ORIGINAL ARTICLE

Food Chemistry, Engineering, Processing and Packaging

Age-Dependent Parameters of the Von Bertalanffy (1938) Growth Model: A Case Study of *Sardinella aurita* (Valenciennes, 1847) along the Central Algerian Coast (Southeastern Mediterranean Sea)

Ryma Azaoui [1] ✉ **Mohamed Toumi** [1] **Rachid Amara** [2]

[1] University of Algiers 1, Faculty of Sciences, Department of Natural and Life Sciences, Laboratory of Living Resources of Economic Interest in Algeria (REVIECO), 2 Didouche Mourad Street, Algiers, Algeria r.azaoui@univ-alger.dz / m.tomi@univ-alger.dz

[2] Univ. Littoral Côte d'Opale, CNRS, IRD, Univ. Lille, UMR 8187, LOG – Laboratoire d'Océanologie et de Géosciences, Wimereux, F-62930, France rachid.amara@univ-littoral.fr

ABSTRACT

Background: Small pelagic teleosts, notably the round sardinella (*Sardinella aurita*), constitute a fundamental component of marine ecosystem structure and reinforce regional food security. Nevertheless, the long-term sustainability of these stocks is increasingly threatened and compromised by synergistic pressures of intensive fishing exploitation and fluctuating environmental factors.

Aims: This study aimed to introduce a modified growth model for short-lived pelagic fish that integrates age-dependent variability with the objective of refining biomass estimates and optimizing stock assessment protocols.

Methods: Monthly biological sampling was conducted from January to December 2023 along the central Algerian coast, yielding a total of 1,128 specimens. Two distinct growth formulations were evaluated: the conventional von Bertalanffy Growth Function (VBGF), which assumes a constant growth coefficient K, and an age-dependent approach in which the parameters (K_n, $L\infty_n$) were estimated independently for each identified age cohort.

Results: Comparative analysis revealed two distinct growth scenarios. The conventional VBGF scenario, characterized by slow growth (K = 0.31 year^{-1}, $L\infty$ = 30.90 cm), projected a maximum lifespan (T_{max}) of 10 years. Conversely, the age-structured model (K_n) exhibited rapid early growth (K_1 = 2.27 year^{-1}) that progressively decelerated to 0.46 year^{-1} by age five, projecting a maximum lifespan of 7 years — although only five age classes were resolved from the sampled population, likely attributable to intense fishing pressure. Asymptotic lengths ($L\infty_n$) ranged from 9.35 cm at age one to 25.10 cm at age five. The growth performance index (Φ') varied from 2.29 to 2.50 across age classes, with a coefficient of variation (CV) of 4%. Total mortality (Z) was estimated at 3.97 year^{-1}. Under the age-structured scenario, natural mortality (M) decreased with age, from 1.10 year^{-1} at age one to 0.43 year^{-1} at age five, in contrast to a static baseline M 0.39 year^{-1} across all cohorts; meanwhile, fishing mortality (F) increased with age, from 2.87 year^{-1} at age one to 3.54 year^{-1} at age five, compared to a constant F of 3.58 year^{-1}.

Conclusions: The age-dependent model (K_n) offers a more robust and biologically realistic depiction of the growth and life-history dynamics of *S. aurita*, thereby supporting sustainable management practices that account for rapid early growth and reproductive energy allocation. This data-parsimonious mathematical framework offers a highly practical alternative for stock assessments in data-limited fisheries, particularly where complex bioenergetic modeling is logistically unfeasible.

Keywords: Pelagic Species; Age Structure; Growth Coefficient; Bioenergetics; Food Security; Mediterranean Sea.

Article Information

✉ **Corresponding authors:** Ryma Azaoui
E-mail : r.azaoui@univ-alger.dz / azaouiryma@hotmail.com
Tel. (+213) 542 606 613

Received: July 13, 2025
Revised: May 18, 2026
Accepted: June 03, 2026
Published: June 16, 2026

Cite this article as: Azaoui, R., Toumi, M., & Amara, R. (2026). Age-Dependent Parameters of the Von Bertalanffy (1938) Growth Model: A Case of *Sardinella aurita* (Valenciennes, 1847) Along The Central Algerian Coast (Southeastern Mediterranean Sea). *The North African Journal of Food and Nutrition Research, 10* (21): 223–233.https://doi.org/10.51745/najfnr.10.21.223-233

1 INTRODUCTION

Pelagic fish, such as sardines, anchovies, and herring, play an essential role not only in marine ecosystems but also in global food security. These small fish provide high-quality proteins and beneficial omega-3 fatty acids, contributing to the diets of human populations (Tacon & Metian, 2013; Sabu, 2024). Additionally, they enhance food security for coastal communities by providing essential nutrients, which could reduce the risk of non-communicable diseases (NCDs) related to dietary imbalances, especially in the context of climate change (Savage *et al.*, 2020).

These species represent approximately 25 – 30% of the global marine catch (Hilborn *et al.*, 2022; Peck *et al.*, 2021) and are particularly significant in regions such as the Mediterranean and West Africa, where they can constitute up to 85% of landings (Sabatés *et al.*, 2009). In nutrient-rich

areas such as the Humboldt and Canary Currents, these fish support the livelihoods of local fishermen and provide sustenance for communities (Dahel *et al.*, 2024; Fréon *et al.*, 2005).

However, the sustainability of pelagic fish is increasingly threatened by overfishing, climate change, and pollution, exacerbating the vulnerability of already fragile stocks (Costello *et al.*, 2016; Dahel *et al.*, 2024). To address these challenges, this study proposes the K_n model, an innovative framework designed specifically for short-lived pelagic species. Unlike traditional models, this approach dynamically adjusts the growth coefficient between age classes, reflecting the progressive reallocation of energy from somatic growth to reproduction after sexual maturity — a fundamental biological trade-off that constant-parameter models cannot capture.

Conventional models, such as the von Bertalanffy growth model (VBGM), often fail to accurately depict the growth of short-lived pelagic species due to their fixed parameters, which overlook age-related variability (Baldé *et al.*, 2019; Van Poorten *et al.*, 2018). In contrast, the K_n model incorporates a flexible growth coefficient that decreases with age—starting high in younger individuals to enhance growth, then declining progressively to prioritize reproduction. It is crucial to note that this does not constitute a novel growth equation per se, but rather an estimation procedure that discretizes the conventional VBGM on a per-age-class basis. This approach responds to recent methodological recommendations advocating the explicit integration of age-related growth variability into stock assessment models (Lee *et al.*, 2020; Van Poorten *et al.*, 2018), particularly for short-lived, fast-growing species subject to intense fishing pressure, for which misspecification of growth can result in positive bias in management quantities such as stock depletion (Correa *et al.*, 2021). To this end, this study aimed to provide a robust and replicable methodological framework that could be extended to further Mediterranean small pelagic stocks with *r*-selected life-history strategies, where dynamic, age-specific growth parameters are essential for accurate biomass estimation and sustainable quota setting.

While advanced models such as the Dynamic Energy Budget (DEB) and individual-based models (IBM) offer improvements, their complexity and data requirements can be impractical for resource-limited fisheries (David *et al.*, 2019; Martin *et al.*, 2012; Liu *et al.*, 2023). The K_n approach incorporates age-related growth variability, reducing uncertainty in stock assessments and supporting marine sustainability initiatives, particularly in line with Sustainable Development Goal 14 (Pikitch *et al.*, 2004).

2 Material and Methods

2.1 Data Collection

Monthly sampling was conducted from January to December 2023 along the central Algerian coast, specifically between Tenes (36° 34' 44'' N; 1° 18' 16'' E) and Dellys (36° 54' 48'' N; 3° 54' 51'' E) (Figure 1). This area was selected for its ecological representativeness of the Mediterranean small pelagic habitats and socioeconomic reliance on *Sardinella* fisheries. Fish specimens were collected monthly from commercial landings at the fishing ports of Algiers (Central Algeria). Sampling was conducted randomly to ensure a representative distribution of the size classes available in the landings. A total of 1,128 specimens were sampled over a one-year period, with the monthly effort (**n**) ranging from 11 in March to 163 in October

Figure 1. Geographic Location of the Central Algerian Coast

(Supplementary Data). Total length (TL) was recorded to the nearest 0.1 cm, while body weight was measured to ± 0.01 g.

2.2 Age Estimation

Age cohorts were resolved employing the Bhattacharya method (1967) in FISAT II v1.2.2 (Gayanilo *et al.*, 2005) to obtain initial estimates, followed by refinement through the NORMSEP (Normal Separation) program (Gayanilo *et al.*, 2005). This method is recommended for small pelagic fish and effectively decomposes age cohorts from size distributions. Although otolith-based aging provides superior precision for individual age determination, it was not employed in the present study. The Bhattacharya method was selected because: (1) it constitutes the standard approach recommended by FAO for length-frequency-based stock assessments of small pelagic fish in the Mediterranean Sea (Gayanilo *et al.*, 2005); (2) the method is prescribed by the Dynamics of Marine Populations (DYNPOP) working group of the Mediterranean Science Commission (CIESM) (Bouaziz *et al.*, 2014); and (3) otoliths of *S. aurita* in the Mediterranean Sea often display multiple hyaline rings per year due to thermal stress, making annual age reading ambiguous without prior validation studies (Campana & Jones, 1992; Morales-Nin & Panfili, 2002).

2.3 Growth Parameters

Two approaches were compared:

A. Conventional von Bertalanffy Growth Model, 1938 (*K*)

Growth parameters (***K, L∞***) were estimated using the ELEFAN I algorithm in FISAT II v1.2.2 (Gayanilo *et al.*, 2005). The von Bertalanffy Growth Model (VBGM) is expressed as:

$$L_t = L\infty \times 1 - \exp^{-K \times (t - t_0)} \quad \text{..... (1)}$$

Where L_t represents the mean length at age t (cm), $L\infty$ represents the asymptotic length (cm), K denotes the growth coefficient (year^{-1}), and t_0 is the theoretical age at which the length is zero (years).

B. Age-Dependent Growth Model (K_n)

To accommodate age-related growth variations, the conventional VBGM was discretized to estimate age-specific parameters (K_n, $L\infty_n$):

$$L_t = L\infty_n \times 1 - \exp^{-K_n \times (t - t_0)} \quad \text{..... (2)}$$

The maximum observed length for each age class ($L_{max(n)}$) is estimated as:

$$L_{max\ (n)} = L_t + SD_n$$

Where L_t is the predicted mean length at age **n**. **SD** is the standard deviation of lengths for age class **n**.

- **Asymptotic length ($L\infty_n$)**

According to Taylor (1958 *in* Froese & Palomares, 2000), the lifespan of fish can be estimated by determining the age at which they attain 95% of L∞, using the following formula:

$$A_p = t_0 - \frac{ln(1-p)}{K}$$

For each age (**n**), the asymptotic length is adjusted as follows (Pauly, 1980):

$$L\infty_n = \frac{L_{max\ (n)}}{0.95}$$

In this context, A_p represents the lifespan in years, t_0 and K are the parameters of the von Bertalanffy growth model (VBGM), and p indicates a fraction of $L\infty$, specifically 0.95 in this instance.

To isolate K_n in the equation (2), the following steps are applied:

Divide both sides by $L\infty_n$:

$$\frac{L_t}{L\infty_n} = 1 - exp^{-k_n \times (t - t_0)}$$

Subtract 1 from both sides:

$$\frac{L_t}{L\infty_n} - 1 = exp^{-k_n \times (t - t_0)}$$

Multiply both sides by -1:

$$\frac{L_t}{L\infty_n} = exp^{-k_n \times (t - t_0)}$$

Take the natural logarithm of both sides:

$$Ln\left(1 - \frac{L_t}{L\infty_n}\right) = -K_n \times (t - t_0)$$

Solve for K_n:

$$K_n = \frac{-ln(1 - \frac{L_t}{L\infty_n})}{(t - t_0)}$$

- **Estimation of Theoretical Age (t_0)**

The theoretical age (t_0) is estimated employing the empirical formula of Pauly (1980):

$$\log_{10}(-t) = -0.39922 - 0.2752 \times \log_{10} L\infty - 1.038 \log_{10} K$$

For the present study, the theoretical age at zero length (t_0) was fixed at zero across all age classes, as is standard practice in length-frequency-based assessments of Mediterranean small pelagics (Gayanilo *et al.*, 2005; Sparre & Venema, 1998). This assumption may lead to a slight overestimate of K_n for younger cohorts, but the effect is systematic and does not alter the downward trend in K_n with age.

- **Estimation of Maximum Age (T_{max})**

Longevity (T_{max}) was calculated employing the formula by Hattour *et al.* (2004):

$$T_{max} = \left(\frac{2.9957}{K}\right) + t_0$$

In the age-dependent scenario, $T_{max(n)}$ was computed by substituting K_n into the above equation.

- **Performance index (Φ')**

The growth performance index (Φ') proposed by Pauly & Munro (1984) is:

$$\Phi' = \log_{10}(K) + 2 \times \log_{10}(L\infty)$$

In the age-dependent framework, this was determined as Φ'_n using K_n and $L\infty_n$ for each specific cohort.

2.4 Mortality Rates

The constant total mortality rate (Z) was estimated through the length-converted catch curve, linearized with FISAT II. The age-specific natural mortality coefficient (M_n) was calculated for each age class via the empirical formula of Djabali *et al.* (1993):

$$log_{10}(M_n) = -0.0278 - 0.1172 \times log_{10}(L_{\infty n}) + 0.5092 \times log_{10}(K_n)$$

Fishing mortality for each age class (F_n) was then derived as:

$$F_n = Z - M_n$$

3 Results

3.1 Age Estimation

The size analysis identified five age groups, all with a separation index (SI) exceeding 2 (Gayanilo *et al.*, 2005), confirming the statistical distinctiveness of each cohort (Table 1 and Figure 2). Individuals aged one year averaged 7 – 9 cm, while those aged five years reached 22 – 25 cm. The specimens varied in total length from 7.1 cm to 25.4 cm. The most abundant age groups were two and three years, representing 34.17% and 57.35% of the catches, respectively. The SI threshold of 2 ensures that the identified components are statistically distinct and reliable, even for the youngest age classes where sample sizes were more limited.

Table 1. Age–Length Key for *S. aurita* from the Central Region of the Algerian Coast

Age	$L_t \pm$ SD	N	SI
1	8.38 ± 0.5	5.16	N/A
2	12.04 ± 1.15	385.45	4.457
3	16.12 ± 1.49	646.9	3.099
4	20.46 ± 0.5	19.13	4.363
5	22.57 ± 1.27	71.36	2.384

Note: L_t: cohort mean length (cm); SD: standard deviation; N: cohort size; and SI: separation index (must be > 2). N/A: not applicable (first cohort has no preceding reference group).

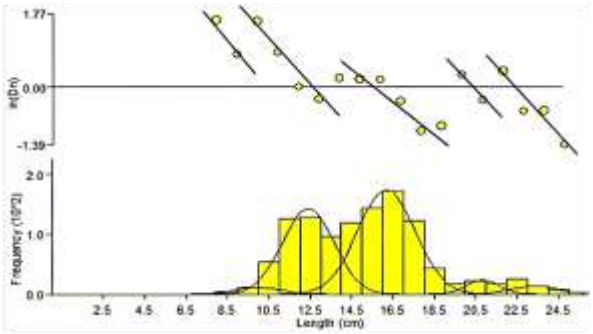

Figure 2. Size-Frequency Distribution Decomposition of *S. aurita* from the Central Algerian Coast (Bhattacharya method, 1967, in FISAT II v1.2.2, 2005)

3.2 Growth Parameters

Conventional Approach (K): Von Bertalanffy Model

The conventional approach assumes a constant growth rate throughout an individual's life as displayed in Table 2. The results indicated a growth coefficient (K) of 0.30 year^{-1}, a maximum asymptotic length ($L\infty$) of 30.90 cm, and a theoretical age (t_0) of 0 years. The growth performance index (Φ') was estimated at 2.46. Notably, $L\infty$ (30.90 cm) substantially exceeds the largest individual observed (L_{max} = 25.4 cm).

Age-Dependent Approach (K_n)

Under the age-dependent growth framework, the growth rate exhibited distinct age-specific variations, as illustrated in Table 2. Specifically, the growth coefficient (K_n) decreased from 2.27 year^{-1} at age 1 to 0.46 year^{-1} at age 5, representing an approximate 80% reduction over the lifespan. Correspondingly, asymptotic lengths ($L\infty_n$) ranged from 9.35 cm at age 1 to 25.10 cm at age five. Based on the growth coefficient of the oldest resolved cohort (K_5 = 0.46 year^{-1}), the predicted maximum lifespan ($T_{max(n)}$) was estimated to be 7 years. Overall, five distinct age classes were identified within

Table 2. Growth Parameters of *S. aurita* from the Central Region of the Algerian Coast: Classical and Developed Approaches

Approach	Age	L_{max}	$L\infty$	K	t_0	Φ'	T_{max}
Classical	-	25.4	30.90	0.30	0	2.46	10
Age-dependent (K_n)	1	8.88	9.35	2.27	0	2.30	1
	2	13.19	13.88	1.01	0	2.29	3
	3	17.61	18.53	0.68	0	2.37	4
	4	20.96	22.06	0.66	0	2.50	5
	5	23.84	25.10	0.46	0	2.46	7

Note: L_{max}: maximum observed length (cm); $L\infty$: asymptotic length (cm); K: growth coefficient (year-1); t_0: theoretical age at zero length (year); Φ': growth performance index; and T_{max}: predicted maximum age (year).

the sampled population. The growth performance index (Φ'_n) varied from 2.29 at age 2 to 2.50 at age 4, demonstrating high stability with a coefficient of variation (CV) of 4%.

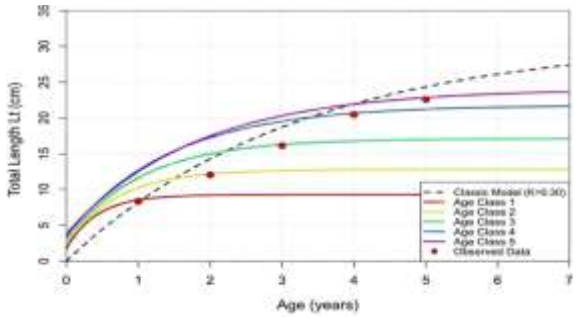

Figure 3. Comparison of *S. aurita* Growth Curves: Classic von Bertalanffy Model Versus Age-Class Adjusted Models Based on Observed Data from the Central Algerian Coast

Figure 3 displays comparison between the conventional VBGM curve and the five age-class-adjusted curves. The empirical data (observed mean lengths per cohort) align more closely with the age-specific curves than with the dashed global curve, supporting the biological relevance of the age-dependent parameterization.

3.3 Mortality Rates

Total mortality (Z) was estimated at 3.97 year^{-1} utilizing $L\infty$ = 30.90 cm and K = 0.30 year^{-1} in the length-converted catch curve, as displayed in Figure 4. Age-specific natural mortality (M_n) was calculated through the equation of Djabali *et al.* (1993) with age-specific parameters K_n *and* $L\infty_n$ (Table 2). The results indicate that M_n decreases significantly with age, from 1.10 year^{-1} at age 1 (M_1) to 0.43 year^{-1} at age 5 (M_5). This contrasts with the constant natural mortality rate of 0.39 year^{-1} within the conventional approach (Table 3).

4 Discussion

The present investigation analyzed the size-frequency distributions of *S. aurita* along the central Algerian coast, revealing an age-length structure consistent with findings of Bouaziz & Caddy (1998) and Bouaziz (2007), and Dahel *et al.* (2024), who employed similar length-frequency decomposition methods for Algerian coastal populations. The observed size overlap within age groups reflects individual variability in growth rates, a common attribute in small pelagic fish populations (Panfili *et al.*, 2002). Maximum longevity in *S. aurita* has been estimated at up to seven years in less-exploited Atlantic populations (Korichi, 1988; Szypuła, 1973), whereas recent Mediterranean studies

Table 3. Variations in Natural Mortality (M_n) of *S. aurita* by Age

Approach	Age	Z	M	F
Classical	-	3.97	0.39	3.58
Age-dependent (M_n)	1	3.97	1.10	2.87
	2	3.97	0.69	3.28
	3	3.97	0.55	3.42
	4	3.97	0.53	3.44
	5	3.97	0.43	3.54

***Note:* Z**: total mortality (year^{-1}); **M**: natural mortality (year^{-1}); and **F**: fishing mortality (year^{-1})

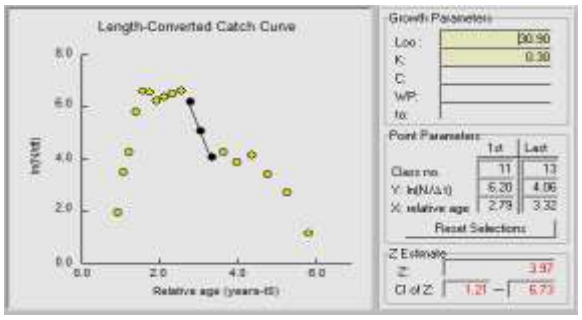

Figure 4. Estimation of Total Mortality (Z) utilizing the Length-Converted Catch Curve for *S. aurita* (FISAT II v1.2.2) - Filled circles (●) indicate points utilized in the regression

consistently report shorter lifespans of five to six years, reflecting the combined effects of higher fishing pressure and distinct environmental conditions (Dahel, 2018; Handjar, 2019; Jurado-Ruzafa *et al.*, 2020). Residual discrepancies among studies are attributable to methodological differences in age determination and interannual environmental variability.

The growth parameters were evaluated under two comparative frameworks. The conventional approach, assuming a constant growth rate (K = 0.30 year^{-1}), falls below the threshold of 0.34 year^{-1} proposed by (Kienzle, 2005). While this outcome aligns with the slow-growth paradigm documented in eastern Mediterranean cohorts (Ananiades, 1952; Mustać & Sinovčić, 2011), it stands in contrast to recent Mediterranean investigations wherein K values range between 0.34 and 0.68 year^{-1} (Benamar, 2019; Dahel *et al.*, 2024; Handjar, 2019; Gomes *et al.*, 2024). This divergence is attributable to the low curvature of the VBGM induced by under-representation of large individuals — a structural consequence of intense fishing pressure on the central Algerian coast (Baldé *et al.*, 2019; Jurado-Ruzafa *et al.*, 2020). Furthermore, $L\infty$ = 30.90 cm substantially exceeds the maximum observed size (L_{max} = 25.4 cm), a known artifact of VBGM fitting to truncated length distributions (Froese & Palomares, 2000). The growth performance index (Φ' = 2.46) falls within the range of 2.28 – 2.74 defined for *S. aurita* in the Mediterranean Sea (Benamar, 2019; Handjar, 2019).

The age-dependent approach (K_n ranging from 2.27 year^{-1} at age 1 to 0.46 year^{-1} at age 5) is more consistent with the biological reality of a short-lived pelagic species. The approximately 80% reduction in K_n across age classes mirrors the progressive reallocation of energy from somatic growth toward reproduction after sexual maturity (Casselman, 1996; Lee *et al.*, 2020; Stearns, 1998), a phenomenon well documented in West African (Baldé, 2019; Gomes *et al.*, 2024) The age-specific $L\infty_n$ values closely approach the maximum observed lengths for each cohort (Table 2), confirming their biological plausibility. The growth performance index (Φ'_n = 2.29 – 2.50) falls within the range defined for *S. aurita* in the Mediterranean Sea (2.28 – 2.74; Benamar, 2019; Handjar, 2019), and its low coefficient of variation (CV = 4%) supports the biological coherence of the approach. The present study confirms that *S. aurita* exhibits a relatively limited lifespan and an age-dependent growth pattern consistent with r-selected life-history strategies documented for small pelagic fish in comparable environments (Amponsah *et al.*, 2017; Baldé *et al.*, 2019; Bouaziz *et al.*, 2014; Sparre & Venema, 1998).

It is imperative to clarify that the K_n age-dependent approach does not constitute a novel growth equation. K_n represents an estimation procedure that discretizes the conventional VBGM on a per-age-class basis. The assumption of t_0 = 0 for all age classes is standard for length-frequency-based assessments of Mediterranean small pelagics (Gayanilo *et al.*, 2005; Sparre & Venema, 1998) and may slightly overestimate K_n for younger cohorts; however, this bias is systematic and does not alter the primary biological signal—the steep, progressive decline in K_n *with age*. *The* $L\infty_n$ values, estimated via Pauly's rule (1980), have been validated for Mediterranean small pelagics in previous studies (Baldé, 2019; Dahel *et al.*, 2024; Ladaimia, 2017). The K_n approach should thus be considered as a robust, data-parsimonious alternative for data-limited fisheries where complex bioenergetic models (e.g., DEB, IBM) are infeasible.

Based on three converging criteria, the age-dependent scenario for stock assessment of *S. aurita* along the central Algerian coast is strongly advocated. First, $L\infty_n$ closely approaches the observed maximum size for each cohort, whereas the conventional $L\infty$ = 30.90 cm exceeds the largest individual sampled (25.4 cm) by more than 5 cm. Second, the progressive decline in K_n (≈80%) is biologically interpretable as the onset of reproductive investment, a well-established life-history trade-off. Third, the projected T'_{max} of 7 years is consistent with maximum ages reported for less-exploited Atlantic cohorts (Korichi, 1988; Szypuła, 1973), while the five resolved age classes reflect a truncated age structure driven by intense exploitation rates. The biological traits of *S. aurita*—notably rapid development and a realized longevity restricted to 5 – 6 years under Mediterranean fishing pressure (Dahel, 2018; Handjar, 2019; Jurado-Ruzafa *et al.*, 2020)—necessitates the implementation of dynamic, adaptive management strategies. Specifically, exploitation quotas should be calibrated against irregular recruitment dynamics, and systematic population assessments are imperative to anticipate rapid demographic fluctuations.

Growth parameters may be influenced by environmental factors such as water temperature, salinity, and dissolved oxygen levels (Kindsvater *et al.*, 2024; Patti *et al.*, 2022), as well as biological factors, including maturity and reproduction (Casselman, 1996; Lee *et al.*, 2020), and biotic interactions such as intra- and interspecific competition (Amponsah *et al.*, 2017). Recent studies indicate that higher temperatures can accelerate growth in small pelagic fish, while decreased prey availability decelerates it (Gomes *et al.*, 2024; Kindsvater *et al.*, 2024; Patti *et al.*, 2022; Vasconcelos *et al.*, 2024). Although these factors are not explicitly incorporated in the current model, they significantly affect growth variables and should be considered in future multi-factor assessments.

The estimated total mortality (Z = 3.97 year^{-1}) exceeds rates reported in several Mediterranean and Atlantic studies (Benamar, 2019; Bouaziz *et al.*, 2001; Bouaziz, 2007; Dahel *et al.*, 2024; Handjar, 2019; Mehanna & El-Aiatt, 2011;

Mustać & Sinovčić, 2011), while aligning closely with findings from West African populations (Amponsah *et al.*, 2017; Dienye *et al.*, 2022). The elevated Z value reflects the compounded effects of high fishing pressure and the natural vulnerability of this small pelagic species. Assessing natural mortality (M) is complex, as it is frequently assumed constant despite annual variations driven by environmental and biological factors (Björnsson *et al.*, 2022; Shibaev, 2023). The conventional estimate (M = 0.39 year^{-1}) falls within the range observed for the Algerian coast: 0.338 – 0.98 year^{-1}as reported by Bouaziz (2007) and Handjar, (2019) and consistent with the ranges established by Djabali *et al.* (1993), Gulland (1969), Pauly (1980), indicating 0.30 < M < 0.6, while adhering to the relationship $K < M < 2K$. These results concur with those of Mustać & Sinovčić (2012) in the Adriatic Sea. Under the age-dependent scenario, M_n decreases progressively from 1.10 year^{-1} at age 1 to 0.43 year^{-1} at age 5, reflecting the well-established pattern of declining mortality with increasing body size (Craig *et al.*, 2006; Sogard, 1997). The high M_1 value (1.10 year^{-1}) reflects the well-documented vulnerability of first-year juveniles to predation and environmental stress (Fuiman & Magurran, 1994; Kraskura *et al.*, 2023; Sogard, 1997).

High first-year mortality is biologically coherent: juvenile fish are particularly vulnerable to predation due to their reduced size, rapid growth, and high metabolic demands. This risk is amplified in warmer waters with intense foraging competition (Fuiman & Magurran, 1994; Kraskura *et al.*, 2023; Lindmark *et al.*, 2023; Parkos III & Wahl, 2010). Standard fishery stock assessment models that ignore this age-related variability in M risk systematically overestimating fishing mortality for juveniles, thereby inflating estimates of overexploitation.

Natural mortality (M) is consistently lower than fishing mortality (F) across all age classes (Table 3), corroborating results from previous studies on *S. aurita* (Benamar, 2019; Bouaziz *et al.*, 2001; Dahel *et al.*, 2024). This pattern indicates that fishing constitutes the predominant source of mortality in this population and that stocks are likely in an overfished state, consistent with evidence of reduced growth potential and reduced biomass (Torri *et al.*, 2023; Vila-Belmonte *et al.*, 2024). Variations in M are further influenced by geographic location, food availability, predation pressure, and sex- and age-related factors (Butt *et al.*, 2022; Kolliyil *et al.*, 2021; Rolland & Romiguier, 2020).

Water temperature directly affects the metabolism and vulnerability of tropical fish, increasing predation risk and mortality rates, particularly in juvenile stages exposed to warm-water thermal stress (Figueira *et al.*, 2019; Kraskura *et al.*, 2023; Le *et al.*, 2022; Lindmark *et al.*, 2023; Rezende & Carter, 2024; Zillig, 2023).

5 Conclusions

The findings of the present study indicate that the age-dependent growth approach (K_n) provides a superior, biologically consistent framework for *Sardinella aurita* compared to conventional models. This methodology effectively aligns asymptotic lengths with observed demographic profiles while accounting for age-specific mortality. By reducing potential biases in fishing mortality estimations, this model offers a critical, age-class-resolved perspective on exploitation pressure, serving as a valuable instrument for data-limited fisheries management. Integrating this framework with systematic seasonal monitoring and dynamic, recruitment-based quota adjustments, represents a relevant pathway toward safeguarding small pelagic resources in the Mediterranean Sea, thereby advancing the conservation targets of Sustainable Development Goal 14.

Acknowledgment: The authors have no external contributions to acknowledge for this study.

Source of funding: This research did not receive any specific grant from any funding agency in the public, commercial, or not-for-profit sectors. All expenses related to this study were personally funded by the corresponding author (R. Azaoui).

Previous submissions: Not applicable.

Author Contribution: Azaoui R.: Conceptualization, Methodology, Data Curation, Formal Analysis, Software, Visualization, Resources, Investigation, Writing - original draft. **Toumi M.:** Investigation, Supervision, Validation, Writing - review & Editing. **Amara R.:** Data Curation, Investigation, Supervision, Validation, Writing - review & editing.

Conflicts of Interest: The authors declare no conflicts of interest associated with this research study.

Preprint deposit: No preprint deposit was performed.

References

Amponsah, S. K. K., Ofori-Danson, P. K., Nunoo, F. K. E., & Ameyaw, G. A. (2017). Population dynamics of *Sardinella aurita* (Val., 1847) within Ghana's coastal waters. *Research in Agriculture Livestock and Fisheries*, 4(3), 237–248. https://doi.org/10.3329/ralf.v4i3.35103 [Crossref] [Google Scholar] [Publisher]

Ananiades, C. I. (1952). Quelques considérations biométriques sur l'allache (*Sardinella aurita* C.V.) des eaux grecques. *Praktika Hell. Hydrobiologie Institut*, *5*(1), 5–45. [Google Scholar]

Baali, A., Belhsen, O. K., Ouazzani, K. C., Amenzoui, K., & Yahyaoui, A. (2021). Age, growth and ovarian histology of *Sardinella aurita* (Valenciennes, 1847) in the south of Atlantic Moroccan coast. *Turkish Journal of Fisheries and Aquatic Sciences*, *21*(4), 191–

204. https://doi.org/10.4194/1303-2712-v21_4_04 [Crossref] [Google Scholar] [Publisher]

Baldé, B. S. (2019). *Dynamique des petits poissons pélagiques* (Sardinella aurita *et* Ethmalosa fimbriata) *au Sénégal dans un contexte de changement climatique: Diagnostic et synthèse bioécologiques* [Doctoral dissertation, Université Cheikh Anta Diop]. [Google Scholar] [Publisher]

Baldé, B. S., Sow, F. N., Ba, K., Ekau, W., Brehmer, P., Kantoussan, J., Fall, M., & Diouf, M. (2019). Variability of key biological parameters of round sardinella *Sardinella aurita* and the effects of environmental changes. *Journal of Fish Biology*, *94*(3), 391–401. https://doi.org/10.1111/jfb.13907 [Crossref] [Google Scholar] [PubMed] [Publisher]

Barhdadi, W., Daly, A. J., Baetens, J. M., & Baets, B. De. (2024). Environment-dependent population dynamics emerging from dynamic energy budgets and individual-scale movement behaviour. *Oikos*, 2024(1), e09986. https://doi.org/10.1111/oik.09986 [Crossref] [Google Scholar] [Publisher]

Benamar, N. (2019). Some parameters of growth, mortality and exploitation rate of round sardinella, *Sardinella aurita* Valencienne, 1847 (Pisces Clupeidae), fished in Oran bay (Algeria). *Biodiversity Journal*, *10*(4), 353–358. https://doi.org/10.31396/Biodiv.Jour.2019.10.4.353.358 [Crossref] [Google Scholar] [Publisher]

Bhattacharya, C. G. (1967). A simple method of resolution of a distribution into Gaussian components. *Biometrics*, *23*(1), 115–135. https://doi.org/10.2307/2528285 [Crossref] [Google Scholar] [PubMed] [Publisher]

Björnsson, B., Sólmundsson, J., & Woods, P. J. (2022). Natural mortality in exploited fish stocks: Annual variation estimated with data from trawl surveys. *ICES Journal of Marine Science*, *79*(5), 1569–1582. https://doi.org/10.1093/icesjms/fsac063 [Crossref] [Google Scholar] [Publisher]

Bouaziz, A. (2007). *La sardinelle* (*Sardinella aurita Valenciennes, 1847) des côtes algériennes: Distribution, biologie et estimation des biomasses* [Doctoral dissertation, Université des Sciences et de la Technologie Houari Boumediene]. https://www.ccdz.cerist.dz/admin/notice.php?id=000000000000000054447000000 [Google Scholar]

Bouaziz, A., Bennoui, A., Brahmi, B., & Semroud, R. (2001). Sur l'estimation de l'état d'exploitation de la sardinelle (*Sardinella aurita* Valenciennes, 1847) de la région centre de la côte algérienne. In *Metting Commission internationale pour l'exploration scientifique de la mer Méditerranée* (Report and minutes No. 36). [Google Scholar]

Bouaziz, A., & Caddy, J. F. (1998). Impact des taux de mortalité par âge sur la dynamique des populations et le diagnostic des stocks exploités en Méditerranée. *Rap. Tech. DYNPOP (CIESM-CIHEAM), Zaragoza (Espagne)*, 1–11.

Bouaziz, A., Kerzabi, F., & Brahmi, B. (2014). Impact of the natural mortality (M) variability on the evaluation of the exploitable stock of sardine, *Sardina pilchardus* (Actinopterygii: Clupeiformes: Clupeidae) of the central region of the Algerian coast. *Acta Ichthyologica et Piscatoria*, *44*(2), 87–97. https://doi.org/10.3750/AIP2014.44.2.01 [Crossref] [Google Scholar]

Butt, N., Halpern, B. S., O'Hara, C. C., Allcock, A. L., Polidoro, B., Sherman, S., Byrne, M., Birkeland, C., Dwyer, R. G., & Frazier, M. (2022). A trait-based framework for assessing the vulnerability of marine species to human impacts. *Ecosphere*, *13*(2), e3919. https://doi.org/10.1002/ecs2.3919 [Crossref] [Google Scholar] [Publisher]

Campana, S. E., & Jones, C. M. (1992). Analysis of otolith microstructure data. *Canadian Special Publication of Fisheries and Aquatic Sciences*, *117*, 73–100. [Google Scholar] [Publisher]

Casselman, J. M. (1996). Age, growth and environmental requirements of pike. In J. F. Craig (Ed.), *Pike: Biology and exploitation* (pp. 69–101). Springer. https://doi.org/10.1007/978-94-015-8775-4_4 [Crossref] [Google Scholar] [Publisher]

Correa, G. M., McGilliard, C. R., Ciannelli, L., & Fuentes, C. (2021). Spatial and temporal variability in somatic growth in fisheries stock assessment models: Evaluating the consequences of misspecification. *ICES Journal of Marine Science*, *78*(5), 1900–1908. https://doi.org/10.1093/icesjms/fsab096 [Crossref] [Google Scholar] [PubMed] [Publisher]

Costello, C., Ovando, D., Clavelle, T., Strauss, C. K., Hilborn, R., Melnychuk, M. C., Branch, T. A., Gaines, S. D., Szuwalski, C. S., & Cabral, R. B. (2016). Global fishery prospects under contrasting management regimes. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(18), 5125–5129. https://doi.org/10.1073/pnas.1520420113 [Crossref] [Google Scholar] [PubMed] [Publisher]

Craig, J. K., Burke, B. J., Crowder, L. B., & Rice, J. A. (2006). Prey growth and size-dependent predation in juvenile estuarine fishes: Experimental and model analyses. *Ecology*, *87*(9), 2366–2377. https://doi.org/10.1890/0012-9658(2006)87[2366:PGASPI]2.0.CO;2 [Crossref] [Google Scholar] [PubMed] [Publisher]

Dahel, A. T. (2018). *Biologie halieutique et exploitation de deux clupéidés, la sardine* Sardina pilchardus *(Walbaum, 1792) et la sardinelle* Sardinella aurita *(Valenciennes, 1847) des côtes Est algériennes* [Doctoral dissertation, Université Badji Mokhtar - Annaba]. [Google Scholar] [Publisher]

Dahel, A. T., Tahri, M., & Djebar, A. B. (2024). Analysis of virtual populations of small pelagic fish most caught in Algeria. *Egyptian Journal of Aquatic Biology &*

Fisheries, *28*(2), 1–16. https://doi.org/10.21608/ejabf.2024.349723 [Crossref] [Google Scholar] [Publisher]

David, V., Joachim, S., Tebby, C., Porcher, J.-M., & Beaudouin, R. (2019). Modelling population dynamics in mesocosms using an individual-based model coupled to a bioenergetics model. *Ecological Modelling*, *398*, 10–22. https://doi.org/10.1016/j.ecolmodel.2019.02.008 [Crossref] [Google Scholar] [PubMed] [Publisher]

Dienye, H., Olopade, O., & Ichendu, C. (2022). Growth, mortality and exploitation rate of round sardinella (*Sardinella aurita*, Valenciennes, 1847) in the New Calabar River, Niger Delta, Nigeria. *Çanakkale Onsekiz Mart University Journal of Marine Sciences and Fisheries*, *5*(1), 39–47. https://doi.org/10.46384/jmsf.1054288 [Crossref] [Google Scholar] [Publisher]

Djabali, F., Mehailia, A., Koudil, M., & Brahmi, B. (1993). Empirical equations for the estimation of natural mortality in Mediterranean teleosts. *Fishbyte*, *11*(1), 35–37. https://aquadocs.org/handle/1834/25779 [Google Scholar] [Publisher]

Figueira, W. F., Curley, B., & Booth, D. J. (2019). Can temperature-dependent predation rates regulate range expansion potential of tropical vagrant fishes? *Marine Biology*, *166*(6), 73. https://doi.org/10.1007/s00227-019-3521-5 [Crossref] [Google Scholar] [Publisher]

Fréon, P., Cury, P., Shannon, L., & Roy, C. (2005). Sustainable exploitation of small pelagic fish stocks challenged by environmental and ecosystem changes: A review. *Bulletin of Marine Science*, *76*(2), 385–462. [Google Scholar] [Publisher]

Froese, R., & Palomares, M. L. D. (2000). Growth, natural mortality, length–weight relationship, maximum length and length-at-first-maturity of the coelacanth *Latimeria chalumnae*. *Environmental Biology of Fishes*, *58*, 45–52. https://doi.org/10.1023/a:1007602613607 [Crossref] [Google Scholar] [Publisher]

Fuiman, L. A., & Magurran, A. E. (1994). Development of predator defences in fishes. *Reviews in Fish Biology and Fisheries*, *4*, 145–183. https://doi.org/10.1007/bf00044127 [Crossref] [Google Scholar] [Publisher]

Gayanilo, F. J., Sparre, P., & Pauly, D. (2005). *FAO-ICLARM Outils d'évaluation des stocks II (FiSAT II). Version révisée* (FAO Computerized Information Series, Fisheries No. 8). Food and Agriculture Organization of the United Nations. https://agris.fao.org/agris-search/search.do?recordID=XF2016039406 [Google Scholar] [Publisher]

Gomes, J. D. P., Baldé, B. S., Faye, S., Barry, I., Demarcq, H., & Brehmer, P. (2024). Growth patterns of small pelagic fish in West Africa. *Sustainability*, *16*(22), 9652. https://doi.org/10.3390/su16229652 [Crossref] [Google Scholar] [Publisher]

Gulland, J. A. (1969). *Manual of methods for fish stock assessment. Part 1. Fish population analysis* (FAO Man. Fish. Sci. Vol. 4). Food and Agriculture Organization of the United Nations. [Google Scholar] [Publisher]

Handjar, H. (2019). *Biologie, écologie et évaluation des stocks de petits pélagiques: Sardina pilchardus (Walbaum, 1792),* Sardinella aurita *Valenciennes, 1847,* Boops boops *(Linnaeus, 1758) et* Trachurus trachurus *(Linnaeus, 1758)* [Doctoral dissertation, Université Ibn Khaldoun, Tiaret]. [Google Scholar]

Hattour, A., Ben Abdallah, L., & Guennegan, Y. (2004). Abondance relative et estimation de la biomasse des petits pélagiques des eaux tunisiennes. *INSTM Bulletin: Marine and Freshwater Sciences*, *31*, 5–16. [Google Scholar]

Hilborn, R., Buratti, C. C., Díaz Acuña, E., Hively, D., Kolding, J., Kurota, H., Baker, N., Mace, P. M., de Moor, C. L., & Muko, S. (2022). Recent trends in abundance and fishing pressure of agency-assessed small pelagic fish stocks. *Fish and Fisheries*, *23*(6), 1313–1331. https://doi.org/10.1111/faf.12690 [Crossref] [Google Scholar] [Publisher]

Jurado-Ruzafa, A., Hernández, E., Duque-Nogal, V., Pascual-Alayón, P. J., Carrasco, M. N., Sancho, A., & Santamaría, M. T. G. (2020). Life history parameters of the round sardinella *Sardinella aurita* in the Central East Atlantic off north-west Africa. *Journal of the Marine Biological Association of the United Kingdom*, *100*(6), 997–1009. https://doi.org/10.1017/s002531542000079x [Crossref] [Google Scholar] [Publisher]

Kienzle, M. (2005). Estimation of the population parameters of the Von Bertalanffy Growth Function for the main commercial species of the North Sea. *Fisheries Research Services Internal Report*, *5*(05), 1–48. [Google Scholar]

Kindsvater, H. K., Juan-Jordá, M., Dulvy, N. K., Horswill, C., Matthiopoulos, J., & Mangel, M. (2024). Size-dependence of food intake and mortality interact with temperature and seasonality to drive diversity in fish life histories. *Evolutionary Applications*, *17*(2), e13646. https://doi.org/10.1111/eva.13646 [Crossref] [Google Scholar] [PubMed] [Publisher]

Kolliyil, S. M., Thayyil, S. V., Elayaperumal, V., Kuriakose, S., Ganga, U., Saraswathy, P. L., & Rekha, N. J. (2021). Application of biological and fisheries attributes to assess the vulnerability and resilience of tropical marine fish species. *PLoS One*, *16*(8), e0255879. https://doi.org/10.1371/journal.pone.0255879 [Crossref] [Google Scholar] [PubMed] [Publisher]

Korichi, H. (1988). *Contribution à l'étude biologique de deux espèces de saurels* Trachurus trachurus *(Linné, 1758) et* Trachurus mediterraneus *(Steindachner, 1868) et de la dynamique de* Trachurus trachurus *(Linné, 1758) en baie de Bou Ismaïl Alger* [Doctoral dissertation, ISMAL]. [Google Scholar]

Kraskura, K., Hardison, E. A., & Eliason, E. J. (2023). Body size and temperature affect metabolic and cardiac thermal tolerance in fish. *Scientific Reports*, *13*(1), 17900. https://doi.org/10.1038/s41598-023-44574-w [Crossref] [Google Scholar] [PubMed] [Publisher]

Ladaimia, S. (2017). *Reproduction, âge et croissance de deux Téléostéens pélagiques des côtes de l'extrême Est algérien (El Kala): l'anchois Engraulis encrasicolus (Linnaeus, 1758) et la sardine, Sardina pilchardus (Walbaum, 1792)* [Doctoral dissertation, Université Badji Mokhtar–Annaba]. [Google Scholar] [Publisher]

Le, M.-H., Dinh, K. V., Vo, X. T., & Pham, H. Q. (2022). Direct and delayed synergistic effects of extreme temperature, metals and food limitation on tropical reef-associated fish juveniles. *Estuarine, Coastal and Shelf Science*, 278, 108108. https://doi.org/10.1016/j.ecss.2022.108108 [Crossref] [Google Scholar] [Publisher]

Lee, L., Atkinson, D., Hirst, A. G., & Cornell, S. J. (2020). A new framework for growth curve fitting based on the von Bertalanffy Growth Function. *Scientific Reports*, 10(1), 7953. https://doi.org/10.1038/s41598-020-64839-y [Crossref] [Google Scholar] [PubMed] [Publisher]

Lindmark, M., Anderson, S. C., Gogina, M., & Casini, M. (2023). Evaluating drivers of spatiotemporal variability in individual condition of a bottom-associated marine fish, Atlantic cod (*Gadus morhua*). *ICES Journal of Marine Science*, *80*(5), 1539–1550. https://doi.org/10.1093/icesjms/fsad084 [Crossref] [Google Scholar] [Publisher]

Lindmark, M., Karlsson, M., & Gårdmark, A. (2023). Larger but younger fish when growth outpaces mortality in heated ecosystem. *eLife*, *12*, e82996. https://doi.org/10.7554/eLife.82996 [Crossref] [Google Scholar] [PubMed] [Publisher]

Liu, Y., Zhang, C., Wei, X., Xu, B., Xue, Y., Ren, Y., & Chen, Y. (2023). Coupling dynamic energy budget and population dynamic models to inform stock enhancement in fisheries management. *Fish and Fisheries*, *24*(6), 924–939. https://doi.org/10.1111/faf.12776 [Crossref] [Google Scholar] [Publisher]

Martin, B. T., Zimmer, E. I., Grimm, V., & Jager, T. (2012). Dynamic energy budget theory meets individual-based modelling: A generic and accessible implementation. *Methods in Ecology and Evolution*, *3*(2), 445–449. https://doi.org/10.1111/j.2041-210X.2011.00168.x [Crossref] [Google Scholar] [Publisher]

Mehanna, S. F., & El-Aiatt, A. (2011). Fisheries characteristics and population dynamics of the blue swimmer crab *Portunus pelagicus* (Linnaeus, 1766) from Bardawil lagoon. *Proceeding of 4th International Conference on Fisheries and Aquaculture* (pp. 1–12). Cairo, Egypt. [Google Scholar] [Publisher]

Morales-Nin, B., & Panfili, J. (2002). Age estimation. In J. Panfili, H. Troadec, H. de Pontual, & P. J. Wright (Eds.), *Manual of fish sclerochronology* (pp. 91–98). Ifremer-IRD coedition. [Google Scholar]

Mustać, B., & Sinovčić, G. (2011). Age and growth pattern of the round sardinella *Sardinella aurita* Valenciennes, 1847 (Clupeidae) in the eastern central Adriatic Sea. *Cahiers de Biologie Marine*, *52*(2), 177–186. [Google Scholar] [Publisher]

Mustać, B., & Sinovčić, G. (2012). Inshore versus offshore length distribution of round sardinella (*Sardinella aurita*) in the middle eastern Adriatic Sea. *Acta Adriatica*, *53*(3), 341–351. [Google Scholar] [Publisher]

Panfili, J., de Pontual, H., Troadec, H., & Wright, P. J. (Eds.). (2002). *Manual of fish sclerochronology*. Ifremer-IRD coedition. [Crossref]

Parkos III, J. J., & Wahl, D. H. (2010). Influence of body size and prey type on the willingness of age-0 fish to forage under predation risk. *Transactions of the American Fisheries Society*, *139*(4), 969–975. https://doi.org/10.1577/t09-098.1 [Crossref] [Google Scholar] [Publisher]

Patti, B., Fiorentino, F., Fortibuoni, T., Somarakis, S., & García-Lafuente, J. (2022). Impacts of environmental variability related to climate change on biological resources in the Mediterranean. *Frontiers in Marine Science*, *9*, 1059424. https://doi.org/10.3389/978-2-83250-739-1 [Crossref] [Google Scholar] [Publisher]

Pauly, D. (1980). On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. *ICES Journal of Marine Science*, *39*(2), 175–192. https://doi.org/10.1093/icesjms/39.2.175 [Crossref] [Google Scholar] [Publisher]

Pauly, D., & Munro, J. L. (1984). Once more on the comparison of growth in fish and invertebrates. *Fishbyte*, *2*(1), 1–21. https://ideas.repec.org/a/wfi/wfbyte/38103.html [Google Scholar] [Publisher]

Peck, M. A., Alheit, J., Bertrand, A., Catalán, I. A., Garrido, S., Moyano, M., Rykaczewski, R. R., Takasuka, A., & van Der Lingen, C. D. (2021). Small pelagic fish in the new millennium: A bottom-up view of global research effort. *Progress in Oceanography*, *191*, 102494. https://doi.org/10.1016/j.pocean.2020.102494 [Crossref] [Google Scholar] [Publisher]

Pikitch, E. K., Santora, C., Babcock, E. A., Bakun, A., Bonfil, R., Conover, D. O., Dayton, P., Doukakis, P., Fluharty, D., & Heneman, B. (2004). Ecosystem-based fishery management. *Science*, *305*(5682), 346–347. https://doi.org/10.1126/science.1098222 [Crossref] [Google Scholar] [Publisher]

Rezende, E. L., & Carter, M. J. (2024). Cumulative heat stress in fluctuating temperatures and implications for the distribution of freshwater fish. *Global Change*

Biology, *30*(12), e17623. https://doi.org/10.1111/gcb.17623 [Crossref] [Google Scholar] [PubMed] [Publisher]

Rolland, J., & Romiguier, J. (2020). Vulnerability to fishing and life history traits correlate with the load of deleterious mutations in teleosts. *Molecular Biology and Evolution*, *37*(8), 2192–2196. https://doi.org/10.1093/molbev/msaa067 [Crossref] [Google Scholar] [PubMed] [Publisher]

Sabatés, A., Salat, J., Raya, V., Emelianov, M., & Segura-Noguera, M. (2009). Spawning environmental conditions of *Sardinella aurita* at the northern limit of its distribution range, the western Mediterranean. *Marine Ecology Progress Series*, *385*, 227–236. https://doi.org/10.3354/meps08058 [Crossref] [Google Scholar] [Publisher]

Sabu, S. (2024). Introduction to fish proteins. In S. Sabu (Ed.), *Fish structural proteins and its derivatives: Functionality and applications* (pp. 3–17). Springer. https://doi.org/10.1007/978-981-97-2562-5_1 [Crossref] [Google Scholar] [Publisher]

Savage, A., McIver, L., & Schubert, L. (2020). The nexus of climate change, food and nutrition security and diet-related non-communicable diseases in Pacific Island Countries and Territories. *Climate and Development*, *12*(2), 120–133. https://doi.org/10.1289/isee.2017.2017-107 [Crossref] [Google Scholar] [Publisher]

Shibaev, S. V. (2023). On the question of adequacy of estimation of the natural mortality of fishes by means of von Bertalanffy growth equation. *Proceedings of the Zoological Institute RAS*, *327*(3), 490–495. https://doi.org/10.31610/trudyzin/2023.327.3.490 [Crossref] [Google Scholar] [Publisher]

Sogard, S. M. (1997). Size-selective mortality in the juvenile stage of teleost fishes: A review. *Bulletin of Marine Science*, *60*(3), 1129–1157. [Google Scholar] [Publisher]

Sparre, P., & Venema, S. C. (1998). *Introduction to tropical fish stock assessment. Part 1: Manual* (FAO Fisheries Technical Paper, No. 306.1, Rev. 2). Food and Agriculture Organization of the United Nations. [Google Scholar] [Publisher]

Stearns, S. C. (1998). *The evolution of life histories*. Oxford University Press. https://doi.org/10.1093/oso/9780198577416.001.0001 [Crossref] [Google Scholar] [Publisher]

Szypuła, J. (1973). Biological characteristic of gilt sardine *Sardinella aurita* Cuv. et Val., 1847 from North West African coast. *Acta Ichthyologica et Piscatoria*, *3*(1), 19–37. https://doi.org/10.3750/aip1973.03.1.03 [Crossref] [Google Scholar] [Publisher]

Tacon, A. G. J., & Metian, M. (2013). Fish matters: Importance of aquatic foods in human nutrition and global food supply. *Reviews in Fisheries Science*, *21*(1), 22–38. https://doi.org/10.1080/10641262.2012.753405 [Crossref] [Google Scholar] [Publisher]

Taylor, C. C. (1958). Cod growth and temperature. ICES *Journal of Marine Science*, *23*(3), 366–370. https://doi.org/10.1093/icesjms/23.3.366 [Crossref] [Publisher]

Torri, M., Russo, S., Falcini, F., De Luca, B., Colella, S., Volpe, G., Corrado, R., Placenti, F., Giaramita, L., & Musco, M. (2023). Coupling Lagrangian simulation models and remote sensing to explore the environmental effect on larval growth rate: The Mediterranean case study of round sardinella (*Sardinella aurita*) early life stages. *Frontiers in Marine Science*, *9*, 1065514. https://doi.org/10.3389/fmars.2022.1065514 [Crossref] [Google Scholar] [Publisher]

Valenciennes, A. (1847). Catalogue des principales espèces de poissons. *Voyage Dans l'Amérique Méridionale*, *5*(2), 1–11.

Van Poorten, B., Korman, J., & Walters, C. (2018). Revisiting Beverton–Holt recruitment in the presence of variation in food availability. *Reviews in Fish Biology and Fisheries*, *28*(3), 607–624. https://doi.org/10.1007/s11160-018-9521-6 [Crossref] [Google Scholar] [Publisher]

Vasconcelos, J., Sanabria-Fernandez, J. A., Tuset, V. M., Sousa, R., Faria, G., & Riera, R. (2024). Rising temperatures, falling fisheries: Causes and consequences of crossing the tipping point in a small-pelagic community. *Reviews in Fish Biology and Fisheries*, *34*(4), https://doi.org/10.1007/s11160-024-09885-9 [Crossref] [Google Scholar] [Publisher]

Vila-Belmonte, M. A. R., Bou, R., Lloret, E., & Lloret, J. (2024). Fatty acid content and profile of round sardinella (*Sardinella aurita*), an expanding thermophilic species in the NW Mediterranean. *Mediterranean Marine Science*, *25*(2), 300–310. https://doi.org/10.12681/mms.35917 [Crossref] [Google Scholar] [Publisher]

Von Bertalanffy, L. (1938). A quantitative theory of organic growth (inquiries on growth laws. II). *Human Biology*, *10*(2), 181–213. https://doi.org/10.1086/401873 [Crossref] [Google Scholar] [Publisher]

Zillig, K. W. (2023). Temperature and fish biology: Insights from metabolism. In *Reference Module in Life Sciences*. Elsevier. https://doi.org/10.1016/B978-0-323-90801-6.00175-0 [Crossref] [Google Scholar] [[Publisher]