Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 28(5): 1151 – 1171 (2024)
www.ejabf.journals.ekb.eg

First Results of the Study on Reproductive Biology of the Frigate Tuna (*Auxis thazard*) in the North Atlantic of Morocco

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ARTICLE INFO
Article History:
Received: May 18, 2024
Accepted: June 30, 2024
Online: Sep. 29, 2024

Keywords:
Frigate tuna,
Size distribution,
Spawning season,
Sex-ratio,
Sexual
maturity

ABSTRACT

To investigate the reproductive behavior of the frigate tuna (*Auxis thazard*) along the North Atlantic coast of Morocco, a comprehensive study was conducted between February and October 2020. A total of 215 frigate tuna specimens, obtained from both artisanal fishery and commercial purse-seiners, were meticulously examined on a monthly basis. The study focused on evaluating various reproductive parameters including sex ratio, condition factor (K), gonadosomatic index (GSI), and sexual maturity progression. The findings of this study revealed that the straight fork lengths of the frigate tuna ranged from 30 to 43cm. Analysis of the sex ratio indicated a slight dominance of females, with a ratio of 1.06 females to every male (observed sex ratio: 1:0.06; X^2 observed = 1.21, which was below the theoretical X^2 = 3.84 threshold at $P< 0.05$). The size at which individuals reached sexual maturity (FL 50) was estimated to be 36cm for females and 38cm for males. Through monthly assessments, it was observed that the variation in maturity stages, GSI, and K values suggested a spawning period predominantly occurring between June and August, with a peak in July. This temporal pattern underscores the importance of understanding the reproductive dynamics of the frigate tuna populations in this region.

INTRODUCTION

The frigate tuna *Auxis thazard* (Lacepède, 1800) is a coastal species found worldwide in tropical and subtropical oceans **(Uchida, 1981)**. In the Atlantic Ocean, the *A. thazard* is distributed on both sides of the tropical and subtropical zones with a most likely presence between 40°N - 35°S, including the Caribbean Sea and the Gulf of Mexico. Although the presence of *A. thazard* has been reported in the Mediterranean **(Collette & Nauen, 1983)**, this species is less common and has a lower probability of presence in the Mediterranean. Consequently, most of the specimens of the genus *Auxis*

captured in the Mediterranean Sea could be specimens of the bonito (*Auxis rochei*) **(Collette *et al*., 2011; Ollé *et al*., 2019)**. There are reports of these species in the eastern Atlantic, reaching as far north as Norway and as far south as South Africa. Reports from the Gulf of Maine (Cape Cod) on the eastern coast of North America in the western Atlantic have been conducted. The species is known to exist off the Atlantic coast of South America as far south as Mar del Plata (Argentina) **(Valeiras *et al*., 2006)**.

The frigate tuna, along with the Spanish mackerel, Atlantic bonito, and little tunny, is one of the most commonly caught small scombrids in the Atlantic Ocean **(ICCAT, 2021)**. The frigate tuna (*Auxis thazard*) primarily feeds on a variety of crustaceans, small fish, and cephalopods, reflecting its role as a pelagic predator. This species typically hunts in groups near the surface, targeting prey such as anchovies, sardines, shrimp, and squid **(Etchevers, 1976; Fischer *et al*., 1990)**. However, these species are known to be an essential prey for a variety of species, particularly large commercial tunas **(Olson, 1982; Frimodt, 1995; IOTC Secretariat, 2017)**.

In Morocco, this epipelagic and neritic species **(Collette & Nauen, 1983)** is distributed along the Atlantic coasts with varying levels of abundance, and they are taken by an artisanal fleet using small scale gillnets and handlines **(Oumarous *et al*., 2015)**. Moreover, this species is a crucial bycatch for commercial purse seine vessels and traps targeting small pelagic and Bluefin tuna, respectively **(INRH/DP 2017)**.

The majority of current management strategies involve evaluating individual stocks based on in-depth biological data and fisheries statistics for only targeted species **(King & McFarlane, 2003)**. Having information on life history parameters, such as reproduction, growth and stock structure analysis (populations genetics), has shown to be greatly advantageous for assessment in data-poor circumstances **(Kokkalis *et al*., 2015; Frédou *et al*., 2017)**. For small tuna stocks, conservation and management plans need to be up-to-date, and region-specific reproductive biology data should be obtained.

Most studies are fairly old and primarily based on other local findings, and no information regarding the reproductive biology of frigate tuna in Moroccan waters can be found. The investigation therefore aimed to determine for the first time the reproduction aspects of the frigate tuna on the North Atlantic coast of Morocco. This research was organized to gain a basic understanding of resource evaluation and to provide scientific guidelines for a sustainable management of the frigate tuna *A. thazard* species by analyzing samples taken from commercial boats operating in coastal seas.

MATERIALS AND METHODS

1. Study area

In this study, a total of 215 frigate tuna were sampled and examined between February 2020 and October 2020. The samples were collected from purse seiners operating in the northern regions of the Moroccan Atlantic seas, as well as from the commercial landings of the Moroccan artisanal fleet utilizing longlines (Fig. 1).

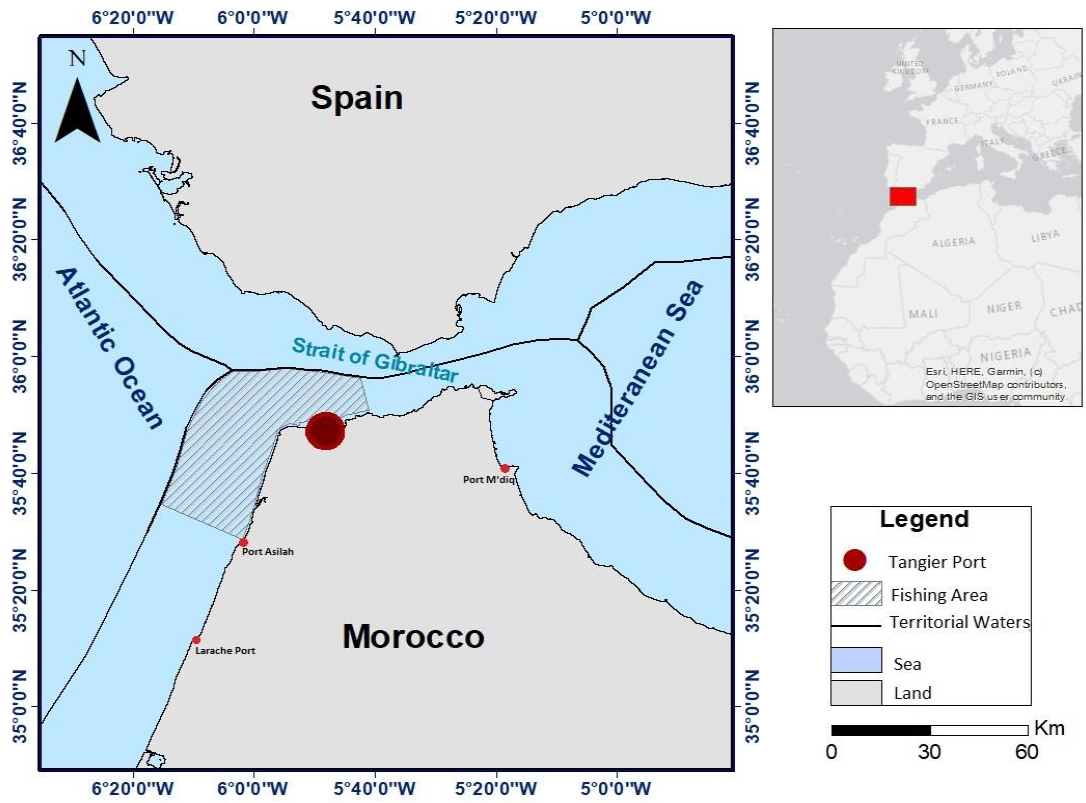

Fig. 1. Geographical location of the study area

The sampling frequency was conducted on a monthly basis, contingent upon the presence and availability of the frigate tuna in the port within our study area. Given the migratory nature of these species, they are not consistently found in the fishing zones where they may be inadvertently caught as by-catch by fleets targeting other pelagic species such as the mackerels, sardines, and swordfish. Moreover, the unpredictability of weather conditions often poses challenges, as unfavorable weather can hinder fishing activities, further influencing the accessibility of the frigate tuna for sampling purposes. Thus, our sampling efforts were intricately tied to both the seasonal movements of the tuna populations and the logistical constraints imposed by weather variability, ensuring a comprehensive understanding of their reproductive biology within the context of dynamic environmental conditions.

2. Reproduction study

To assess the morphological characteristics and reproductive status of each specimen, fork length (FL) and total weight (TW) were measured. The gonads were excised, macroscopically identified by sex, and weighed using a precision balance with an accuracy of ±0.01g. Using a fish measuring board, the length of each fish was determined to the nearest centimeter, and an independent samples t-test was applied to assess potential differences in the mean length between male and female. To identify the spawning period, we employed both qualitative and quantitative methods. Qualitatively,

we tracked monthly shifts in the distribution of gonad development stages, assessing the progression toward spawning readiness. Quantitatively, we monitored monthly changes in the gonadosomatic index (GSI) **(Lahaye, 1980)**, which measures the relative size of the gonads to the rest of the body, providing insight into reproductive activity. Additionally, we tracked changes in the condition factor K **(Do Chi, 1978)**, which evaluates the overall body condition of the specimens, potentially indicating optimal spawning conditions.

$$GSI = \left[\frac{GW}{TW-GW}\right] \times 100$$

(Gibson & Ezzi, 1980) (1)

Where, the abbreviation GW represents the weight of the gonad in grams (g), while TW denotes the total weight of the individual specimen in grams (g).

$$K = \left[\frac{TW-GW}{FL^3}\right] \times 100$$

(Htun-Han, 1978) (2)

In this equation: TW refers to the total weight of the individual (in grams), FL represents the fork length (in centimeters), and GW signifies the weight of the gonads (in grams).

The sex ratio was calculated by using the formulas:

$$(\%M) = \left(\frac{M}{M+F}\right) \times 100 \; ; \; (\%F) = \left(\frac{F}{M+F}\right) \times 100$$

(3)

The proportion of each sex in the population, denoted by M for males and F for females, is determined through macroscopic observation of gonads, as shown in the stage descriptions in Table (1). The χ 2 test was employed to compare these sex proportions, involving the comparison between observed and theoretical values.

$$\mathbf{X2obs} = \frac{\Sigma\,(\mathbf{Nobs}-\mathbf{Nthe})^2}{\mathbf{Nthe}}$$

(4)

In this context, Nobs represents the observed effective sex in the samples, while Nthe signifies the calculated theoretical effective sex in the samples. The primary

hypothesis posits equal sex proportions, while the alternative hypothesis suggests a significant disparity in proportions between the two sexes:

If χobs is less than χ μ at a significance level of 0.05, the primary hypothesis is accepted.

If χobs is greater than χ μ at a significance level of 0.05, the primary hypothesis is rejected.

We determined, subsequently, the values corresponding to the sizes at the first sexual maturity set above from an equation whose curve is sigmoid and which is of the form:

$$P = \frac{1}{1-e^{-(b+aFL)}} \quad (5)$$

In the context provided, P denotes the proportion of mature individuals within the population, while FL signifies the fork length of the fish, measured in centimeters (cm).

The values of the constants a and b are computed using the least squares method, which consists of transforming equation (1) into a linear form:

$$\ln\left(\frac{P}{1-P}\right) = b + aFL \quad (6)$$

This equation is of the form Y = aX + b considering L and Ln (P / 1-P), the variables X and Y of equation (2)

Table 1. Maturity stages of ovaries and male gonads (macroscopic stating method) **(Diouf, 1980)**

Reproductive stage	Females	Males
1. Juvenile	Gonads shaped like small ribbons, impossible to determine sex with the naked eye	At this stage, the gonads resemble small ribbons, rendering it challenging to discern the sex without magnification.
2. Early developmental and regenerative (recovering)	Immature; gonads elongated and thin, but sex determination possible with the naked eye	At the immature stage, the testicles appear very thin, flattened, and ribbon-shaped, yet sex determination is feasible without magnification
3. Mature (late development)	Late maturity; swollen gonads, visible oocytewith the naked eye.	Testicles swollen, adopt a triangular shape in cross-section, no sperm flows from the central canal
4. Reproductive stage (maturity)	Once the stage of maturity is reached, the ovaries exhibit a robust, well-developed state, characterized by a distinct yellow-orange coloration. Within, the presence of opaque oocytes is observed, indicating readiness for reproduction.	The testes exhibit significant enlargement with prominent superficial blood vessels, displaying a pinkish hue. A substantial volume of sperm is released effortlessly under minimal pressure.
5. Regressing	At the post-spawning stage, which encompasses both spawned and post-spawning fish, the specimens exhibit remnants of mature ova with varying degrees of resorption, along with remnants of mature ova measuring 1.0 mm in diameter	At the flaccid stage, the testicles appear bloodstained with a dark red surface, and few or no sperm are present in the central canal

RESULTS

The fork length measurements of the sampled specimens exhibited a range from 30 to 43cm (where no size under 30cm have been reported by fishing boats in this geographical area). The total weight exhibited a range spanning from 0.424 to 1.378 kilograms. Female sizes spanned from 30 to 43cm, while males ranged from 31 to 42cm. The independent samples t-test revealed that there exists no statistically significant

difference in mean length between males and females ($P > 0.05$). Size distributions show a bimodal appearance; the highest modal value corresponds to 36cm, complemented by a secondary (minor) peak around 40cm (Fig. 2).

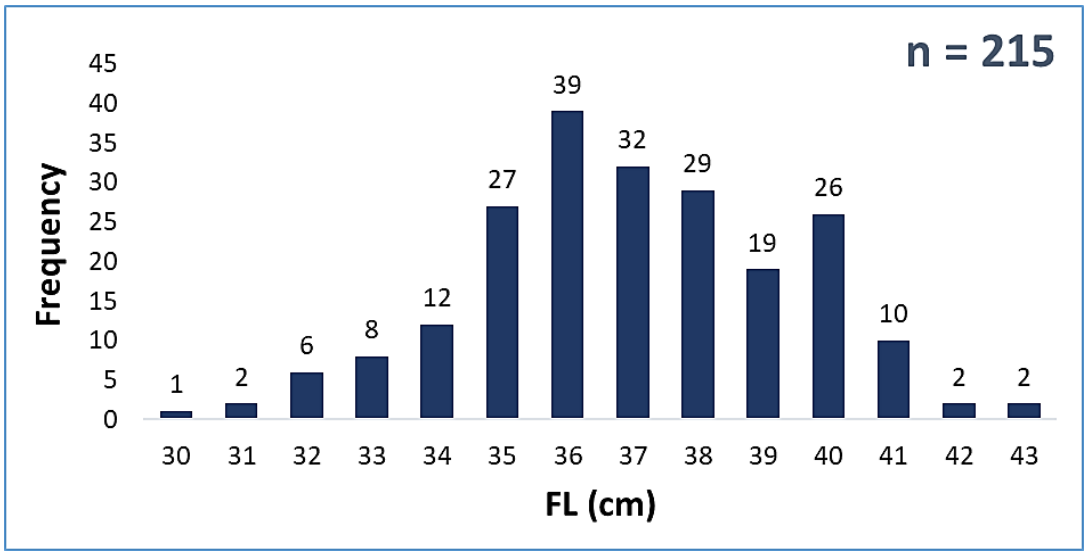

Fig. 2. Length frequency distribution of the frigate tuna (*Auxis thazard*) (n=215, both sexes combined)

Monthly gonadosomatic index (GSI) values were computed separately for both females and males and depicted in Figs. (3, 4), respectively. Overall, these values showed a notable increase during the summer months, coinciding with heightened reproductive activity, reaching its peak in July. Figs (3, 4) also illustrate the monthly variation in condition factor (K) values for females and males. The GSI values increased as the condition factor dropped, particularly notably in June, July, and August for both sexes. This trend was consistent with the monthly observations of the percentage of mature individuals, as the proportion of mature individuals (stages 4 and 5) was the highest in June (45%), July (100%), and August (65%), as highlighted in Figs. (5, 6).

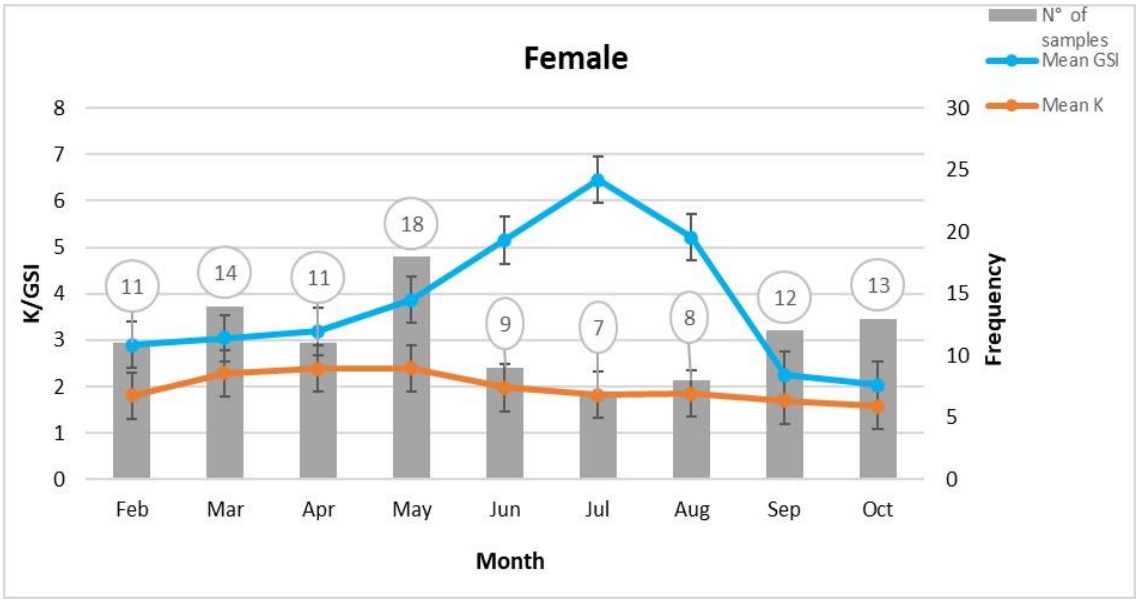

Fig. 3. Monthly changes in the mean gonado-somatic-index (GSI) and condition factor (K) in females of the frigate tuna (*Auxis thazard*)

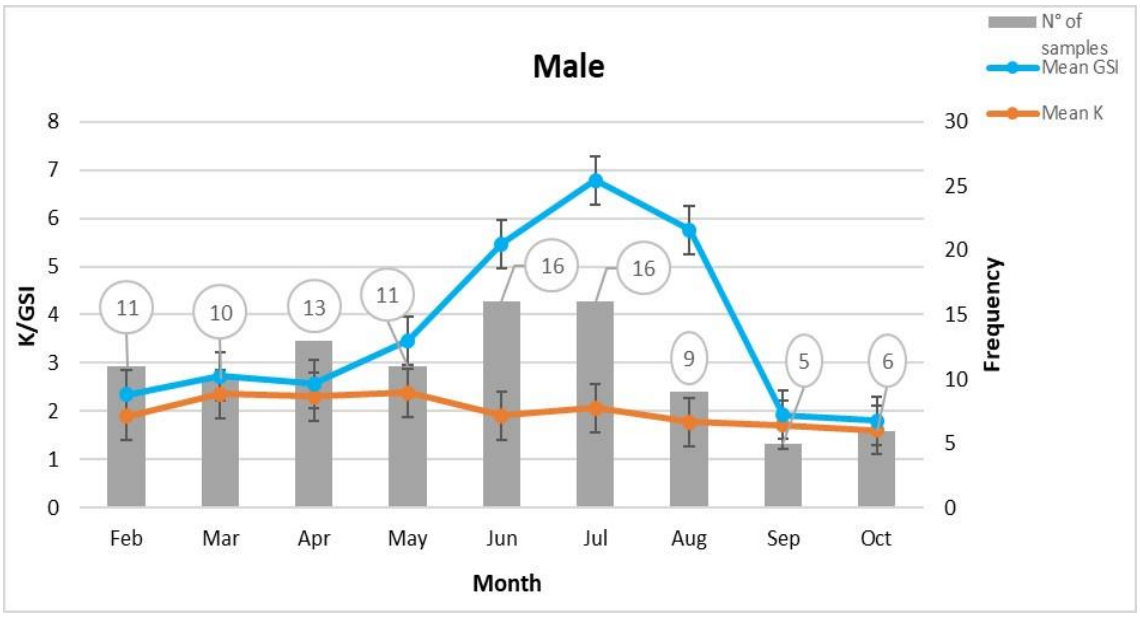

Fig. 4. Monthly observations in the mean gonado-somatic index (GSI) and condition factor (K) in males of the frigate tuna (*Auxis thazard*)

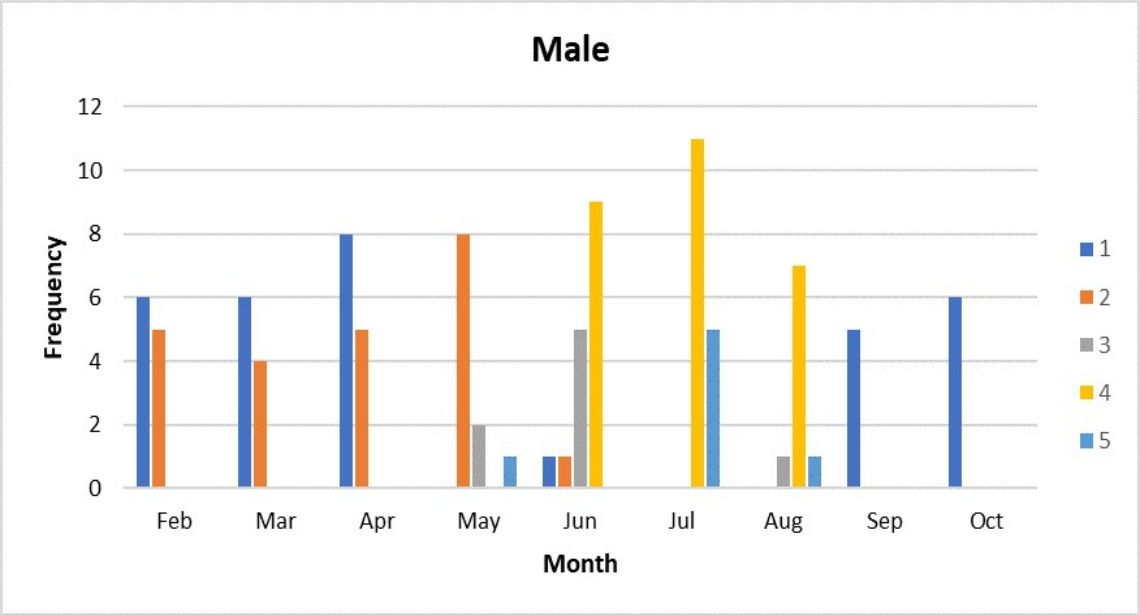

Fig. 5. Sexual maturity stages of the males frigate tuna (*Auxis thazard*) (1, 2…5, are the maturity stage)

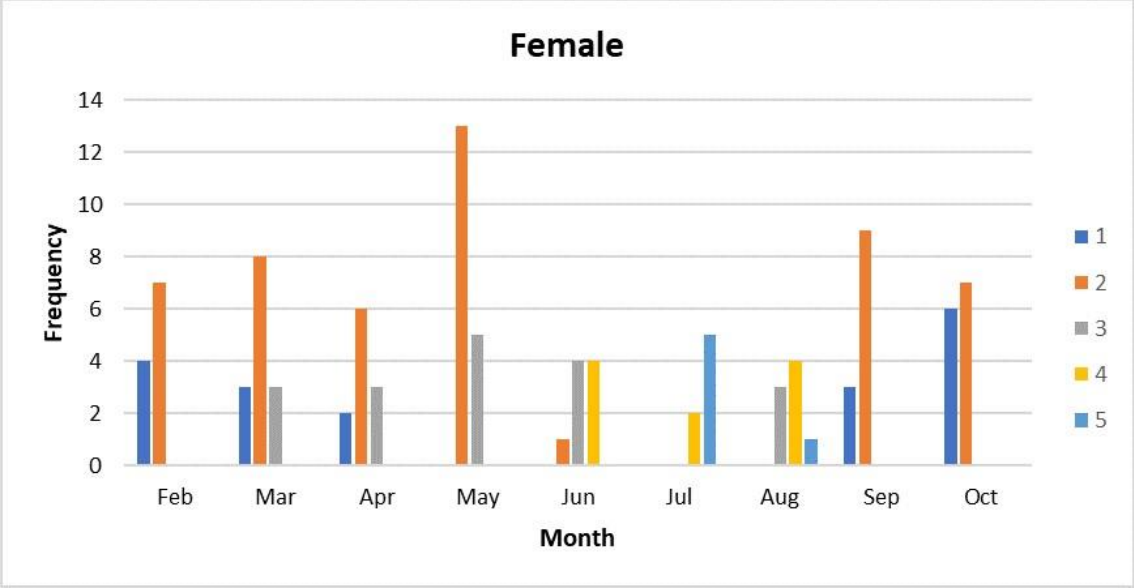

Fig. 6. Sexual maturity stages of the females frigate tuna (*Auxis thazard*) (1, 2…5, are the maturity stage)

Mature individuals were defined by the presence of gonads in stage three or later, which signified their readiness for reproduction. The size at which fifty percent of individuals achieve maturity, referred to as the size at first maturity (LF50), is a crucial parameter in comprehending the reproductive mechanisms of the frigate tuna. The results

show that the LF50 values for females and males to be 36 and 38cm, respectively. These results offer significant insights into the initiation of sexual maturity in the specimens under investigation (Fig. 7).

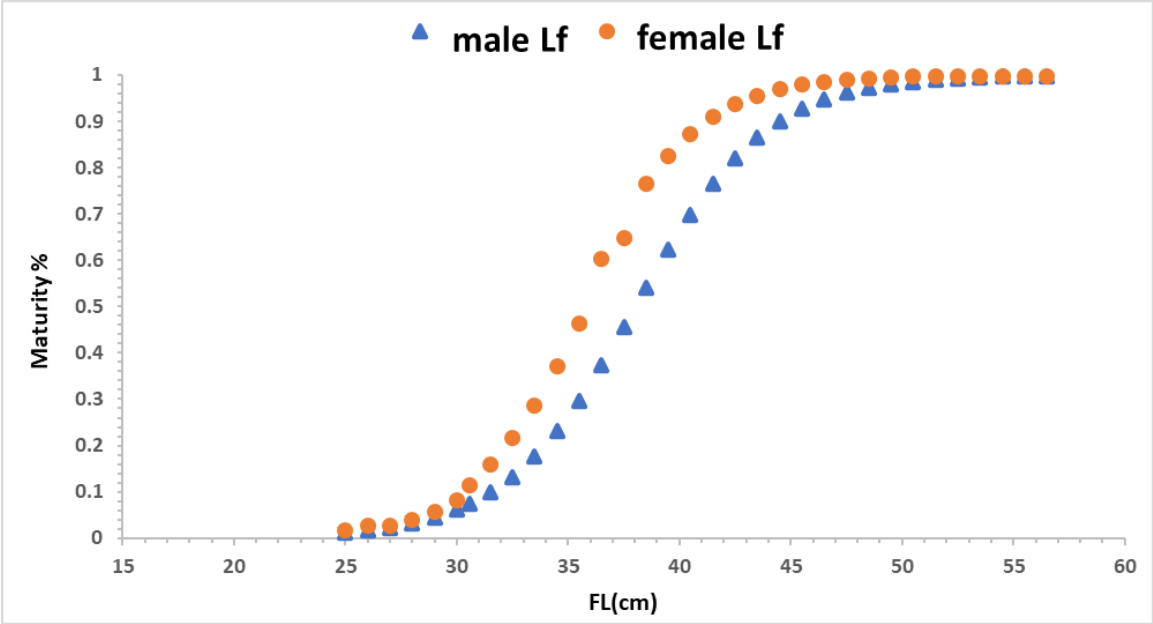

Fig. 7. Calculated sizes at first sexual maturity for males and females of frigate tuna samples (*Auxis thazard*) in the northern Atlantic waters off the Moroccan coast

Throughout this investigation, the sex of each specimen was ascertained through visual examination of the testies for males and ovaries in females. Out of the total 215 specimens examined, 103 individuals (48%) were identified as female, while 97 specimens (45%) were classified as male. However, due to the immaturity of some specimens and the consequent difficulty in discerning their sex based on the thread-like appearance of their gonads, approximately 6% of the sampled fish remained unclassified. The resulting sex ratio was calculated to be 1:1.06. Utilizing the chi-square test, it was deduced that the sex ratio of the frigate tuna exhibited an equilibrium, with no statistically significant deviation observed ($P > 0.05$).

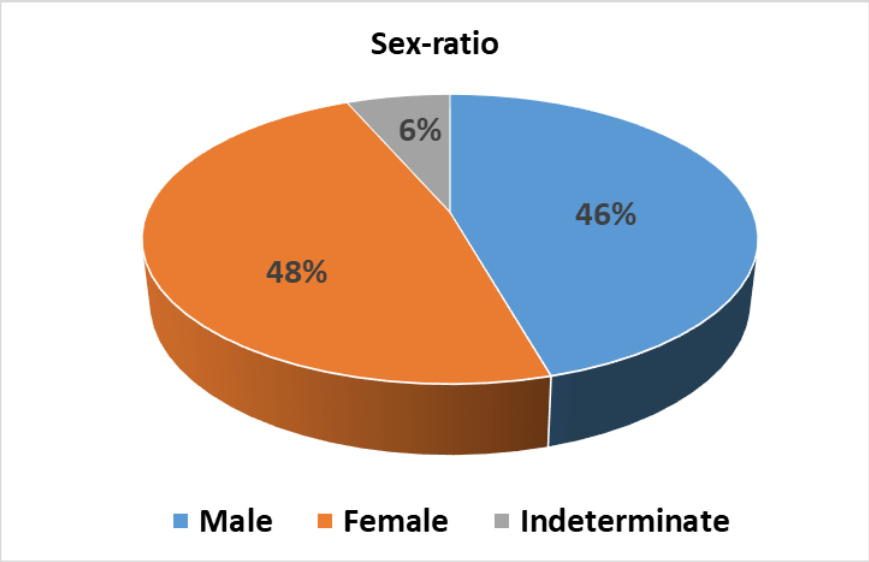

Fig. 8. Proportions of males and females of the frigate tuna (*Auxis thazard*)

DISCUSSION

1. Size frequency

The size frequency results of the frigate tuna in the North Atlantic of Morocco illustrates a dominance of adult and premature individuals, whose size is larger than 35cm, with a range from 30 to 43cm of the whole sampled specimens represented in the catches of this study.

In the context of the study area, our results are similar to those reported for the Strait of Gibraltar, as **Roda (1966)** found that the size frequency range for this species caught in coastal waters by traps was from 34 to 45cm. Additionally, a study conducted in the Northeast Atlantic, specifically in the waters south of Morocco, Mauritania, and Senegal, indicated that the size range of the frigate tuna was between 21 and 48cm **(Petukhova, 2019)**. These significant differences can primarily be attributed to the methodology, as the catches in the study were conducted using Russian research trawls operating at depths ranging from 23 to 1350 meters, covering several hundred meters of depth.

As shown in Table (2), the size range of this study is relatively different compared to those found in other areas around the world : [New Zealand waters: 26-41cm **(Roberts *et al.*, 1977)**; Mediterranean and Spanish South Atlantic: 21-48cm **(Ramos *et al.*, 1986)**; North Andhra Pradesh India: 30-46cm **(Deepti & Sujatha, 2012)**; Taiwan Strait: 25-40cm **(Tao *et al.*, 2012)**; Ivory Coast waters: 25-48cm **(Bahou *et al.*, 2016)**; Gulf of Guinea: 26-49cm (**Abekan *et al.*, 2017)**; Northern Persian Gulf and Oman Sea waters: 21-49cm **(Darvishi *et al.*, 2020)**]. Furthermore, we deduce that the size distribution

observed in our sampling is representative of the population, as it aligns with the findings reported in the majority of earlier research studies.

Table 2. Length distribution of the frigate tuna (*Auxis thazard*) specimens in different areas

Authors	Area	Number of samples	Lmin-Lmax (cm)
(Roda, 1966)	Strait of Gibraltar	-	34 - 45
(Roberts *et al*., 1977)	New Zealand waters	176	26-41
(Ramos *et al*., 1986)	Mediterranean and Spanish south Atlantic	-	21-48
(Deepti & Sujatha, 2012)	North Andhra Pradesh, India	2185	20-49
(Tao *et al*., 2012)	Taiwan strait		25-40
(Jawad *et al*., 2012)	Bay of Oman	55	32.1-43
(Tampubolon *et al*., 2016)	West coast Sumatera, eastern Indian ocean	5673	19-42
(Bahou *et al*., 2016)	Ivory Coast waters	496 females	25-48
(Abekan *et al*., 2017)	Gulf of Guinea	-	26-49
(Joachim And Razafimandimby 2017)	Madagascar	-	25-58
(Petukhova, 2019)	Northeast Atlantic	-	21-43
(Mudumala *et al*., 2018)	North West Coast of India	924	27-55
(Darvishi *et al*., 2020)	Northern Persian Gulf and Oman Sea waters	2083	21-49
(Vieira *et al*., 2022)	Southeastern Brazilian coast	650	26,5–49,4
Present study	**North Atlantic of Morocco**	**215**	**30-43**

2. Condition factor (K)

The investigation into the monthly evolution of the condition factor (K) revealed that throughout the year, as the frigate tuna's reproductive organs mature, both male and female fish manage their energy intake in a similar manner to support this process. The months that precede the start of reproduction correspond to the maximum values of K. This indicates that the liver loses weight, which may be a sign that the hepatic reserves

for gonad development are being metabolized **(Bailey, 1952; Smith, 1957)**. For many fish species, the storage and accumulation of fat in the liver during ovary development is a well-known phenomenon, which is then transferred to the generation of the gametes **(Baibbat *et al*., 2016)**.

In this investigation, the condition factor K was used to assess the overall health and diet of the frigate tuna. It takes into consideration the weight and length of the fish, providing insights into the habitat suitability for feeding conditions **(MacGregor, 1959)**. Once the gonads attain stage of maturity, a clear decline in the condition factor was noticed indicating that frigate tuna during this time became thin, probably because of insufficient feeding intensity. Because the energy supply from food consumption poorly compensated for energy needs from the muscular origin, energetic reserves held within the liver were being utilized, which contributed to the condition factor being reduced **(Djadji *et al*., 2013)**.

3. GSI

During this study, the monthly variations in male and female development stages revealed that the spawning period occurred mainly from June to August, peaking in July, which correlated with the increase in water temperature. This conclusion is supported by a macroscopic observation of gonads. Indeed, this reproductive season is inferred from the significant presence of males and females in stages IV-V of maturity (mature-spent) in samples collected from June to August. These results are consistent with the findings from the previous studies cited in Table (3), which suggest that the frigate tuna fish prefer warm waters (>20 °C) for spawning **(Schaefer, 2001)**. This was also reported by **Rao (1964)**, **Rudomiotkina (1984)**, **Muthiah (1985)** and **Bahou *et al*. (2016)**. However, other studies have proven that the frigate tuna could also spawn in cold waters and during different seasons of the year **(Jones & Kumaran, 1964; Yesaki & Arce, 1991; Ghosh *et al*., 2012; Vieira *et al*., 2022)**. The spawning behavior of the *Auxis* genus is documented across a wide range of habitats, from coastal to oceanic waters, spanning tropical and subtropical regions **(Collette & Nauen, 1983)**.

4. Size at first maturity

Previous research on the frigate tuna has predominantly concentrated on determining the size at which individuals reach initial sexual maturity, a crucial aspect of their life history. Understanding a fish's length at this stage enables predictions regarding its catchable size, a factor intricately linked to the environment inhabited by the studied population **(Mattingly *et al*., 1996)**. The present study contributes to this knowledge by revealing that the male frigate tuna typically achieve sexual maturity at 38cm (fork length), whereas females attain it at 36cm. These findings deviate from those reported in several earlier studies, as summarized in Table (3). The highest size at first maturity has been reported by **Rao (1964)** with a L50 reaching 41,6cm in India. Nevertheless, the smallest size was found in Japanese waters with 29cm **(Collette & Nauen, 1983)**.

Table 3. Comparison of selected aspects of reproductive biology of the frigate tuna (*Auxis thazard*) from different regions

Authors and year	Spawning period	Size at first maturity (FL)	Region
(Tester & Nakamura, 1957)	–	35 cm	Hawaiian Sea
(Jones & Kumaran, 1964)	January-April	–	Lakshadweep Sea
(Rao, 1964)	August-September	41.6 cm	Vizhingam, South-West Coast (India)
(Klinmuang, 1978)	–	37 - 41	Gulf of Thailand and east coast of Peninsular Malaysia
(Chiampreecha, 1979)	–	37 cm	Thailand and off east coast of Peninsular Malaysia
(Collette & Nauen, 1983)	–	29 cm	Japanese waters
(Rudomiotkina, 1984)	April-September	–	Off the coast of Sierra Leone
	Summer period	–	Gulf of Guinea
	November-December	–	Off Congo and Angola
(Muthiah, 1985)	August-September	30 cm for males 30.5 cm for females	Mangalore - India
(Yesaki & Arce, 1991)	–	Male-31 Female-34	Indo Pacific region
James *et al*. (1992)	August-November	30 cm	India
(Fonteneau, 1993)	–	30 cm	Southeast Atlantic stock
(Yesaki, 1994)	December-March	38 cm	West coast of Thailand
(Vinh, 2001)	April to June	34 cm	South China Sea, (Vietnam)
(Jude *et al*., 2002)	-	30.8 cm for males 32.8 cm for females	Thoothukkudi waters, southeast coast of India
(Deepti & Sujatha, 2012)	Between March and April	36.7 Cm for males 38.5 cm for Females	North Andhra Pradesh - India
(Ghosh *et al*., 2012)	-	29.7	Indian waters
(Tampubolon *et al*., 2016)	-	34.89	The Indian Ocean's Eastern (Prawira)
(Bahou *et al*., 2016)	June to November	29.88	Coastal marine waters of Côte d'Ivoire
(Abekan *et al*., 2017)	throughout the year	–	Gulf of Guinea
(Zapadaeva, 2021)	-	30.1	Northeast Atlantic
Present study	**June to August**	**Male 38 Female 36**	**North Atlantic of Morocco and strait of Gibraltar**

The disparities between the findings of our study and previous research could stem from the adverse effects of fishing pressure and compensatory mechanisms, both of which influence variations in maturation size **(Walker & Ellis, 1998)**. Additionally, environmental factors may contribute to this discrepancy, leading to phenotypic plasticity in fish and subsequent alterations in maturity size **(Ishida *et al*., 1993; Cox & Hinch, 1997; Pyper *et al*., 1999; Wertheimer *et al*., 2004)**.

CONCLUSION

In conclusion, this study enhances our understanding of the reproductive biology of the frigate tuna (*Auxis thazard*) along the North Atlantic coast of Morocco, an area that has been understudied. Our findings indicate a size frequency distribution dominated by adult and premature individuals, ranging from 30 to 43cm, consistent with previous studies in similar regions.

We observed significant variations in the condition factor (K) and gonado-somatic index (GSI) linked to the reproductive cycle, with peak GSI values occurring during the summer months (June to August), indicating heightened reproductive activity associated with warmer water temperatures. Notably, males reach sexual maturity at 38cm and females at 36cm.

Overall, this research emphasizes the necessity of region-specific studies to inform effective conservation and management strategies for small tuna stocks. By providing essential baseline data, our study supports the sustainable exploitation of marine resources and the long-term viability of fish populations in the Atlantic waters off Morocco. Continued research and monitoring are recommended to further these efforts in managing the frigate tuna fisheries in the region.

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