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Seasonal Variations in Length-Weight Relationship and Condition Factor of Atlantic Mackerel (*Scomber scombrus*) in the Coastal Waters of Tripoli, Libya

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ABSTRACT

This study provides a comprehensive assessment of the length-weight relationship (LWR) and physiological condition of the Atlantic mackerel (*Scomber scombrus*) in Tripoli waters, Libya, based on seasonal sampling from Autumn 2022 to Summer 2023. A total of 120 specimens were collected, with 114 retained for final analysis (15.0–33.0 cm TL; 52.0–337.0 g TW) following the removal of six outliers. The overall LWR was established as $W=0.0109 \cdot L^{2.986}$ ($R^2=0.99$), indicating an isometric growth pattern ($b \approx 3.0$). However, seasonal regression analyses revealed highly dynamic growth strategies throughout the study period. The population exhibited strong negative allometry during Autumn 2022 ($b=1.546$) and Winter 2023 ($b=2.169$), transitioned to isometric growth in Spring 2023 ($b=2.712$), and shifted to positive allometry in Summer 2023 ($b=3.360$). Fulton's condition factor (K) mirrored these biological cycles, peaking in Winter 2023 (1.09±0.26) and reaching its minimum in Summer 2023 (0.92±0.07). Statistical analysis showed no significant sexual dimorphism in condition ($t=1.34$, $p=0.090$). One-way ANOVA confirmed that seasonal fluctuations in condition were statistically significant ($F=4.86, p=0.003$), reflecting the metabolic costs of reproduction and shifting environmental productivity. These findings highlight a unique growth response in the Tripoli population, underscoring the necessity of incorporating localized, seasonal coefficients into regional fisheries management for the Southern Mediterranean.

العلاقة بين الطول والوزن ومعامل الحالة الصحية لسمك الاسقمري -الكوالي- الأطلسي (*Scomber scombrus*) في المياه الساحلية لمدينة طرابلس، ليبيا

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تقدم هذه الدراسة تقييماً شاملاً لعلاقة الطول بالوزن (LWR) والحالة الفسيولوجية لأسماك الاسقمري–الكوالي– الأطلسي (*Scomber scombrus*) في مياه مدينة طرابلس، ليبيا، بناءً على عينات موسمية تم جمعها في الفترة من خريف 2022 إلى صيف 2023. تم جمع ما مجموعه 120 عينة، استُبقيت منها 114 عينة للتحليل النهائي (يتراوح الطول الكلي بين 15.0–33.0 سم، والوزن الكلي بين 52.0–337.0 جم) بعد استبعاد ست قيم شاذة. تم تحديد العلاقة الإجمالية بين الطول والوزن بالمعادلة التالية: $W=0.0109 \cdot L^{2.986}$ ($R^2=0.99$)؛ مما يشير إلى نمط نمو متماثل (isometric growth) حيث بلغت قيمة معامل النمو ($b \approx 3.0$) ، ومع ذلك، كشفت تحليلات الانحدار الموسمي عن استراتيجيات نمو ديناميكية للغاية خلال فترة الدراسة؛ حيث أظهرت الأسماك نمواً ألومترياً سالباً قوياً خلال خريف 2022 ($b=1.546$) وشتاء 2023 ($b=2.169$) ، ثم انتقلت إلى نمو متماثل في ربيع 2023 ($b=2.712$) ، لتتحول أخيراً إلى نمو ألومتري موجب في صيف 2023 ($b=3.360$). وقد انعكست هذه الدورات البيولوجية على معامل الحالة لـ "فولتون (K)"، الذي سجل أعلى قيمة له في شتاء 2023 (1.09±0.26)، تزامناً مع فترة ما قبل التبويض وتراكم الاحتياطات الطاقة، بينما سجل أدنى قيمة

له في صيف 2023 (0.92±0.07). أظهر التحليل الإحصائي عدم وجود فروق ذات دلالة إحصائية في معامل الحالة بين الجنسين(t=1.34,p=0.090) ، على الرغم من أن الإناث حافظت على متوسط معامل حالة أعلى قليلاً (1.018±0.23) مقارنة بالذكور (0.957±0.15). أكد اختبار تحليل التباين الأحادي (One-way ANOVA) أن التقلبات الموسمية في معامل الحالة كانت ذات دلالة إحصائية(F=4.86,p=0.003) ، مما يعكس التكاليف الأيضية للتكاثر وتغير الإنتاجية البيئية في جنوب البحر الأبيض المتوسط. تسلط هذه النتائج الضوء على استجابة نمو مرنة وفريدة لمجتمع هذه الأسماك في مياه طرابلس، مما يؤكد ضرورة إدراج معاملات النمو الموسمية والمحلية في نماذج إدارة المصايد وتقدير الكتلة الحيوية لأسماك الاسقمري الاطلسي في جنوب البحر المتوسط .

INTRODUCTION

The analysis of length-weight relationships (LWR) of fish species involves a variety of methodologies and approaches in order to understand more about the population structure, the growth rates of specific groups, and the general condition of the stock (Gonzalez Castrillon & Dominguez-Petit, 2026). These LWRs are key to estimating average weight at a length, converting length frequencies to biomass, and making cross population comparisons at various spatiotemporal scales (Kuriakose, 2017). LWRs help in developing growth models and in estimating the status of a population by converting field data to important biological parameters (Gonzalez Castrillon & Dominguez-Petit, 2026). This relationship can be expressed mathematically using a power function as:

$$W=aL^b$$

In this equation, W refers to the weight, L is the length, "*a*" is the growth intercept (initial growth coefficient) and "*b*" is the allometric coefficient. The parameter "*b*" is a key indicator of the species growth strategy. Specifically, it signifies whether the species growth is isometric (b=3) or allometric ($b\neq3$). This, in turn, conveys the positive or negative signs of the physiological status and structural adjustments of the population (Domínguez-Petit et al., 2022; Şen et al., 2024).

The Atlantic mackerel (*Scomber scombrus* Linnaeus, 1758), is an extremely mobile fish species that is important both commercially and ecologically. Atlantic mackerel are found throughout the Atlantic Ocean, Mediterranean Sea, and the Black Sea. *Scomber scombrus* are critical for the ecological stability in the marine trophic web. They are fundamental consumers of zooplankton and are prey for top-level marine predators like Atlantic cod, whales, and certain species of seabirds (Giannoulaki et al., 2017). Because the species is highly abundant and commercially valuable, it is fished in Europe and the Mediterranean, especially in Spain, Portugal, Turkey, and Greece (Bal & Türker, 2019) in addition to Libya and other north African states. This makes it vital for us to understand the life-history traits and reproductive biology of the fish in order to ensure sustainable fishing of the species (El-Aiatt & Shalloof, 2020).

Research shows the biological metrics of *S. scombrus* are not fixed and vary with seasonal cycles of the environment, as influenced by climatic variations (water temp, food, and man-induced changes) (Sinovčić, 2001). The last few decades have seen the Mediterranean populations demonstrate significant changes in demographics and 'miniaturization'. This is the phenomena of diminished adult sizes, shorter lifespans, and an earlier onset of sexual maturity compared to the earlier data sets (Meneghesso et al., 2013). Historical studies in the Adriatic Sea documented ages of up to 9 years, now the stock are considerably younger and, in some cases, have maximum ages of 3 (Bottari et al., 2004; Meneghesso et al., 2013). The recent ecological changes, such as the mucilage events in the Sea of Marmara, have required a re-evaluation of the condition factors and growth parameters in the small adults and juvenile (Şen et al., 2024).

Understanding *S. scombrus* in some areas of the Mediterranean has been limited due to data being either fragmented or outdated, especially regarding how these stocks respond to changing climate scenarios and local environmental stressors. Although historical data shows a baseline, environmental changes at a rapid pace require contemporary analysis to aid in the changes of management reference points and habitat suitability models (Giannoulaki et al., 2017). The absence of up-to-date data on LWR and condition factors will likely lead to incorrect biomass estimations, resulting in poor management choices, which will threaten the long-term sustainability of the stock (Dürrani, 2023).

The primary objective of this research is to characterize the biometric and physiological profile of the Atlantic mackerel (*Scomber scombrus*) population inhabiting the coastal waters of Tripoli, Libya. Specifically, this study aims to quantify morphometric variability by establishing seasonal baseline distributions for total length and weight, while simultaneously determining the length-weight relationship (LWR) to define the species' growth dynamics—ranging from isometric to allometric—within the southern Mediterranean ecosystem. Furthermore, the study evaluates the physiological well-being of the population using Fulton's condition factor (K), investigating the potential influences of sexual dimorphism and seasonal biological cycles on energy reserves. By synthesizing these biometric parameters, this research seeks to elucidate the seasonal periodicity of growth strategies and metabolic costs, providing critical insights into how reproductive phases and environmental fluctuations impact the life history of this stock.

MATERIALS AND METHODS

I. Study Area and Research Design

The study was conducted along the Mediterranean coast of Tripoli, Libya, a region characterized by its productive shelf waters and significant commercial fishing activity. Sampling was conducted seasonally to capture the biological variations across the annual cycle: Autumn (n=30), Winter (n=30), Spring (n=30), and Summer (n=30). Following collection, specimens were transported to the laboratory for immediate biometric processing. This temporal framework was selected to account for the previously reported influence of seasonal environmental fluctuations—such as sea surface temperature and prey availability—on the physiological condition and growth dynamics of the Atlantic mackerel (*Scomber scombrus*) (Giannoulaki et al., 2017). Sampling was strategically timed to encompass the species' vital biological cycles, including the peak spawning periods observed in Mediterranean stocks (El-Aiatt & Shalloof, 2020).

II. Sampling and Biological Data

A total of 120 specimens of *S. scombrus* were obtained through random sampling of commercial catches at major landing sites and local Bab Elbahar fish market in Tripoli. Samples were collected monthly to ensure representative seasonal coverage. To maintain biological integrity, specimens were transported to the Department of Biology laboratory within insulated containers with ice. Biological data collection followed standardized ichthyological protocols (Kuriakose, 2017). Total length (TL) was measured from the tip of the snout to the longest caudal fin ray using a graduated measuring board accurate to 0.1 cm. Total weight (W) was recorded using a high-precision electronic digital balance (icVantA model no. B0D9LR4RB7) with an accuracy of 0.001 g.

III. Laboratory Procedures

Upon arrival at the laboratory, fish were rinsed with distilled water to remove debris and excess mucus. To mitigate measurement bias, all biometric assessments were performed by the same researcher using calibrated instruments. To ensure data quality, any specimens showing signs of physical damage or dehydration that could skew weight measurements were excluded from the final analysis. To confirm the species as Atlantic Mackerel, the characteristic feature of gas bladder absence (Chanet & Guintard, 2019) was used as key taxonomic confirmation evidence.

IV. Data Analysis and Equations

Out of the 120 collected specimens, 6 outliers were discarded based on residuals (> 2 SD) from the initial regression, 114 individuals were retained for the final LWR analysis. The relationship between total length and total weight was calculated using the non-linear power function (Kuriakose, 2017):

$$W=aL^b$$

where a is the intercept (condition factor) and b is the slope (growth exponent). To estimate these parameters, the data were log-transformed (base10) into a linear regression model:

$$log_{10}(W)=log_{10}(a)+blog_{10}(L)$$

Following the methodology of Froese (2006), the log-log plots were visually inspected for anomalies. To ensure the "best fit" reflected the majority of the population, a robust regression was performed where outliers—defined as individuals with residuals exceeding two standard deviations (±2SD) from the initial regression line—were excluded.

The allometric coefficient (b) was utilized to determine growth types: isometric growth (b=3), positive allometric growth (b>3), or negative allometric growth (b<3). Furthermore, the physiological well-being of the fish was evaluated using Fulton's Condition Factor (K), calculated as (Nash et al., 2006):

$$K=100\times(W/ L^3)$$

where 100 is a factor used to bring the value of K near unity. The growth pattern was classified as isometric if the slope (b) was equal to 3.0. Independent t-test was employed to test whether differences in condition factor (K) is statistically different between males and females. All statistical analyses were performed at a 95% confidence level (α=0.05).

RESULTS AND DISCUSSION

The biometric analysis of 120 *Scomber scombrus* specimens collected from Tripoli, Libya, yielded a total length (TL) range of 15.0 to 33.0 cm and a total weight (W) range of 52.0 to 337.0 g. Descriptive statistics categorized by season are detailed in Table 1.

Table 1. Seasonal Mean Length (cm) and Weight (g) for *Scomber scombrus* collected from Tripoli waters, Libya in 2022-2023.

Season	n	Length Range (cm)	Mean Length ± SD (cm)	Weight Range (g)	Mean Weight ± SD (g)
Autumn 2022	26	19.0 – 25.0	22.05 ±1.48	82 – 155	111.04 ±17.73
Winter 2023	28	15.0 – 32.0	22.62 ±4.48	58 – 276	128.21 ±59.78

Spring 2023	30	21.0 – 33.0	25.78 ±3.37	104 – 337	171.63 ±66.44
Summer 2023	30	20.5 – 30.0	25.12 ±2.46	68 – 257	151.17 ±50.43

The relationship between total length (L, cm) and total weight (W, g) was described by the power function:

$$W = 0.0109 \cdot L^{2.986} \ (R^2 = 0.99)$$

The model showed a high coefficient of determination (R^2 = 0.99), indicating that length explained most of the observed variation in weight. The allometric growth exponent b = 2.986 did not differ significantly from the isometric value of 3 (P<0.001), suggesting an isometric growth pattern for this population.

When analysed by sex, the length-weight relationship demonstrated that both sexes exhibited near isometric growth, though the coefficients differed. For females (N=66), the relationship was established as $W=0.0105 \cdot L^{2.997}$ (R^2=0.99, P<0.001). For males (N=48), the relationship was calculated as $W=0.0116 \cdot L^{2.986}$ (R^2=0.98, P<0.001).

Seasonal regression analyses indicated that the allometric coefficient (*b*) fluctuated significantly throughout the study period (Figure 2, Table 2). In Autumn 2022 (*b*= 1.546) and Winter 2023 (*b* =2.169), the species exhibited negative allometric growth. Spring 2023 was characterized by isometric growth (*b* =2.712), while Summer 2023 showed positive allometric growth (*b* =3.360).

Table 2 Seasonal length-weight relationship (LWR) parameters for *Scomber scombrus* collected from Tripoli waters, Libya in 2022-2023.

Season	n	Intercept (a)	Slope (b)	R2	P-isometry (b=3)	Growth Type
Autumn 2022	26	0.9230	1.546	0.458	< 0.001	Negative Allometric
Winter 2023	28	0.1389	2.169	0.882	< 0.001	Negative Allometric
Spring 2023	30	0.0244	2.712	0.914	0.077	**Isometric**
Summer 2023	30	0.0029	3.360	0.960	0.009	Positive Allometric

Length-Weight Relationship

The relationship between total length (TL) and total weight (W) for the Atlantic mackerel (*Scomber scombrus*) population in Tripoli, Libya, was determined using a robust regression analysis (Figure 1). Based on the analysis of 114 specimens, the resulting power function was established as:

$$W=0.0109 \cdot L^{2.986}$$

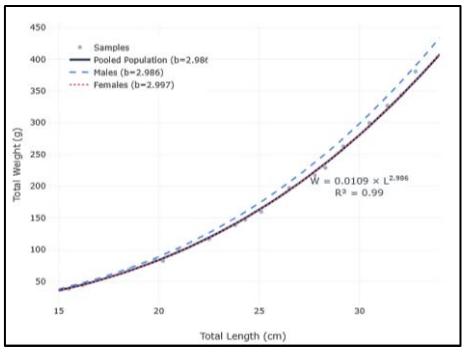

Figure 1. Length-weight relationship of *Scomber scombrus* from Tripoli waters. The solid line represents the robust best fit ($W=0.0109 \cdot L^{2.986}$), indicating an isometric growth pattern (b≈3.0) for the pooled population. Dashed lines represent sex-specific fits, showing no statistically significant difference in growth strategy between males and females (p=0.090).

When LWR was investigated by sex, both male and female *S. scombrus* exhibited isometric growth type, though males demonstrated a slightly lower coefficient (*b*=2.986) compared to females (*b*=2.997). This very slight difference in somatic growth rates between sexes is frequently observed in pelagic species and is typically attributed to the differential energetic costs of reproduction (Bottari et al., 2004). Females often channel a significantly larger proportion of their energy reserves into gonadal development and egg production, resulting in a slenderer somatic profile relative to their length, particularly during and immediately following the spawning season.

The length-weight relationship for the pooled population was expressed by the equation: $W = 0.0109* TL^{2.986}$, R^2 = 0.99). The growth coefficient (b) was found to be 2.986, which is not significantly different from the theoretical value of 3.0 (t-test, p > 0.05), indicating an **isometric growth pattern**. Seasonal analysis showed that *b* values ranged from 2.502 in Autumn to 3.056 in Winter (Table 2), suggesting a stable growth strategy for the Tripoli population compared to other regional stocks compared to other regional stockssuch as the Gulf of Tunis (b=3.37) (Cherif et al., 2008) and the Gulf of Gabes (b= 3.24) (Ghailen et al., 2013) , suggesting that the Tripoli population exhibits a distinct growth strategy influenced by marine environmental productivity and food availability. The transition of the b value from 1.546 in Autumn to 3.360 in summer highlights a distinct seasonal growth strategy (Table 2, Figure 2). The isometric growth observed in Spring (b=2.712) aligns with the reproductive cycle of Mediterranean mackerel, which are typically winter spawners (El-Aiatt & Shalloof, 2020). The subsequent shift to positive allometry in Summer indicates a post-spawning recovery phase characterized by rapid weight gain relative to length.

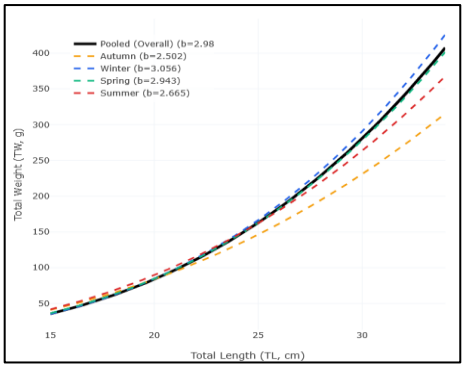

Figure 2. Comparative seasonal length-weight relationships of Scomber scombrus. The solid black line represents the pooled population (b = 2.986). Axes are set to originate from zero to show the full growth trajectory. Summer exhibits positive allometric growth (b = 3.360), while Autumn (b = 1.546) and Winter (b = 2.169) show significant negative allometric growth reflecting shifts in environmental and physiological conditions associated with the pre-spawning season

Sexual Variation in Condition Factor

The data indicates a slight difference in the physiological status between the sexes, though it did not reach statistical significance at the standard α=0.05 level.

Condition Factor (K): Female specimens exhibited a higher mean condition factor (1.018±0.224) compared to their male counterparts (0.957±0.210). This suggests that while females may prioritize length over mass as they grow, they maintain sufficient physiological reserves to remain on par with males in overall condition.

An independent t-test was conducted to evaluate these differences (t=1.34, P=0.090). The results suggest that while females appear to be in slightly better physiological condition, the difference between sexes in this population is not statistically significant.

Seasonal Variation in Condition Factor

Seasonal fluctuations in the condition factor were more pronounced (Table 2)., likely reflecting the biological cycles and environmental variations of the Mediterranean ecosystem (Bouzzammit et al., 2022)

The highest mean condition factor was observed in Winter 2023 (K=1.09), Table 3. This suggests that despite colder temperatures, the fish maintained high energy reserves or were preparing for spawning. Interestingly, while Summer 2023 had the highest growth slope (b=3.36), its mean condition factor was the lowest (0.92). This often occurs in fish populations where rapid length growth slightly outpaces the volumetric accumulation of mass, or indicates post-spawning weight loss. Summer 2023 also showed the lowest Standard Deviation (0.07), indicating that the population was in a very uniform physiological state compared to the high variability seen in Winter (0.26).

The higher condition factor in females (1.018) compared to males (0.957) aligns with reproductive biology trends observed in other Mediterranean regions, where females often maintain higher energy reserves for egg production (Giannoulaki et al., 2017). However, the lack of statistical significance (p>0.05) suggests that for the population in Tripoli, both sexes are exposed to similar environmental pressures and feeding opportunities during the study period. The peak condition observed in Winter (1.0901.0586) coincides with the accumulation of somatic energy before the peak spawning period typically recorded between December and March in the Mediterranean (El-Aiatt & Shalloof, 2020). The subsequent decline through Spring and into Summer (0.967 to 0.919) reflects the metabolic cost of reproduction and the influence of rising water temperatures on fish physiology.

The comparative analysis for sexual (independent t-test) and seasonal (One-Way ANOVA) variations in the Fulton's Condition Factor (k) of the studied Atlantic mackerel are detailed in Table 3.

Table 3. Fulton's Condition Factor (K) for *Scomber scombrus* by fish sex and across seasons.

Factor	Group	Mean *K* (±SD)	Statistical Test	Value	p-value
Sex	Female	1.018 ± 0.23	Independent t-test	t = 1.34	0.090
	Male	0.957 ± 0.21			
Season	Autumn 2022	1.04 ± 0.17	One-way ANOVA	F = 4.86	0.003
	Winter 2023	1.09 ± 0.26			
	Spring 2023	0.97 ± 0.11			
	Summer 2023	0.92 ± 0.07			

The mean *K* values reported here (Table 3) are consistent with studies from the Sea of Marmara (Bal & Türker, 2019; Şen et al., 2024) and the Adriatic Sea (Bottari et al., 2004; Sinovčić, 2001), confirming that *S. scombrus* in the Southern Mediterranean follows the same general health trends as Northern Mediterranean stocks, despite differences in absolute growth coefficients (b).

A one-way ANOVA was utilized to compare K values across all four seasons. The analysis revealed a statistically significant difference in fish condition between seasons (F=4.86, p=0.003). Post-hoc analysis indicates that the condition factor was highest in Winter (1.09 ±0.26) and declined significantly toward Summer (0.919 ±0.07).

Despite the significant findings, this study is subject to certain limitations. The sample size (n=114), while sufficient for a localized assessment, may not fully capture the broader migratory dynamics of the species

across the Libyan coast. Furthermore, the absence of concurrent environmental data (e.g., water temperature and prey density) limits the ability to explicitly link physiological shifts to specific external stressors. Future research should incorporate multi-year sampling and satellite-derived environmental metrics to further validate these seasonal growth models.

CONCLUSION

This study confirms that *Scomber scombrus* in the coastal waters of Tripoli exhibits a stable **isometric growth pattern** (b = 2.986), indicating that the species maintains its body shape as it grows. Significant seasonal variations in the condition factor were observed, peaking in Winter (K = 1.09), likely linked to pre-spawning physiological preparation. These findings provide essential baseline data for the sustainable management of mackerel stocks in the Southern Mediterranean.

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