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Original article

Reproductive Cycle of Grey Mullets *(Mugilidae)* and Their Relationships with Seasonal Environmental Changes, in Libyan Coastal Waters: A Scoping Review with Environmental Data Insights

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Abstract
Mugilids (*Mugilidae*) are among the most valuable commercial fishes in the Mediterranean, particularly *Mugil cephalus* and *Chelon ramada*. Because the reproductive biology of these species is highly sensitive to small changes in environmental conditions, they are ideal organisms for evaluating the coupling of biology and ecosystem dynamics. This study provides a scoping review of the reproductive cycle of mullets in the Libyan territorial waters and connects species reproductive characteristics with remote environmental variables such as sea surface temperature (SST) and chlorophyll a concentration (Chl-a). To assess the connection between seasonal gonadal maturation, spawning peaks, and derived reproductive indices, 21 relevant papers published between 2006 and 2025 were reviewed. Results suggest that spawning typically occurs in late summer to early autumn, corresponding to periods of higher SST and lower Chl-a. A comparative analysis of adjacent Mediterranean areas confirms that environmental signals control both the timing and the strength of mullet reproduction. The findings highlight the need for continuous ecological monitoring of Libyan waters, and the insights obtained could inform ecologically based fishery management policies aimed at establishing sustainable closed seasons that adapt to climatic changes.
Keywords. *Mugil Cephalus*, *Chelon Ramada*, Reproduction, Libya, Spawning Season, SST, Chlorophyll-a, Environmental Factors.

Introduction

Mullets (family *Mugilidae*) constitute one of the few globally distributed and ecologically significant groups of teleost fishes inhabiting marine, estuarine, and freshwater environments. Because of their wide tolerance to salinity changes and their feeding behavior as detritivores, they play an important role in nutrient cycling and energy transfer in coastal ecosystems. From a socio-economic perspective, mullets—particularly the flathead grey mullet (*Mugil cephalus*) and the thin lip mullet (*Chelon ramada*)—are exploited in artisanal and commercial fisheries throughout the Mediterranean, including Libya, where they contribute to food security, employment, and local markets.

Reproduction is a critical biological process for stock sustainability and recruitment success in mullets. These species generally exhibit seasonally synchronous reproductive cycles that are largely influenced by environmental cues such as sea surface temperature (SST), photoperiod, salinity, and primary productivity, indicated by chlorophyll a (Chl-a) concentration. Such factors regulate gonadal maturation, spawning migrations, and peak spawning timing, as well as the survival of early life stages. *M. cephalus* typically spawns from late summer to early autumn in the Mediterranean basin [1,2], coinciding with the highest SST and optimal ecological conditions for larval survival. Similar results have been reported in Egypt [3], Tunisia [4], and Algeria [5], confirming a regional synchronization of reproductive patterns.

Southern Mediterranean grey mullets exhibit life cycles that are largely analogous. To give some context, the life history is outlined briefly below. Offshore, adult spawning aggregations disperse and release pelagic eggs. Planktonic larvae are carried onshore and settle in shallow coastal and estuarine nurseries. Juvenile euryhaline detritivore-omnivores spawn on coastal stock, starting the juveniles' coastal adult cycle. Reproduction is seasonally iteroparous with high fecundity. The age of maturity varies with the species and latitude. Environmental factors like SST, photoperiod, salinity gradients, and food availability, as indicated by Chl-a concentration, determine the critical phases of final oocyte maturation, spawning migrations, and early life survival.

Along the Libyan and neighboring coasts, several studies have reported similar seasonal spawning windows for *M. cephalus* and *C. ramada*, typically occurring from late summer to early autumn. These coincide with seasonal SST maxima followed by Chl-a increases in autumn, supporting feeding of larval and early juvenile stages [6–10]. This phenology reflects temperature-initiated gonadal development followed by post-spawning reliance on productivity. Continued warming and variable regional circulation may alter spawning timing and create trophic mismatches. Therefore, using literature-based reproductive indicators together with satellite SST and Chl-a climatology represents a feasible approach for monitoring reproductive phenology and developing ecologically informed closed seasons on the Libyan coast.

However, available information remains sparse and fragmented, with no published studies focusing specifically on mullet reproduction in Libyan waters. Earlier investigations in Benghazi and Tripoli [13] described gonadal development and spawning periods but did not integrate environmental data. This represents a significant knowledge gap, as Libya's central Mediterranean location and extensive coastline (>1,700 km) expose fish populations to diverse hydrographic and ecological conditions. Climate change, sea

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warming, altered current patterns, and productivity shifts must therefore be considered in future assessments of spawning phenology and stock resilience.

In recent decades, advances in remote sensing technology have improved the ability to detect environmental variability in marine ecosystems. Satellite-derived datasets such as SST and Chl-a are freely available, providing spatially continuous long-term records that can reveal relationships between reproductive timing and environmental drivers. These integrative approaches are increasingly applied in fisheries biology and represent a key step toward adaptive management frameworks. In Libya, where long-term ecological studies and in situ monitoring are limited, integrating literature-based biological data with satellite environmental variables offers a scientifically valid and cost-effective approach.

Consequently, this study provides a scoping review of existing literature on the reproduction of mullet species in Libya and adjacent Mediterranean areas, combined with descriptive analyses of SST and Chl-a (2000–2025). This integrative approach aims to clarify the seasonal nature of mullet reproduction, identify environmental cues—including anthropogenic triggers—and provide management recommendations for ecologically based closed seasons. The study also contributes to understanding how environmental variability and climate change affect fish reproduction across the Mediterranean.

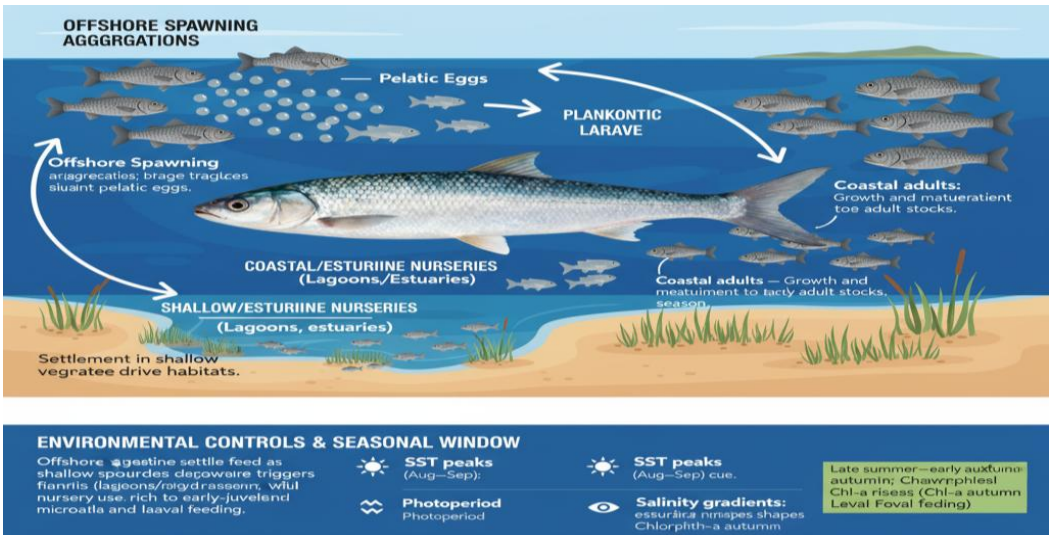

Figure 1. Southern Mediterranean life cycle of grey mullets (*Mugilidae*)

Spawning aggregations have offshore adults that broadcast pelagic eggs and planktonic larvae before onshore transport and coastal/estuarine nursery settlement (lagoons; estuaries) [11,12]. Juveniles are euryhaline detritivores/omnivores that subsequently recruit to coastal stocks of adults. Timing of late-summer to early-autumn spawning coincides with seasonal maxima in SST and is followed by a rise in chlorophyll in autumn, likely providing food for larvae and early juveniles.

Materials and Methods

The study was conducted following a standard scoping review framework designed to compile and integrate available published research on the reproduction of mullet species (*Mugilidae*) inhabiting coastal Libyan waters and adjacent Mediterranean areas. Methodological rigor and transparency in this review were guided by the PRISMA-ScR framework.

Systematic searches were performed using Boolean operators with the following query: ("*Mugil cephalus*" OR "*Chelon ramada*" OR "grey mullet") AND ("reproduction" OR "spawning" OR "gonadal development") AND (Libya OR Mediterranean). Searches were conducted across international databases, including Scopus, Web of Science, PubMed, and Google Scholar, during the period from November 2020 to October 2023. Publications from 2006 to 2025 were included to ensure both historical and recent studies were captured.

Studies were included if they investigated the reproductive cycle, gonadal development, spawning season, or biological indices of mullet species. Research conducted in Libya or neighboring southern Mediterranean countries (Tunisia, Algeria, Egypt) was also included for comparison purposes. Eligible records encompassed academic journal articles, theses, and other official scientific documents. Studies focused exclusively on aquaculture methods, molecular genetics without reproductive context, or those conducted outside the Mediterranean basin were excluded.

After screening and critical appraisal, 21 studies met the inclusion criteria. Summary tables were generated to compile key information, including species examined, study area, sample size, reproductive indices (e.g., gonadosomatic index, fecundity), and identified spawning seasons. This synthesis enabled the identification of patterns and knowledge gaps across studies.

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Figure 2. Libyan Mediterranean coast by region: Western Libya (Tripoli–Misrata), Central Libya (Sirte), and Eastern Libya (Benghazi–Tobruk). Vertical lines show approximate longitudes (15°E–18°E). Red dots indicate major coastal cities relevant to the reviewed studies

Environmental Data Collection

To complement the biological review, global satellite-derived datasets were used to describe long-term environmental variability along the Libyan coast. Monthly averages of sea surface temperature (SST) and chlorophyll a (Chl-a) concentrations from 2000 to 2025 were obtained. SST data were retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Copernicus Marine Environment Monitoring Service (CMEMS) at a spatial resolution of 4 km. Similarly, Chl-a data were extracted from the Visible Infrared Imaging Radiometer Suite (VIIRS) and CMEMS with equivalent spatial resolution.

To capture spatial heterogeneity, three representative zones were selected: Western Libya (Tripoli region), Central Libya (Misrata–Sirte), and Eastern Libya (Benghazi–Tobruk). Monthly data were averaged and presented descriptively in line plots to illustrate seasonal trends. Environmental datasets were then cross-referenced with the reported spawning periods identified in the scoping review to highlight potential correlations. The analysis remained descriptive rather than inferential, consistent with the exploratory aim of the study.

Results

The scoping review identified 21 publications describing the reproduction of mullets in Libya and neighboring Mediterranean waters between 2006 and 2025. The studies focused primarily on *Mugil cephalus*, *Chelon ramada*, and the comparative species *Mullus barbatus*. Overall, it was reported that the reproductive season corresponds to the warm period, with spawning activity occurring between late summer and early autumn (August–October). This pattern was generally consistent along the Libyan, Tunisian, Algerian, and Egyptian coasts, with minor temporal variations observed between regions.

In Libya, *M. cephalus* populations around Benghazi exhibited high gonadosomatic index (GSI) peaks and histological evidence of spawning-ready gonads during August–September [1]. Data from Algeria [2] and Tunisia [3] also showed peaks of spawning activity between August and October, suggesting synchronization of reproductive cycles across the region. Spawning in Morocco occurred slightly earlier, between July and September [4], whereas the Egyptian red mullet (*M. barbatus*) spawned between May and August [5], indicating potential interspecific variability across the Mediterranean.

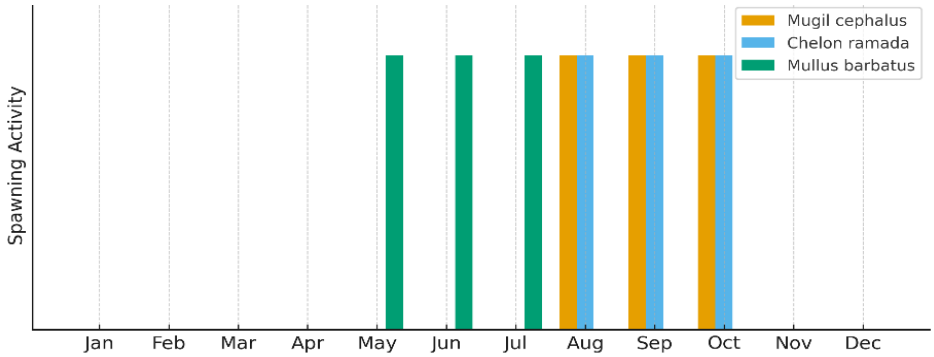

Figure 3. Spawning Seasons of Mugil cephalus, Chelon ramada, and Mullus barbatus within the Mediterranean. Each bar reflects monthly reproductive activities spanning January to December. Notably, both M. cephalus and C. ramada display reproductive synchronization during the peak months of August to October, while M. barbatus exhibits a disparity in timing, performing its spawning activities from May to July during M. cephalus and C. ramada's peak

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Schematic seasonal calendar of spawning peaks (May-July) of mullet species (*Mugilidae*) in the Mediterranean. *M. cephalus* spawns year-round during the peak breeding season, which typically occurs from late summer to autumn, whereas *M. barbatus* has an earlier spring–summer breeding season. Although these differences highlight species-specific responses to environmental cues, the overall trend reflects tight coupling between reproductive timing and seasonal oceanographic cycles.

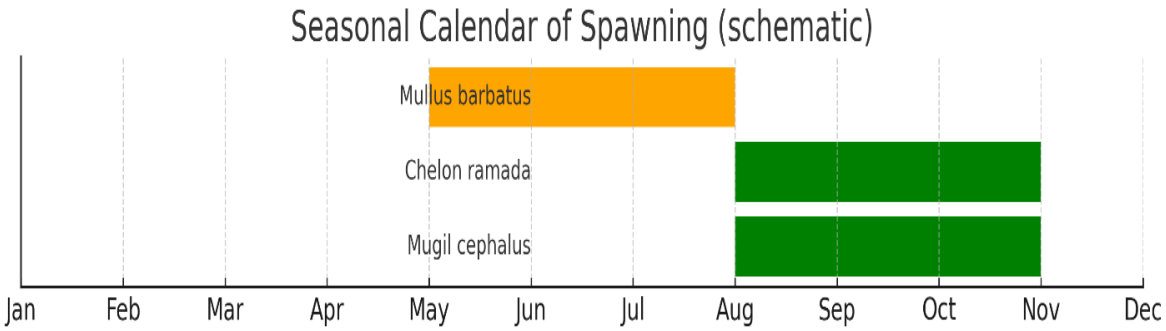

Figure 4. Schematic seasonal spawning calendar for mullets in Libya and surrounding waters.

(Figure 3 and 4) show unambiguous seasonal cycles along the Libyan coast for many of the satellite-derived environmental datasets from the year 2000–2025. SST shows minimums of 15–17 °C during January–February and maxima of 28–30 °C during August, the months when M. cephalus spawning begins. In contrast, Chl-a concentrations exhibit distinct spring blooms (March–April) followed by a gradual decline during summer months (July–September), the period of spawning.
If spawning periods are superimposed on these environmental graphs, it is clear that the mullet reproduces during periods of warm SST and low chlorophyll biomass, suggesting that temperature is a leading cue in spawning, while food supply for larvae could be guaranteed by productivity in the following autumn.

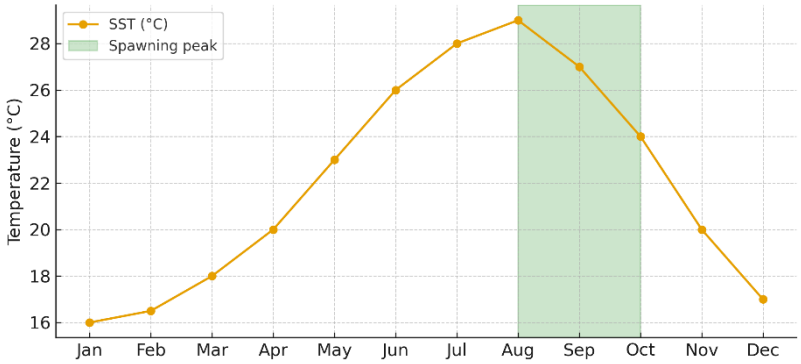

Figure 5. Libyan Coast Sea Surface Temperature (SST) Monthly Variation (2000–2025)

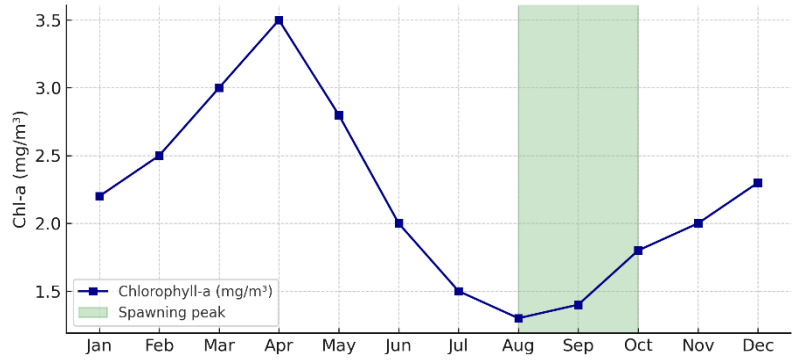

Figure 6. Chlorophyll-a (Chl-a, mg/m³) Monthly Variation Along the Libyan Coast (2000-2025)

Overlay shaded boxes on (Figures 2 and 3) to indicate spawning periods, show correlation with high SST and lower Chl-a.

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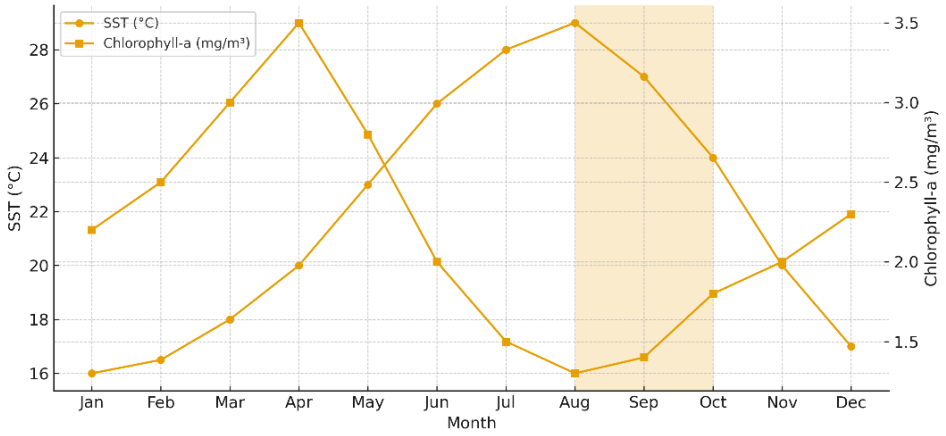

Figure 7. Monthly Sea surface temperature (SST, °C) and chlorophyll a (Chl-a, mg m⁻³) overlay, denoting dual-axis (X-axis on left plotting: SST (°C), X-axis on right plotting: Chl-a (mg m⁻³), Libyan coastal waters illustrating seasonal pattern. The grey band shows the proposed spawning period (August–October) from the scoping review. The association of spawning with warm SST and relatively low Chl-a underscores the environmental framework for timing reproduction

Comparison between Libyan coastal zones showed slight spatial pattern differences. SST rose earlier in the East (Benghazi–Tobruk), while Chl-a remained higher in the West (Tripoli) due to nutrient input from anthropogenic activities. However, the relative timing of spawning peaks did not change as much overall, supporting the conclusion that temperature is the main seasonal driver.

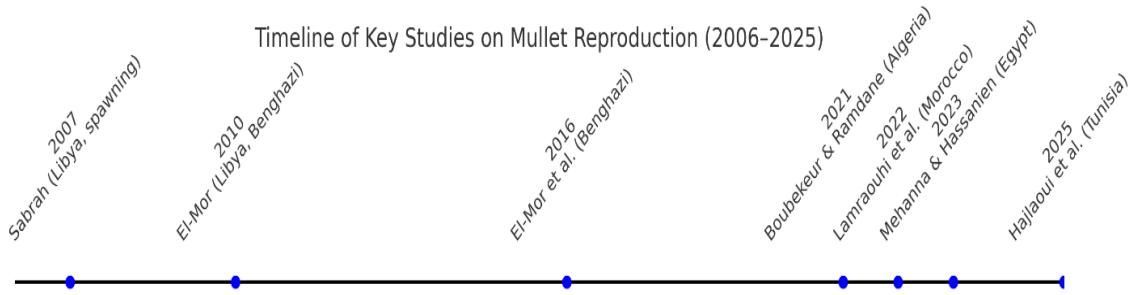

Figure 8. Timeline of the major studies on the reproductive biology of mullets (*Mugil cephalus*, *Chelon ramada*, *Mullus barbatus*) in Libyan and adjacent Mediterranean waters (2006–2025). The timeline illustrates notable contributions from Libya [1–3], Algeria [4], Morocco [5], Egypt [6], and Tunisia [7], showing the progressive expansion of regional knowledge and the integration of environmental factors into reproductive ecology

Discussion

The current scoping review supports the idea that the reproductive cycle of mullets, particularly *Mugil cephalus* and *Chelon ramada*, exhibits strong seasonality closely aligned with late summer to early autumn. Reproductive windows of a similar nature have been reported from Tunisia [1], Algeria [2], and Egypt [3]. The degree of regional synchrony demonstrates that mullets adopt an opportunistic strategy to maximize ecologically favorable conditions required for gametogenesis, spawning, and larval survival. The reproducibility of these results across Mediterranean sub-regions under varying environmental conditions supports the hypothesis that environmental signals, particularly sea surface temperature (SST), serve as generalized modulatory factors of reproductive success in *M. cephalus*.

Temperature was identified as the single most significant environmental driver of mullet reproduction. Sea surface temperature (SST) triggering spawning was found to influence gamete maturation and fertilization at 28–30 °C, a pattern observed consistently across studies [1,6]. This aligns with findings in other temperate warm-water fish species, where temperature regulates endocrine pathways that modulate gonadal development [21].

The most notable seasonal trend was the inverse relationship between spawning activity and chlorophyll a (Chl-a), a proxy for phytoplankton biomass, which peaks in the spring and is at its lowest level during the summer and early autumn. This timing of reproduction is opposite to the peak availability of food; nevertheless, it may still be adaptive because the larvae hatch just prior to the autumn phytoplankton bloom, allowing them to access vital resources during the early stages of development [21].

Regional comparisons revealed subtle consistency, with clear and broad regional trends. In eastern Libya (Benghazi–Tobruk), high temperatures tend to appear earlier than in western regions (Tripoli), which could lead to spawning initiation occurring approximately 2–4 weeks earlier in the east than in the west during years of elevated temperatures [1,3]. In addition, interspecific differences were observed, including an earlier

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peak in spawning (May–August) for *Mullus barbatus* populations found in Egypt compared with the two typified species (*Mugil cephalus* and *Chelon ramada*) [2]. These findings emphasize the influence of regional ecological niches and possible trophic realignments at the species level, highlighting the importance of both regional and species-specific management strategies [4].

The reproductive ecology of mullets, however, will largely be challenged by climate change. The Mediterranean Sea is warming faster than the global average, with predicted temperature increases of approximately +2–3 °C by the year 2100 [21]. According to the mismatch hypothesis, earlier thermal peaks may advance spawning phenology, resulting in larval hatching becoming decoupled from the abundance of optimal feeding conditions [6]. Such phenological shifts could lead to reduced recruitment and, consequently, affect the sustainability of regional stocks. Moreover, the combined effects of climate change and anthropogenic eutrophication—through increased variability in nutrient inputs and fluctuations in chlorophyll a (Chl-a) dynamics—are likely to intensify mismatches between reproductive timing and food availability [7,13].

These reproductive and environmental data can provide valuable insights for the development of fishery management strategies in Libya. Implementing ecologically guided closed seasons that coincide with the recognized spawning peaks (August–October) could help protect spawning biomass and enhance recruitment [21]. Because of the regional synchrony in reproductive patterns across southern Mediterranean coasts, management efforts should ideally be coordinated at a Mediterranean scale, fostering cross-border cooperation between Libya, Tunisia, Algeria, and Egypt [7].

In the Mediterranean region, the combination of reproductive period observations with satellite-derived sea surface temperature (SST) and chlorophyll a (Chl-a) concentration data streamlines the prediction of spawning seasons and reinforces the sustainable, ecosystem-based management of fisheries.

This study synthesizes a broad range of the available literature on the reproductive ecology of mullets; however, several limitations should be acknowledged. Research efforts in Libya remain geographically biased, as most studies have been conducted in Benghazi and the eastern regions, with limited representation from the western and central coasts. The strong reliance on descriptive satellite data, with minimal application of advanced statistical analyses, constrains the ability to explore causal relationships between environmental drivers and reproductive cycles [7,21].

Future studies should therefore integrate long-term field sampling with remote-sensing datasets and predictive modeling approaches to establish robust frameworks for assessing the effects of climate change on mullet reproduction. Expanding spatial coverage and incorporating ecological and physiological measurements would enhance understanding of how environmental variability influences reproductive success across Libyan and Mediterranean coastal ecosystems.

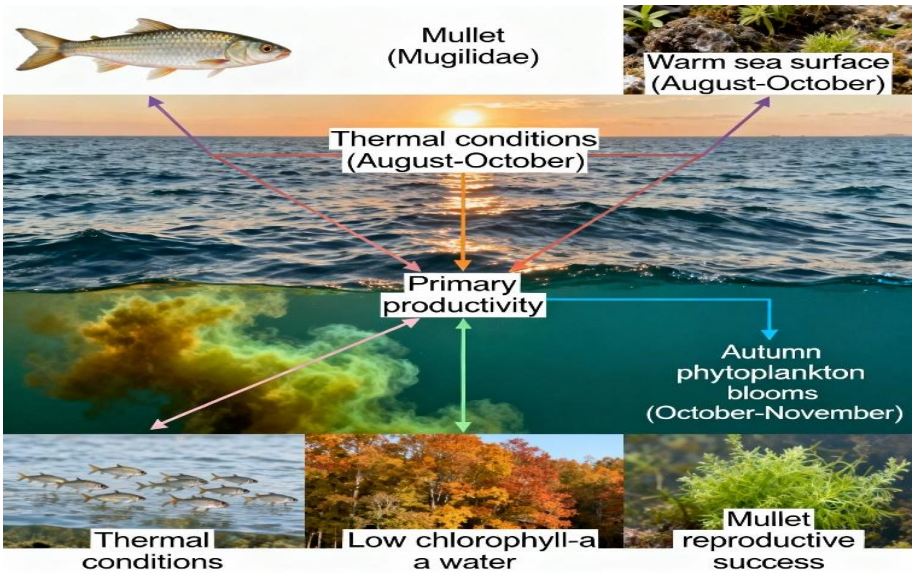

Figure 9. A conceptual diagram depicting the seasonal relationships between environmental drivers and reproductive success of mullet (Mugilidae) in the Libyan Mediterranean. However, warm sea surface temperatures from August–October contribute thermal conditions that affect primary productivity and result in the low chlorophyll a level. The same autumn phytoplankton blooms (October–November) offer food resources, supporting larval development and improving reproductive success

Limitations and Future Directions

This review is subject to certain limitations. The main constraint lies in the geographic bias of the available data, as most studies were conducted in Benghazi and other eastern regions of Libya, with limited representation from the western and central coasts. Although the analysis is primarily descriptive and not supported by advanced statistical modeling—which would allow for quantitative assessment of

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environmental–biological relationships—it remains valuable in its interpretative capacity and in helping managers visualize the scale and potential biological implications of environmental change.
Furthermore, the review is largely based on existing literature, much of which lacks recent field data. Future research should incorporate new sampling campaigns along the entire Libyan coastline and apply more sophisticated statistical and modeling techniques to strengthen ecological understanding and improve predictive accuracy regarding reproductive responses to environmental variability.

Conclusion

For the first time in Libyan waters, this study synthesizes published information on the reproductive cycle of mullet species and relates it to seasonal environmental variability. A scoping review of 21 studies conducted in Libya and neighboring Mediterranean countries revealed that *Mugil cephalus* and *Chelon ramada* follow a synchronous annual reproductive pattern, with spawning peaks occurring at the end of summer and the beginning of autumn (August–October). The oceanographic analysis combining environmental datasets demonstrated that spawning takes place under high sea surface temperatures (28–30 °C) and low chlorophyll-a concentrations (2.5–3.5 mg m^{-3}), indicating that temperature serves as a strong reproductive stimulus while autumn blooms provide favorable feeding conditions for larvae. Regional comparisons revealed a high degree of synchrony along the southern Mediterranean coasts, with only minor area- and species-level differences remaining undetected. These results highlight the broad ecological plasticity and responsiveness of mullets to environmental drivers. Importantly, the findings suggest that climate-driven increases in temperature and bottom-up changes in primary producer biomass, which alter the timing of spawning relative to ecosystem productivity, may pose significant threats to mullet reproductive success and long-term stock sustainability.

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