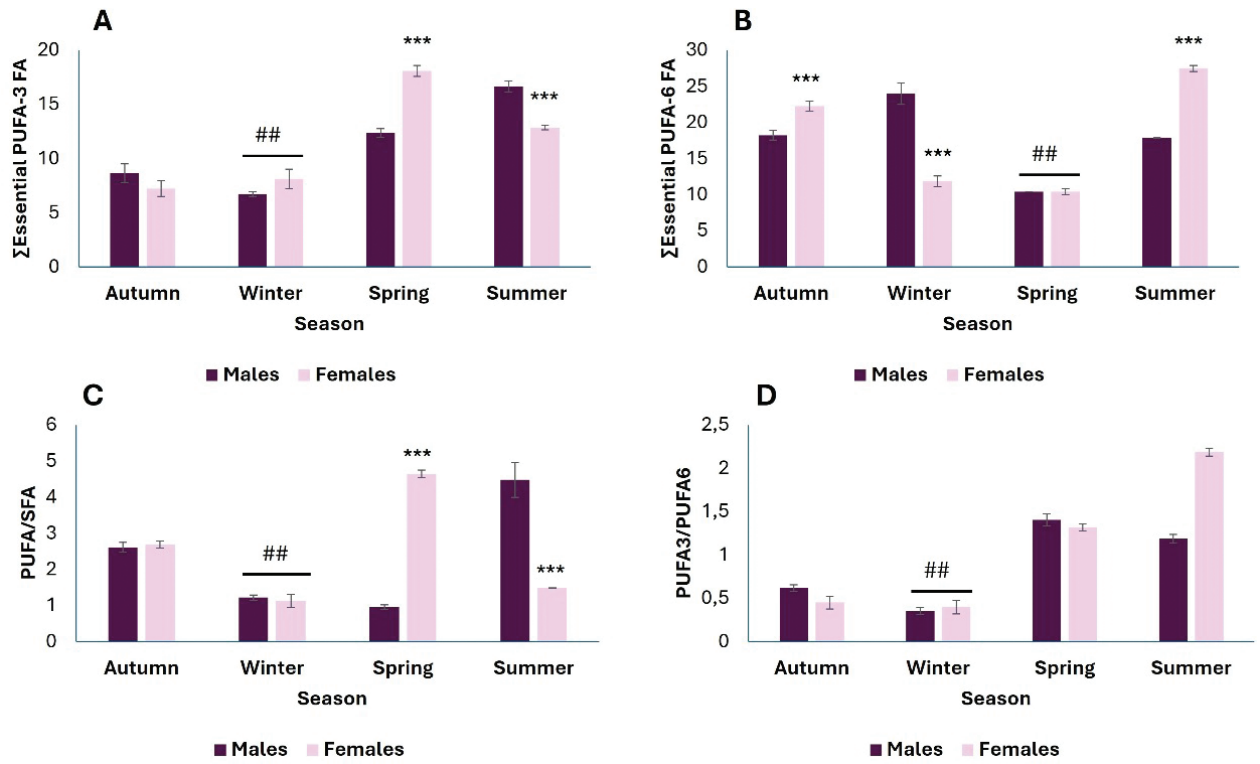

Figure 5. Nutritional quality indices of *Helicolenus dactylopterus* (male and female) collected in northern Tunisia during four seasons of 2022. Values are presented by mean and standard deviation. Differences between seasons (#) and sexes (*) are noted at 5%.

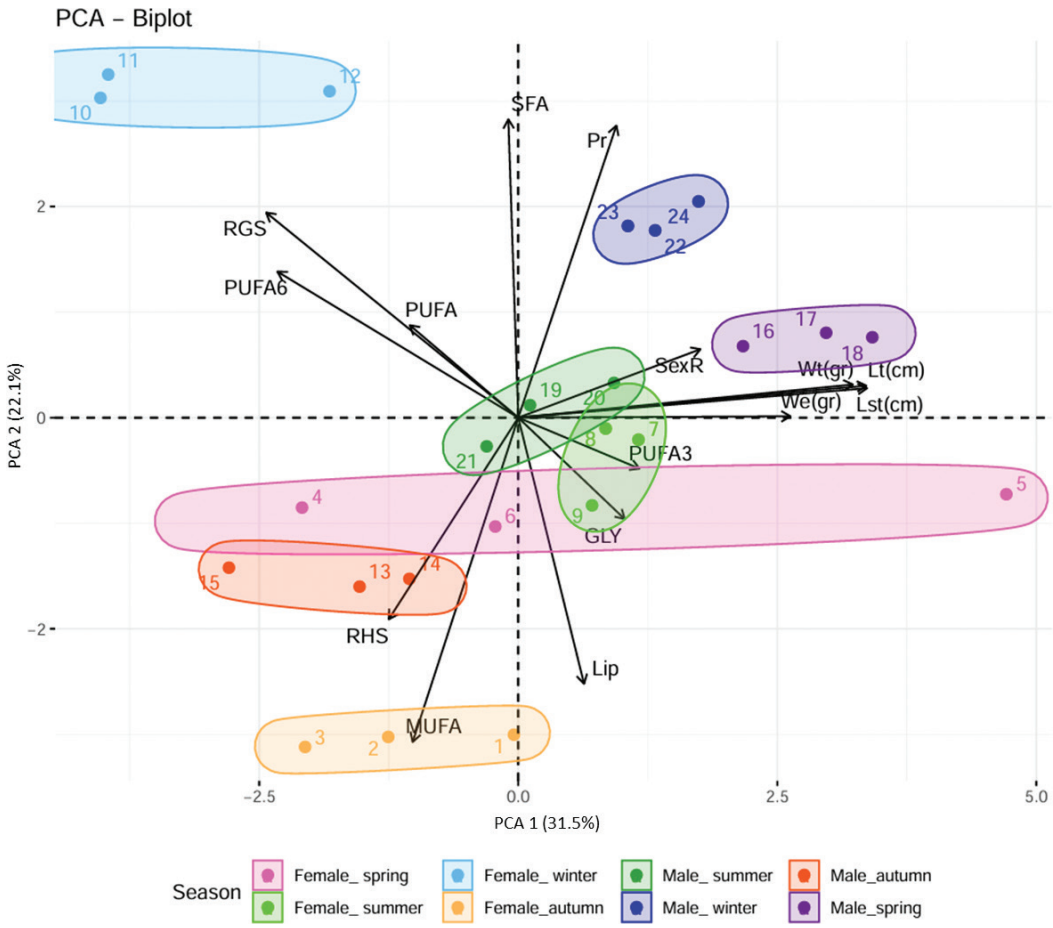

Figure 6. Integration, using PCA analysis, between biological and biochemical indices of *Helicolenus dactylopterus* males and females collected in northern Tunisia during four seasons of 2022.

Overall, the PCA highlights clear seasonal variation, with spring samples for both sexes distinguished by size and reproductive traits. Partial separation between sexes along both axes indicate differences in growth and biochemical composition. PCA1 predominantly reflects morphometric variation, while PCA2 captures biochemical and reproductive differences. Biochemical variables such as PUFA, GLY, and lipids strongly drive separation along PCA 2, and some seasonal clusters, particularly summer males and females, are positioned closely, reflecting similar physiological and biochemical profiles during that period.

Discussion

Examining fish characteristics at a regional level is essential for improving their viability as food resources and supporting the development of new industrial ventures, thereby contributing economic value to the sector. Species inhabiting deep waters, like the bluemouth rockfish, *Helicolenus dactylopterus*, are deemed sensitive to the impact of fisheries pressure (Mili et al. 2016). Additionally, their biological traits make them very accessible to trawling (Pirrera et al. 2009).

The length–weight relationship (LWR) is influenced by many factors, such as sex, maturity, diet, satiety, but also by methodological aspects such as sample size, sampling duration, and the area studied (Moutopoulos and Stergiou 2002; Ragheb et al. 2022). In the presently reported study, the *t*-test applied to the allometric coefficient (*b*) revealed negative allometric growth for the length–total weight (LTW) relationship in all specimens. For the length–eviscerated weight (LEW) relationship, growth showed negative allometry, except for autumn, when positive allometry was observed. However, as the growth profile reflects the cumulative trend of cohorts, it is less likely that it truly varies seasonally; the observed variations could instead result from the limited sample size available at certain periods. This methodological limitation must therefore be taken into account when interpreting the results.

Comparatively, negative allometry has been previously reported for *H. dactylopterus* on the northern Tunisian coast (Mili et al. 2016), while other studies in the Mediterranean have described positive allometry or isometric growth (Massutí et al. 2000; Consoli et al. 2010). These discrepancies may be explained by environmental, nutritional, and bathymetric differences (D'Onghia et al. 1992; Froese 2006). Indeed, the maximum size (25 cm) observed in our study area is smaller than that reported elsewhere, likely due to the bathymetric distribution: larger individuals are generally associated with greater depths, less accessible to trawling (Massutí et al. 2000; Deval et al. 2018).

Regarding the sex ratio, our results indicate a predominance of males in the cold season and females in the warm season. This trend differs from some observations in the western Mediterranean, where a 1:1 balance has been reported (Muñoz et al. 2000; Dércia et al. 2017). However, other studies show a dominance of males in large sizes and females in small and medium sizes (Deval et al. 2018). The seasonal variation observed in our study could be linked to environmental factors, particularly the effect of temperature on embryonic development (Ragheb et al. 2022).

Overall, the analysis of biological indices and growth of *H. dactylopterus* highlights plasticity related to ecological and methodological factors, highlighting the importance of considering these limitations when interpreting the results.

Beyond the biological indices, which provide insights into growth dynamics, reproductive investment, and population structure of *H. dactylopterus*, the biochemical parameters (proximate composition and fatty acid profiles) offer complementary information on the species' physiological status and energy allocation. Variations in lipid, protein, and glycogen contents, together with fatty acid composition, can reflect seasonal changes in metabolism, reproductive activity, and feeding ecology. Linking these biochemical patterns with the observed biological traits allows a more integrated understanding of the species' life-history strategy, highlighting how environmental factors and reproductive cycles jointly influence both somatic growth and nutritional value.

The proximate composition of *H. dactylopterus* varied significantly among different seasons. The biochemical composition of fish is subject to various factors, encompassing biological variables (such as species, sex, size, and age), dietary habits, the geographic location of the catch, and seasonal variations (Orban et al. 2011). High ash content was observed in both female and male specimens. According to Ragheb et al. (2022), this could be related to the fish size and composition of feeding habits. *H. dactylopterus* showed high moisture levels ranging from 71.7% to 89.7%. The moisture content can be influenced by several factors, including species, season, age, and diet can affect the moisture content (Seham et al. 2015). The glycogen level varied among seasons and reached the lowest values in winter. Glycogen is a vital energy substrate for bluemouth rockfish. During the cold season, the depletion of the glycogen reserves can be attributed to their use in reproduction. Protein levels observed in *H. dactylopterus* are following those reported by Koca et al. (2023) (19.68%), Olgunoğlu and Artar (2016) (20.25%) from Turkish waters. The reason for the high protein content found in *H. dactylopterus* may be due to its feeding habits and diet preference for high-protein resources, such as shrimp and rockfish. Neves et al. (2012) reported that *H. dactylopterus* exhibits a varied diet, primarily focused on small crustaceans. Then, as individuals mature, a noticeable shift towards increased consumption of shrimps and fish occurred. As regards lipid content, lower levels were observed in the present study as compared to proteins for both females and males of *H. dactylopterus.* According to Ackman (1990), the

total lipid content of fish can be classified as lean fish (<2%), low fat (2%–4%), medium fat (4%–8%), and high fat (>8%). Based on the current results, Tunisian *H. dactylopterus* can be considered a low to medium-fat fish with a fat level reaching 5%. Lower lipid levels for this species were reported (0.6%, 0.82%, and 0.95%, respectively) by Afonso et al. (2013), Olgunoğlu and Artar (2016), and Koca et al. (2023) in the Mediterranean Sea. Therefore, we think that seasonal lipid content differences may be related to nutrient availability, environmental parameters, and reproduction. To sum up, the lowest levels of lipid, protein, and carbohydrate in *H. dactylopterus* were observed in winter. This coincides greatly with the decrease of both gonadosomatic (GSI) and hepatosomatic (HSI) indices in winter for both sexes, which probably reflects the spawning period of this species. The decrease in GSI, which indicates the proportion of body weight attributed to the gonads, highlighted the reproductive status of this species. Consequently, *H. dactylopterus* undergoes seasonal changes in energy allocation due to the reproductive process, leading to lower levels of stored nutrients. The simultaneous decrease in gonadosomatic and hepatosomatic indices supports the idea of a seasonal shift in the fish's physiological priorities throughout different seasons. The onset of the spawning period triggers a metabolic shift in fish. The energy stored in lipids, proteins, and carbohydrates is mobilized to support the energy-intensive activities associated with spawning (Albo-Puigserver et al. 2020). It must be taken into consideration that during winter, factors such as reduced prey availability and lower water temperatures may limit feeding opportunities, contributing to a decline in nutrient intake and storage (Volkoff and Rønnestad 2020). In summary, the observed decline in *H. dactylopterus* energetic reserves during winter is likely a result of seasonal adaptations, where energy resources are allocated towards reproductive and metabolic activities. The integration of biological and biochemical indices provides a more comprehensive understanding of the life cycle of *H. dactylopterus*, revealing how morphological and physiological variations respond to environmental and reproductive constraints. Seasonal fluctuations in allometric growth, sex ratio, and gonadosomatic (GSI) and hepatic (HSI) indices appear closely correlated with changes in biochemical composition, such as variations in lipids, proteins, carbohydrates, and glycogen. The concomitant decline in these energy reserves in winter coincides with the decline in GSI and HSI, reflecting a shift of energy from somatic and hepatic tissues toward reproduction and reflecting an adaptive strategy of energy redistribution according to the season (Volkoff and Rønnestad 2020; Queiros et al. 2024).

This physiological coupling is supported by recent studies on other Mediterranean and Atlantic species, which demonstrate that the joint analysis of biological and biochemical parameters using multivariate approaches (PCA, correlations, linear mixed models) makes it possible to identify the complex interrelationships between growth, reproduction, and energy metabolism (Campbell 2015; Lloret-Lloret et al. 2022). This work highlights that biochemical variations are not isolated but integrated into the reproductive cycle and growth dynamics, providing a functional perspective on the physiological plasticity of fish in the face of environmental constraints.

Thus, in *H. dactylopterus*, an analytical approach combining biological and biochemical indices could not only quantify energy redistribution over the seasons but also predict critical periods for reproduction and somatic development. The adoption of targeted statistical analyses would strengthen the understanding of the underlying physiological interactions and position this study as a significant contribution to the knowledge of energy allocation strategies of Mediterranean demersal species.

In the presently reported study, fatty acids (FAs) changed significantly among the seasons. The dominant fatty acids for *H. dactylopterus* were determined as PUFA > MUFA > SFA. The most dominant PUFAs were eicosapentaenoic (C20:5n-3, EPA) and docosahexaenoic (C22:6n-3, DHA) acids. These n-3 long-chain PUFAs play crucial roles in supporting various aspects of human health. They have been associated with cardiovascular health as they have the potential to reduce the risk of cardiovascular diseases. They may lower blood pressure, improve blood vessel function, and reduce inflammation (Ander et al. 2003). It has been reported previously that PUFAs were the predominant fatty acids in muscles of *H. dactylopterus* from the Portuguese (Afonso et al. 2013) and Turkish coasts (Koca et al. 2023). It is worth mentioning that the omega-3 content in fish can vary based on factors such as species, diet, and environmental conditions (Ghribi et al. 2023). Additionally, since fish obtain EPA and DHA from their diet, the omega-3 levels in fish can be influenced by the omega-3 content of the marine organisms they consume. Among the omega-6, the most dominant FA was the arachidonic acid (C20:6n-4, ARA) for both sexes. ARA, being an omega-6 fatty acid, is essential for some physiological functions, including the synthesis of certain signaling molecules (Tallima and El Ridi 2018). Generally, an imbalance in the intake of omega-3 and omega-6 fatty acids, where omega-6 fatty acids predominate, has been associated with certain health concerns. The SFA levels varied among seasons and were the lowest fraction in the total FA profile of *H. dactylopterus.* The most dominant FA in this group was followed by palmitic acid (C16:0) and stearic acid (C18:0). High levels of saturated fatty acids (SFAs) in human foods are considered undesirable. SFAs can pose health risks, as elevated total cholesterol levels can lead to the formation of blockages in arteries, both in the heart and throughout the body (WHO 2016). Therefore, the observed FA variation seems to be closely affected by seasons, food availability, and reproduction. In terms of food quality, *H. dactylopterus* can be considered an interesting species due to its high protein, acceptable lipid levels, and nutritional omega-3 FAs.

Fatty acids, which are highly unsaturated and prominently present in fish tissues, are susceptible to

environmental fluctuations and the reproductive cycle of the species (Kumar et al. 2019). Our study revealed that the major Nutritional Quality Index (NQI) in both *H. dactylopterus* male and female specimens was lower during cold seasons compared to warmer ones. Intriguingly, only essential PUFA-6 exhibited an opposing trend, with an increase during cold seasons observed in both male and female fish. These variations can be attributed to the reproductive cycle, as the cold seasons align with the spawning period of *H. dactylopterus*. Importantly, our results highlight that *H. dactylopterus* flesh possesses superior nutritional quality with potential health benefits. This is evident in the higher PUFA3/PUFA6 ratio, surpassing the recommended ratio of 0.25 published by the UK Department of Health. These results underscore the positive impact of incorporating *H. dactylopterus* into human diets to enhance nutritional well-being. In general, *H. dactylopterus* sourced from northern Tunisia (GFCM-GSA 12) plays a crucial role in promoting human health, as evidenced by numerous studies conducted on fish sampled from the Tunisian coast (Ben Smida et al. 2014; Hajji et al. 2016).

Conclusion

This comprehensive study of *Helicolenus dactylopterus* in the southern Mediterranean Sea provides a detailed account of its seasonal reproductive cycle and associated energetic strategies. Our findings demonstrate significant seasonal variations in biological indices (GSI, HSI), allometric growth, and biochemical composition, all intrinsically linked to a defined cold season spawning period. The species mobilizes its energy reserves for reproduction, as evidenced by the significant winter depletion of hepatic glycogen, muscle lipids, and proteins. Despite this seasonal mobilization, *H. dactylopterus* maintains a consistently favorable nutritional profile year-round, characterized by high protein content and a valuable fatty acid composition dominated by PUFAs, with a high n-3/n-6 ratio beneficial for human health. These insights are crucial for sustainable management. The occurrence of spawning in winter highlights a period of peak vulnerability, suggesting that seasonal fishing restrictions could be a critical conservation measure. Furthermore, the demonstrated nutritional and commercial value of *H. dactylopterus* underscores the economic importance of ensuring its population sustainability in the Mediterranean Sea through informed management strategies.

Acknowledgements

The authors extend their appreciation to Taif University, Saudi Arabia, for supporting this work through project number (TU-DSPP-2024-158). The authors would like to thank the students from the ISSMB for their involvement in this work. We extend our gratitude to Ms. Hajer Zarouk for her proofreading and language editing.

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