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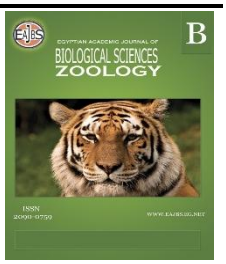

A Comparative Study of the Variations in Fish Eggs in the Arabian Gulf: A Morphological, Physiological, and Utilisation Perspective

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ABSTRACT

This study provides a narrative literature review of the variability of fish eggs in the Arabian Gulf, with emphasis on their morphology, physiological adaptations, biochemical properties and ecological implications. Fish eggs found in this region present remarkable adaptations to the extreme environmental challenges they face, including high salinity, temperature fluctuations and low oxygen levels. Biochemically, these eggs are loaded with proteins, lipids, and omega-3 fatty acids, which are crucial both for ecological sustainability and the economic benefits of fish species. Seasonal and spatial patterns of fish eggs are closely associated with recruitment of fish populations, as distributions are driven by physical and biological factors such as temperature, salinity and availability of plankton. Furrthermore, anthropogenic stressors such as fisheries overexploitation and habitat degradation are compromising the viability of fish eggs. Future research should incorporate molecular techniques such as environmental DNA (eDNA) and genetic sequencing to improve the identification of species threatened by changing conditions and better inform conservation and fisheries management of this dynamic marine ecosystem.

INTRODUCTION

1-Background and Importance of Fish Eggs:

From the perspective of a marine ecosystem function, fish spawn as fish eggs or roe, which is the first step of fish reproduction. They ensure sustainable fish catch volumes which allows fish pioneers to reproduce one of the most important aspects of ecosystem balance (Lin *et al.,* 2021). As key components of the marine food web, fish eggs represent an organic food source for numerous plankton predators, larval fish or larger size organisms (Hansen *et al.,* 2018). Their presence and prevalence are intimately linked to the health and balance of aquatic food webs.

Fish eggs have very high ecological importance, but represent also a significant economic value in fisheries and aquaculture. The roe of many species, such as sturgeon caviar or mullet bottarga (Sharifinia *et al.,* 2019), is highly regarded in international seafood markets. Eggs of fish are also commonly used in hatchery-aquaculture where eggs of commercially important fishes are spawned and the hatchery and early life stages of the reputable fish species are reared under controlled conditions (M.T.K. Al-Okailee, 2022). A better understanding of the morphological, physiology and biochemical composition of fish eggs would increase efficiency in aquaculture systems and is a key component of sustainable fishery management in a marine ecosystem.

One of the world's most extreme environments, the Arabian Gulf has high salinity, high temperature, and low freshwater inflow (T.K. Al-Okailee, 2022). Together, they create an inhospitable environment for organisms from the survival of fish eggs, through hatching and larval survival. Due to the semi-enclosed characteristics of Gulf leading to limited water exchange, it is very susceptible to environmental perturbations and anthropogenic stressors such as pollution and climate change (Santanumurti *et al.*, 2024).

Warming seas and salinity changes associated with climate change are also more serious threats to area fishes. Overfishing, habitat loss and pollution from industrial and coastal activities increase pressures on fish reproduction and biodiversity (Qasim and Al-Zaidy, 2024).

As such, examining fish eggs within such context can be crucial in understanding how species acclimatise to these challenging extremes whilst also, ultimately, ensuring proper fishery management approaches are fostered (M.T.K. Al-Okailee, 2022). The role of female morphology in fish oviparity recognition of reproductive behaviours and biochemistry of fish ova may also enhance conservation practises and facilitation of aquaculture aside from improvements management of marine resources around the Arabian Gulf (Wang *et al.*, 2025).

2-Problem Statement:

There is still minimal research on fish eggs from the Arabian Gulf, especially regarding their morphological, physiological, and biochemical similarities and differences. Although various studies examined particular species or environmental variables, the authors note that few studies track multiple species or aspects of fish eggs, making synthesising data difficult. Extreme temperatures and high salinity characterise the Arabian Gulf Sea environment, affecting fish egg morphology, survival, and biochemistry. However, these influences have been under-documented and under-analysed in the literature.

One of the key impediments in fisheries management and aquaculture is the lack of a readily accessible consolidation of knowledge from different studies. Currently, most of the research done into fish egg variability in this region has been entirely localised, and there has not been an overarching understanding of how fish use this area and the variability in their eggs. The literature on fish eggs' presence in the Arabian Gulf and the primary environmental drivers is scarce. There is an urgent need for a critical review that compiles the previous scientific studies on fish eggs based on secondary sources to fill the knowledge gap and understand future studies' directions.

3-Research Objectives:

- To review and contribute towards existing research on fish egg morphology.
- To analyse the physiological adaptation of fish eggs in gulf surroundings.
- To examine fish roe's biochemical composition and commercial significance.

The current study aims to compile and present a thorough review of previously published research articles on the morphological, physiological and biochemical composition of fish eggs within the Arabian Gulf. To distinguish various species, the study aims to quantify and describe variations in the morphology of fish eggs within the region, including its shape, size, surface texture, and other physical traits. Such discrepancies are essential for accurate species identification and fisheries management.

Besides morphology, this study will investigate the physiological adaptations of fish eggs to the harsh environmental conditions of the Arabian Gulf. These adaptations are critical in the face of environmental stressors such as high salinity, high temperature and fluctuating oxygen levels, which affect developmental processes. This review examines these adaptations to clarify how species differ in their strategies to cope with environmental stressors. Finally, this paper will explore the current literature on protein, lipid, and omega-3 fatty acid content in fish eggs. These findings will contribute to the evaluation of both the commercial viability of fish gonad consumption as a value-adding commodity at the consumer market and the life-changing role of high-value fish roe as a quality macro-nutrient in the sustainable supply of aquaculture diet especially towards the global demand of the aquaculture industry over time towards green pasture and frontier fish industries.

4-Research Questions:

Three major research questions inform this work, through which this review focuses on addressing key gaps in existing literature on Arabian Gulf fish eggs.

1-What are the morphological differences observed in fish eggs found in the Arabian Gulf?

The first question addresses the morphological diversity of fish eggs here. For species identification, ecology and fisheries management, an in-depth understanding of differences in size, shape, yolk composition, surface texture, etc., is essential. Since the Arabian Gulf hosts a variety of fish communities, identifying these morphological characters assists with species classification and identifies their reproductive strategies.

2-How do fish eggs psychologically adapt to extreme salinity and temperature conditions?

The second question examines how the physiological characteristics of fish eggs are adapted to the extreme environment of the Gulf. The high salinity, temperature and limited freshwater inflow make spawning for fish difficult. The research analyses how fish eggs respond to these conditions to understand species resilience better, successfully hatching and the survival rates of larval fish.

3-What is the biochemical composition of fish roe, and what are the impacts when commercially used?

The third question investigates the biochemistry of fish eggs for their nutritional value and industrial utilisation. Estimating protein, lipid and omega-3 fatty acids content may help evaluate their potential use for food or aquaculture feed. Investigating these biochemical traits aids sustainable fisheries and brings economic benefits to the area.

This study aims to provide an overview of findings related to fish eggs in the Arabian Gulf (and neighbouring regions) using a literature review of secondary sources (i.e. peer-reviewed journal articles, government reports, and academic books). The morphological, physiological, and biochemical features of fish roe from these broad ranges of published studies have been examined in this review. This paper reviews the available literature on the variability of fish eggs in the study region, which has the potential to open the way for future work in either research or policy for enhancing fisheries management and aquaculture development.

This study has significant limitations, though, because it does not collect primary data, unlike laboratory-based morphometric analysis, physiological experiments and biochemical testing on fish offspring. It is limited to only the literature available. Thus, any literature gap or literature inconsistency will lead to a less complete set of outcomes. Some studies on fish eggs in the Arabian Gulf also remain unavailable for either dissemination in a non-English language or due to publication limitations. Overall, notwithstanding these limitations, this review seeks to thoroughly integrate what is currently known while identifying potential directions for future work.

Literature Review:

1-Fish Egg Morphology and Classification:

The morphology of fish eggs varies significantly by species, habitat, and environmental conditions. Fish eggs can be classified based on their structure and ecology into four major types: pelagic, demersal (also called benthic), buoyant, and adhesive. Pelagic eggs are floating in the water column, typically transparent and with a high oil content that provides buoyancy, as described for several species in the Arabian Gulf (Ali *et al.*, 2019).

The principal sources of such float-type eggs are species that spawn in open waters, like Clupeidae and Scombridae. Conversely, demersal eggs are deposited on substrates such as sand, rocks or vegetation, which provides relatively more protection from predation but lowers dispersal ability, a characteristic typically associated with coral reef and estuarine inhabitants (Lin *et al.*, 2021).

Buoyant eggs (also pelagic eggs) rest in the water column like true pelagic eggs but lack the oil globules. This is relatively common in species living in environments that frequently transition between habitats, such as in estuaries where salinity fluctuates, thus affecting development (Ben-Hasan *et al.*, 2018). In contrast, adhesive eggs remain stuck to a surface (aquatic plant, rock, or artificial structure), keeping them in place in more turbulent waters and is characteristic of many groups of fish that spawn in shallow coastal environments (Chermahini *et al.*, 2020).

Table 1: Total number and abundance (egg/10 m²) of fish eggs collected from two stations in the N.W. of Arabian Gulf (Source: M.T.K. Al-Okailee, 2022).

Families	Total number	%
Sciaenidae	1324	45.6
Clupidae	876	30.1
Solidae	538	18.5
Polynemidae	90	3.1
Engraulidae	65	2.2
Ariidae	9	0.3
Total	2902	

Taxonomic features based on egg morphological characteristics such as egg diameter, yoke blob distance, chorion depth, and oil globule proximity in cod have been used to describe and predict relatedness (Sundt-Hansen et al., 2017). For instance, Al-Okailee (2022) studied the association between ichthyoplankton abundance and environmental factors including temperature and salinity in the Arabian Gulf (Table 1).

The fish egg shape likewise microhabitat life history strategy where the ones that undergo extreme salinity conditions are producing large resistant eggs (Qasim & Al-Zaidy, 2024). Awareness of these divergences is essential information for fisheries management and conservation to explain expected species distributions, spawning seasonality, and potential for reproductive success in an impacted environment (Sharifinia *et al.,* 2019).

Such advancements enhance the resolution upon which species can be discriminated, particularly in regions where fish diversity is high, whilst species discrimination remains challenging (Santanumurti *et al.,* 2024). Due to persistent environmental stresses on the Arabian Gulf, fish egg morphology studies will continue to play an essential role in conserving biodiversity and managing fish stocks.

2-Physiological Adaptations of Fish Eggs in Extreme Environments:

Many Gulf fishes' eggs, or embryos, show physiological adaptations to endure extreme environmental conditions such as elevated salinity, significant spatial and temporal hydrographic fluctuation, and limited freshwater influx (benthic embryos). Due to high evaporation and low river outflows, the region has unique hydrographic characteristics that severely limit the success of fish spawning and larval development. Most fish species have developed mechanisms to compensate for these stressors: eggs can have physiological adaptations such as buoyancy and osmotic regulation, and fish can have metabolic adaptations (Ben-Hasan *et al.,* 2018).

One of the modifications relates to the stimulation of osmotic stability of fish eggs in answer to salinity changes. The eggs of some species have a thick chorionic layer producing anti-desiccation and anti-osmotic stress protection (Jawad *et al.,* 2021). Pelagic eggs with significant lipid content remain buoyant and suspended in oxygenated layers of the water column (Ali *et al.* 2019).

However, the variations in ambient conditions to which Arabian Gulf fish species are eliciting plasticity in reproduction are sufficient to threaten the resiliency of many natural fish populations. Yet, many species remain resilient with plasticity in reproductive strategy sufficing to adapt to contrasting ambient conditions (Freije, 2015). The instigation by climate and anthropogenic changes to marine environments represents a salient cause of fish population changes, and clarification of these adaptations is essential for fish conservation and management.

Some demersal fish show that they have adhesive eggs that are attached to stable substrates, which could make them less susceptible to being displaced by strong tidal currents (Chermahini *et al.,* 2020). It is also known that temperature regulation is essential for fish eggs and that many fish in the Arabian Gulf have evolved to hatch in a temperature-dependent manner. Although increased water temperatures may accelerate embryonic growth, they increase metabolic rates and the need for dissolved oxygen.

The development of fish eggs in this area, as shown in (Table 2**)**, is synchronised with seasonal temperature cycles so that hatching occurs at times when plankton is the highest available food for the larvae (Lin *et al.,* 2019). Species such as *Pampus candidus* exhibit spawning biology that suggests a relationship between spawning seasons and environmental triggers to enhance hatchling survivorship (Qasim & Al-Zaidy, 2024).

Table 2: Overall frequency (Freq) and abundance (Abun) of the juveniles of the top 40 most frequently caught fish species in spring and summer from 2013 to 2016 (Source: Lin *et al.*, 2021)**.**

Species	Freq	Abun	Species	Freq	Abun
Upeneus doriae	127	2004	*Lagocephalus lunaris*	24	100
Leiognathus oblongus	124	1377	*Nemipterus japonicus*	22	64
Argyrops spinifer	123	657	*Penaeus semisulcatus*	21	74
Saurida undosquamis	106	468	*Epinephelus bleekeri*	20	29
Saurida tumbil	92	865	*Sepia pharaonis*	20	26
Pentaprion longimanus	85	741	*Lethrinus nebulosus*	19	71
Leiognathus bindus	57	383	*Scolopsis taeniatus*	19	48
Fistularia petimba	51	101	*Nemipterus peronii*	18	66
Upeneus tragula	48	336	*Diagramma pictum*	18	53
Epinephelus areolatus	45	77	*Pomadasys stridens*	17	435
Selaroides leptolepis	44	567	*Lethrinus borbonicus*	17	125
Nemipterus randalli	33	145	*Gerres oyena*	17	118
Lagocephalus guentheri	31	223	*Lepidotrigla bispinosa*	17	34
Sepia sp.	31	89	*Netuma thalassina*	16	31
Sphyraena forsteri	27	317	*Decapterus russelli*	15	72
Trachurus indicus	27	184	*Nemipterus bipunctatus*	14	32
Carangoides caeruleopinnatus	27	139	*Carangoides malabaricus*	14	27
Grammoplites suppositus	26	49	*Pseudorhombus arsius*	13	13
Ariomma indicum	25	86	*Carangoides chrysophrys*	12	61
Loligo duvauceli	25	63	*Triacanthus biaculeatus*	12	53

3-Biochemical Composition and Nutritional Significance:

Fish eggs serve as a significant source of nutrition for other marine life and are a potential human food item due to their high biochemical constituent content. Predominantly, they contain proteins, lipids and omega-3 fatty acids required for embryogenesis, energy storage and metabolism. The adaptation of the fish egg is shown through their unique biochemical response to extreme environmental conditions in the Arabian Gulf (Bouwmeester, 2020).

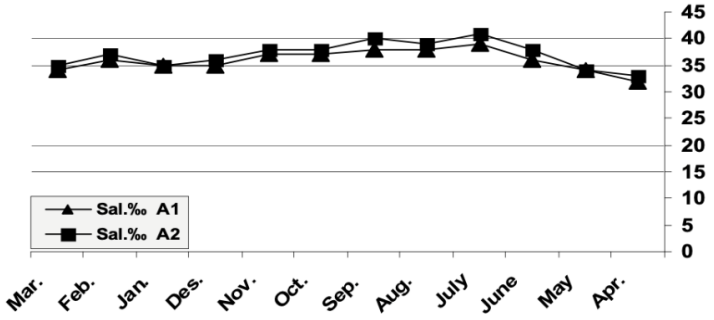

Fig. 1: Monthly variations in salinity (‰) at the two sampling stations (Source: M.T.K. Al-Okailee, 2022).

Monthly variation of salinity at two sampling stations (A1 and A2) shows higher values August to July and lower before May and April, highlighting seasonal variations as is shown in (Fig.1). The synthesis of lipid content is known to be higher in species from this area to compensate for salinity and temperature fluctuations, and thus, it plays a significant role in buoyancy and serves as an energy source for embryogenesis (Ali *et al.*, 2019). The fish egg consists mostly of proteins, essential for cell specialisation and chemical reactions (enzymes). Previous studies on ichthyoplankton in the Gulf revealed high variability in protein levels, and this variability appeared to be species-dependent since demersal fish eggs had more than 77% of their total protein as structural proteins, probably due to a protective chorionic layer (Chermahini *et al.*, 2020).

Lipids, such as triglycerides (TG) and phospholipids (PL), are the first source of

energy for embryos in early development, and omega-3 fatty acids (FAs), especially docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), are fundamental kinds of fatty acids for neural and visual development (Ben-Hasan *et al.*, 2018). These fatty acids are at comparatively high levels in fish roe, which is economically essential for aquaculture and human nutrition (Hansen *et al.*, 2018).

Nutrient transport is also implicated during seasonal fluctuations, as eggs laid during the cooler months exhibit higher protein levels to benefit the larva during non-ideal life circumstances (Qasim & Al-Zaidy, 2024). Moreover, anthropogenic stressors (for example, nutrients, contaminants, and habitat degradation) may modify the fish–egg nutritional composition and hence, reduce fitness and commercial significance (Sharifinia *et al.*, 2019).

4-Previous Research on Fish Eggs in the Arabian Gulf:

Research on fish eggs in the Arabian Gulf has focused primarily on species composition, environmental influences, and recruitment dynamics. These first studies, as shown in **(Fig. 2)**, dealt with inter-annual and seasonal distribution and abundance patterns of ichthyoplankton, frames of reference trends in fish egg production largely associated with temperature and salinity-driven forces (Ali *et al.*, 2019). It was also discovered that freshwater ichthyoplankton species spawning cycles are promoted by transitional seasons, leading to significantly greater species richness and abundance relative to the more variable seasons.

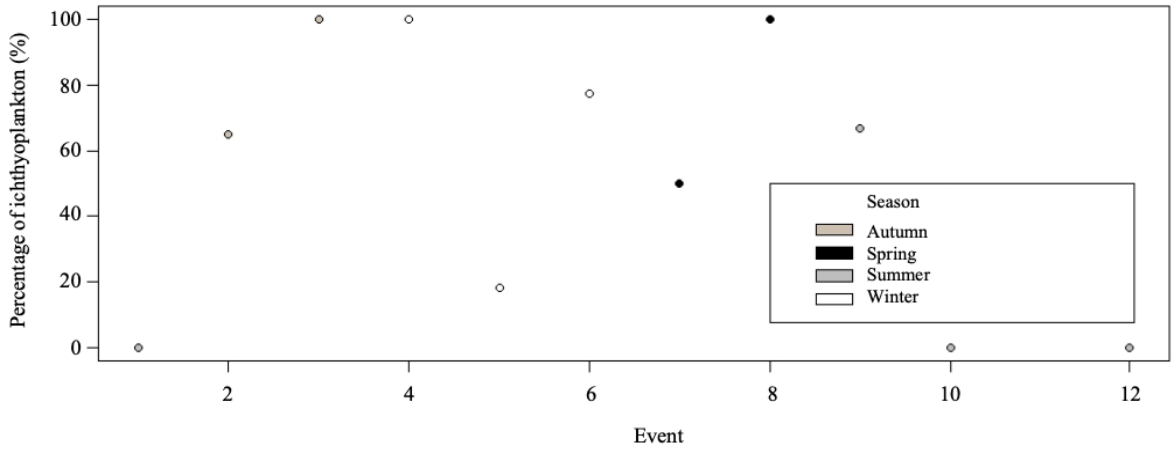

Fig. 2: Percentage of ichthyoplankton (%) among the collected zooplankton samples at each sampling event (Source: Ali *et al.*, 2019).

In accordance, another study indicated that on average, the highest abundance of larval fish was found in inlets influenced by freshwater, supporting the premise that the estuary plays a key role at the larval stage of the generalised life cycle (Chermahini *et al.*, 2020). The most significant impact on fish egg recruitment across the northwestern Arabian Gulf has been due to changes, mainly reduced freshwater inflow from the Tigris-Euphrates system.

Some more recent studies also have used molecular techniques like environmental DNA analyses that allow the identification of species and spawning dynamics (Hansen *et al.*, 2018). However, little is known about the impact of anthropogenic stressors such as pollution and habitat degradation on fish egg viability (Sharifinia *et al.*, 2019). Future studies should return to the effects of climate change and conservation measures on regional fish stocks

MATERIALS AND METHODS

For this review, a narrative literature review approach is taken, where secondary

sources are synthesised to identify fish eggs occurring within the Arabian Gulf. It lays out the research design, the approaches to data collection, criteria for selection of sources, and analytical techniques used to conduct the methodical, trustworthy review.

The inclusion criteria for the study are that the sources identified, need to be peer-reviewed journal articles, reports by the government, or any academically published books, as part of resource screening in the PRISMA framework (**Fig. 3**), whereby the year of publication is also ensured to be between 2015 and 2025. The focus of the studies needs to be on fish egg morphology, physiology, biochemical composition, and ecological influences presently found in the Arabian Gulf.

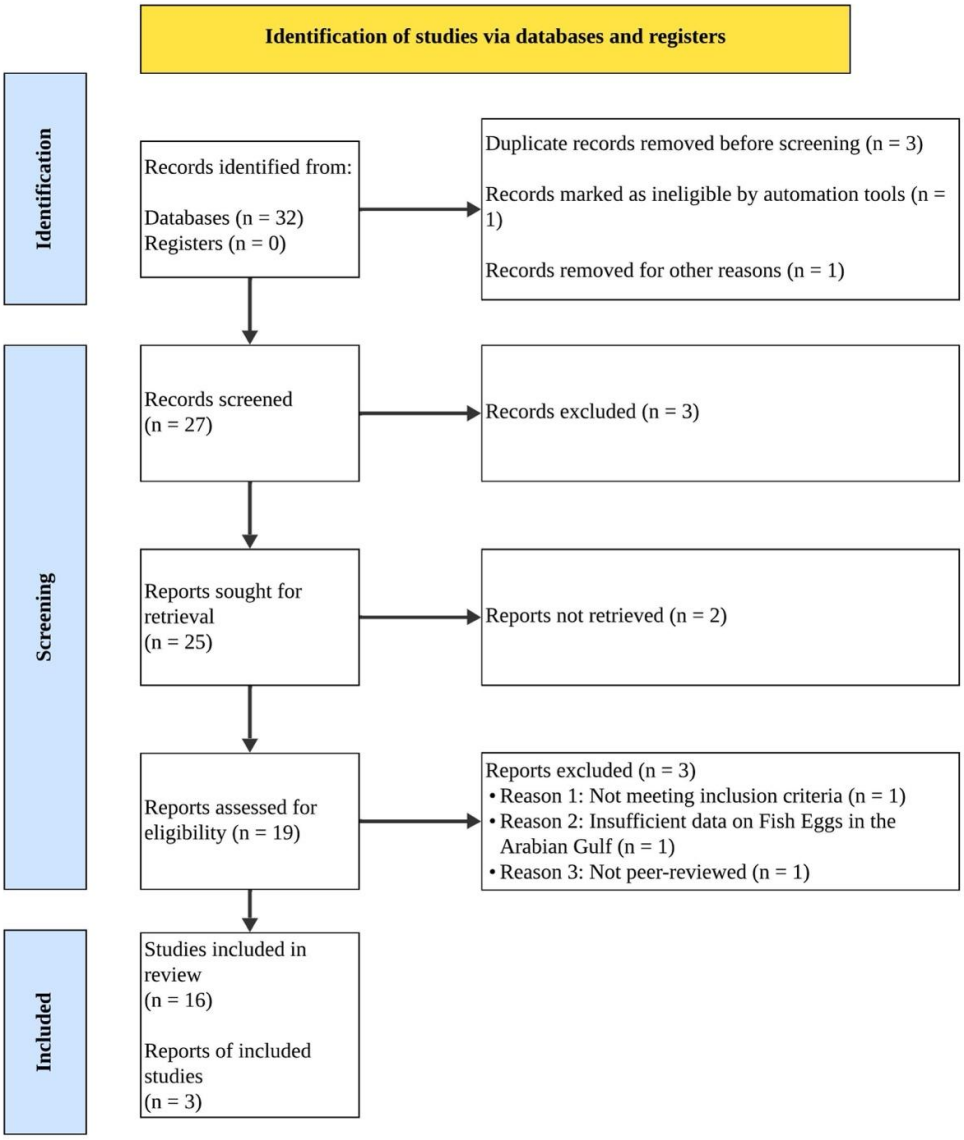

Fig. 3: PRISMA Diagram for sources review.

As part of the exclusion criteria, the papers that are opinion based, have Gray literature and do not contain any citations, are non-peer-reviewed sources, as well as are studies that are not relevant to the fish egg dynamics of the Arabian Gulf will be the ones that are not included in this review study, so that the research is more reliable, whereby only relevant and key findings are highlighted.

1-Research Design:

This review is a narrative literature review synthesises existing knowledge of fish eggs morphology, physiological adaptations and biochemical constituents in Arabian Gulf. A meta-analytic approach is employed to systematically extract results from various secondary

sources, including peer-reviewed journal articles and government and academic publications. In contrast to systematic reviews that apply strict inclusion and exclusion criteria often alongside meta-analyses, this review is qualitative and descriptive. It aims to synthesise the current knowledge in an assembled manner, rather than a statistical composite.

Based on the study objectives, the research process is organised into an outline of the main thematic areas: (1) morphology and classification of fish eggs; (2) physiological adaptations to extreme environmental conditions; (3) biochemical composition and nutritional value; and (4) fish roe for commercial purposes. This study contributes to fisheries management, aquaculture development, and conservation efforts in the Arabian Gulf by identifying key findings, gaps, and literature trends.

2-Data Collection and Source Selection:

This study uses secondary data collected from established academic databases of international peer-reviewed sources. High-impact scientific publications were accessed from Google Scholar, Web of Science, ScienceDirect, Scopus, and ResearchGate. The scholarly articles were filtered by applying Boolean operators in the search strategy besides a combination of keywords such as "fish eggs Arabian Gulf," "ichthyoplankton distribution Arabian Gulf," "fish roe biochemical composition," "physiological adaptations of fish eggs", and "fish egg morphology in extreme environments."

This study is mainly based on research conducted between 2015 and 2025 to avoid obsolescence in findings and thus reflect the current state of fisheries and marine biology. Older papers were only included when they were essential for understanding fish egg categorisations and ecological adaptations. Reference studies were included, which means studies that have passed peer review, are backed by the government, or are published in a major academic journal. In contrast, the study excluded non-peer-reviewed sources, opinion articles, and Gray literature to ensure reliability.

Through a systematic review of these publications, the present study combines the knowledge released on fish eggs in the Arabian Gulf with a species-specific review to compare their general characteristics, environmental effects, and biochemical traits. The literature reviewed has been classified under morphological, physiological, and biochemical categories for a systematic discussion of the findings.

3-Data Analysis Approach:

The reviewed literature was categorised and interpreted according to qualitative thematic analysis. Thematic coding was performed in which studies were assigned to pre-existing categories, according to the aims of the particular study, namely the categories of morphology, physiology, biochemical composition, and commercial uses. We evaluated each research paper for its key findings, methodologies and limitations to maintain consistency in our analysis.

The study also used comparative analysis, which assessed similarities and differences between research findings. Studies on closely related fish species in other regions were cited for greater ecological context. Research related to environmental changes, including high salinity, thermal stress, and human pollution, to fish egg development was given special attention.

Using this method, the review grounded insights into fish egg viability, recruitment success, and nutritional potential by systematically synthesising literature for applied use by those in fisheries and aquaculture.

4-Limitations of the Methodology:

Although the narrative literature review offers a holistic overview of the current literature, it has limitations. It does not involve new meta-data, laboratory analysis, field sampling, or experimental validation. Consequently, this widens the scope of the findings, limited by what the world of academia publishes, reflecting a potentially biased public perception of finding the literature (publication bias) due to not having inconclusive or negative results represented.

A second limitation is one of area; although the study is specific to the Arabian Gulf, other results may be based on extrapolations from nearby marine areas. Furthermore, minor discrepancies in results may also arise because of variations in sampling methods, study designs, and data reporting standards between reviewed sources.

Language obstacles and limited access to regional investigations also created issues since some government documents or regionally conducted studies were not available in

international databases. Despite these limitations, this study uses multiple references and relies on peer-reviewed scientific literature to ensure objectivity and validity to the best possible extent.

RESULTS AND DISCUSSION

1-Morphological Variations Among Fish Eggs in the Arabian Gulf:

Fish eggs of different species found in the Arabian Gulf vary in morphology and depend on species characterisation and environmental conditions. These are categorised into pelagic, demersal, buoyant, and adhesive eggs, corresponding to particular reproductive strategies. They are usually transparent and spherical and contain a large oil globule that helps to keep the eggs suspended in the water column where they can be surrounded by oxygen-rich water a vital component required for embryo development and survival (Sahoo *et al.*, 2016).

In contrast, demersal eggs are deposited on or close to the seabed and have a thicker chorion and more yolk volume, both of which provide extra nutrients for more advanced embryonic development. While buoyant eggs float partially and are found in mid-water layers, adhesive eggs attach to mainly rocks, vegetation or somewhat artificial structures and thus avoid being carried away by currents (Chermahini *et al.*, 2020).

A comparison of morphometric parameters reveals large interspecific distinctions in size, yolk volume, oil globules and chorion thickness. Fish eggs measured from 0.5 to 1.8 mm, and differences were observed in the segmentation of the yolk and a number of oil globules (M.T.K. Al-Okailee, 2022).

Yolk size is positively correlated with salinity level as larger yolk reserves increase larval survival in nutrient-poor waters. The chorions of egg float from estuarine environments, however, are typically thinner, which promotes higher rates of oxygen exchange during conditions of changing salinity (Hasan, 2017).

Egg morphology is greatly influenced by environmental conditions such as temperature, ocean currents and salinity. An additional study found that when species spawn in high-energy coastal areas produce smaller, phenotypically streamlined eggs, they generate less drag and thus disperse more efficiently (Chermahini *et al.*, 2020).

In contrast, low-energy estuarine habitats produce more significant, more robust eggs that maintain stability in changing salinity environments. The range of shapes, sizes, and structures in the Arabian Gulf fish eggs illustrates evolutionary adaptations to extreme marine environments that drive recruitment and species distributions across the region.

Seasonal variations of species compositions and abundance of fish eggs in the Persian Gulf are shown in (Fig. 4**)**. The highest number and abundance of species occurred in summer, particularly of Clupeidae and Engraulidae, and the lowest diversity and abundance occurred in winter season (Wang *et al.*, 2025).

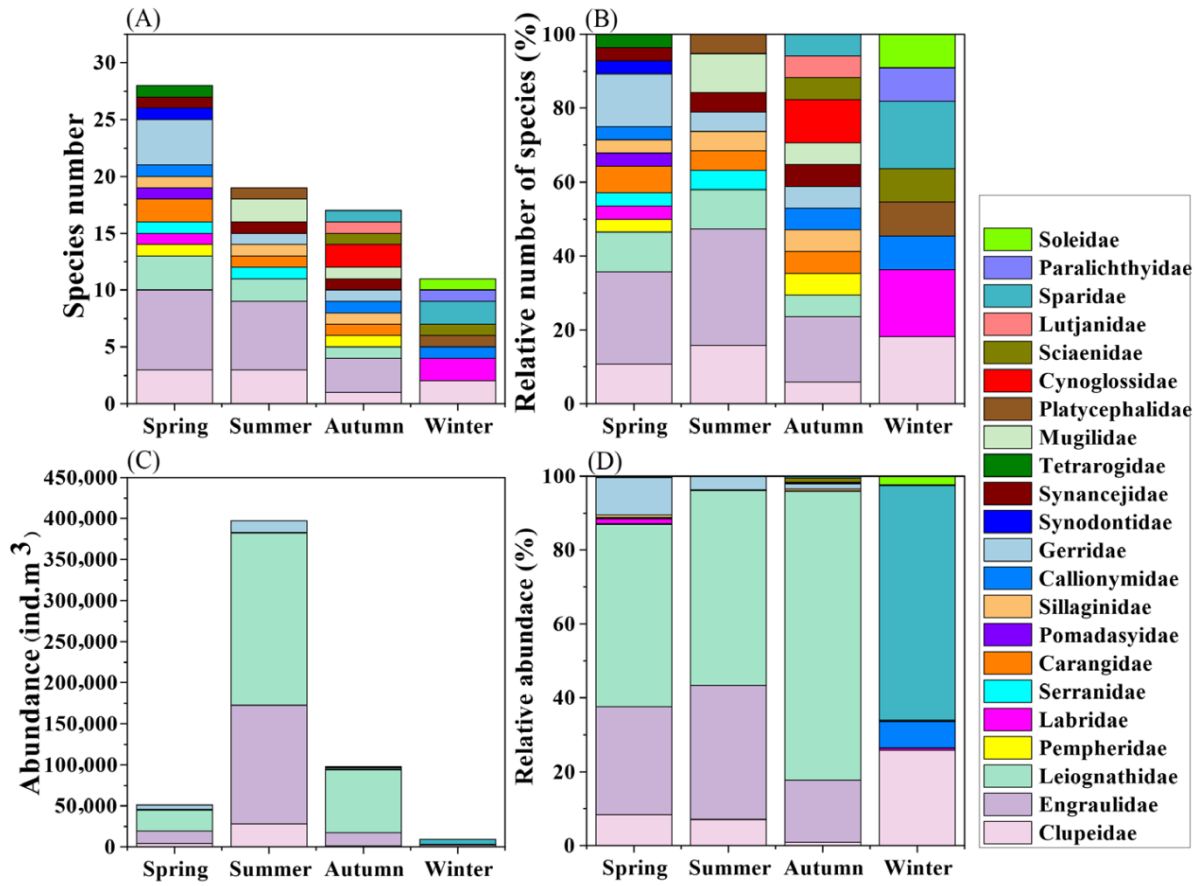

Fig. 4: Species and abundance percentage of fish eggs in Persian Gulf (Source: Wang et al., 2025).

2-Physiological Adaptations of Fish Eggs to Extreme Environmental Conditions:

However, fish eggs in the Arabian Gulf have to cope with high salinity, extreme temperatures and fluctuating oxygen levels, which create significant barriers for the normal development of embryos and the survival of larvae. Elevated salinity (of > 40 ppt) due to high evaporation rates and low freshwater inflow in the Gulf disturb the osmotic balance of fish eggs (Karam *et al.,* 2019).

For example, seasonal temperatures between 15 °C and 35 °C modulate metabolic activity, hatching success, and developmental rate. Oxygen is also an essential bio-geo-chemical factor for many different habitats. Still, the availability is also variable and is particularly influenced by eutrophication and heat stratification in coastal and estuarine environments (Sundt-Hansen e*t al.* 2017).

Fish eggs have evolved several physiological adaptations (e.g., osmotic regulation, fast embryonic development, and modified chorion) to tolerate such harsh conditions. In addition to chorion plasticity, eggs laid in hypersaline waters have thicker chorions to retain water and for structural protection (Sahoo *et al.,* 2016).

The rapid embryogenesis that occurs in a challenging salinity range can cause eggs of multiple species to hatch before developing. These osmoregulatory adjustment, for example, ion transportation mechanism, can make the organism maintain internal homeostasis by external salinity fluctuation (Lin *et al.,* 2021).

Egg survival and dispersal patterns are ultimately influenced by mixing with freshwater inflows and estuarine mixing. Intra-fraction salinity moving into relatively low salinity spawning grounds due to reduced river discharge leads to shifting recruitment and ultimately, lesser egg viability (Sahoo *et al.,* 2017).

Estuarine-spawning species have been shown to have various levels of physiological plasticity to adjust reproductive strategies in response to local environmental cues (Wang *et al.*, 2025). This change in spawning location is likely to benefit species in transitional zones, as shown in the Arabian Gulf, and lead to either a season- or location-shift of spawning with

changing salinity regimes. Such adaptations are critically important to fisheries management and conservation.

3-Biochemical Composition and Nutritional Significance of Fish Roe:

Based on nutritional market and commercial aspects, fish roe is assessed for its nutritional importance as a source of protein, lipid and fatty acids in Arabian Gulf. Due to the large amount of protein found in fish eggs, which typically account for 18% to 28% of their weight, they provide a significant source of these nutrients for the embryo and larva. Lipophilic organic molecules are used in the form of mainly sterols, triglycerides and phospholipids, whose composition can differ between species as well as in time under environmental conditions.

Larvae have a high requirement for omega-3 fatty acids, particularly docosahexaenoic acid (DHA) and eicosatetraenoic acid (EPA), for normal neural and visual development. The availability of these nutritional elements improves the profitable functionality of fish roe and enables fish roe to be made a worldwide commodity (Wang *et al.*, 2025).

Higher lipid content than temperate regions in fish roe from the Arabian Gulf has been considered a key adaptation to the changing salinity and temperature. Environmental stressors such as seasonal temperature and the quality of available water can also alter the biochemical profiles of fish eggs when resource allocation is affected (Karam *et al*., 2019).

The higher lipid reserves observed in larvae held at higher temperatures were likely essential to ensure adequate energy stores for survival. Nonetheless, habitat degradation and alteration of plankton by pollution can change biochemical components and consequently modify roe quality, with implications for both natural recruitment and aquaculture purposes (Hansen *et al.*, 2018).

The use of environmental DNA (eDNA) approaches enhanced those monitoring capabilities and in addition, the ability to investigate genetic signatures to potential adaptive biochemical effects between populations of the same fish species (Saeed *et al*., 2015). The technology facilitates the evaluation of roe quality, reproductive performance, and population genetics, which can help guide conservation and aquaculture efforts throughout the Arabian Gulf.

4-Ecological and Environmental Influences on Fish Egg Distribution and Abundance:

Seasonal variation in temperature, salinity, and primary productivity majorly affect fish egg distribution and abundance in the Arabian Gulf (Ibrahim and Attia, 2022). Routine reproduction occurs during the warmer months, with maximum clutch size occurring during spring and summer when temperature and plankton abundance are positive for larval survival.

In contrast, winter months show no spawning, probably because the metabolic rates are lower, and adult fish simply do not have enough energy to reproduce. In estuarine and coastal zones, oscillation of salinity, more than other factors, which again affects through egg disperse and survival and shows differences between species tolerances to hypersaline (Chermahini *et al.*, 2020)

Some ichthyoplankton distributions exhibit spatial trends whereby fish eggs are abundant in nutrient-laden coastal waters and adjacent estuarine habitats, where the productivity of the plankton community can sustain embryonic development. Notably, high plankton abundance regions are associated with higher egg lipid content and cell membrane saturation, which comprise more remarkable survival to hatch and post-hatch, similar to the importance of primary production in recruitment success (Ali *et al.*, 2019).

In a different reproductive cycle and larval dispersal study in the Gulf of Pampas, Candidus by Qasim and Al-Zaidy (2024), this species underwent different spawning cycles and patterns. The outcomes indicate that species have specific ranges of temperature and salinity in which they spawn to transport larvae to ideal nursery habitats (Ibrahim and Attia, 2022). These dependencies on various environmental variables emphasise the need to monitor climatic and anthropogenic changes that may influence the viability of fish eggs in the region.

5-Commercial and Fisheries Implications of Fish Egg Variability:

Fish roe constitutes an economic asset in domestic and international seafood markets as a direct food source as well as a feed source for aquaculture and the pharmaceutical industry. Commercially important species , including Pampas candidus and groupers, are

known to furnish high-quality roe in the Arabian Gulf. Fish egg monitoring can potentially improve stock assessment and conservation planning toward more sustainable fisheries management.

Nonetheless, the availability of fish eggs has been severely affected by overfishing and habitat destruction (Sharifinia *et al.,* 2019), which revealed that the Persian Gulf biodiversity is highly sensitive to human-induced stresses. Conservation is needed to protect spawning habitats and drive fish sustainability.

6-Limitations and Future Research Directions:

Unfortunately, the present study is based on secondary data sources; thus, direct observations on fish egg variability and related physiological adaptations are impossible. The discrepancies in data from various sources make it difficult to reach any definitive conclusions. Another poorly understood area is the genetic adaptation of fish eggs to extreme conditions in the Arabian Gulf.

Molecular and genetic surveys are required to assess the potential for species to keep pace with climate change and habitat change. In another study, Al Jazza Alqahtani (2022) underscored the need for genetic studies on Serranidae biodiversity and advocated for future research on integrating molecular tools, such as eDNA and genome sequencing, for species identification and conservation.

Conclusion and Future Works

This paper presents a first overview of the published work on Arabian Gulf fish eggs, considering spatial and seasonal variation in their morphology, adaptations to their habitat, biochemical composition and ecological factors affecting them. Within this area, we observe high morphological diversity in fish eggs comprising pelagic, demersal buoyant, and adhesive types adapted to various abiotic and biotic conditions.

Thermophiles and hypersaline species that flourish within these extreme climates possess specialised physiological mechanisms to achieve osmotic regulation, increased embryonic development and a reconfiguration of metabolic processes that facilitate survival. The biochemical composition of fish roe underlines their considerable commercial and ecological significance, expressed in their high content of protein, lipid, and omega-3 fatty acids supporting the development of larvae for commercial aquaculture and human consumption.

Nonetheless, the nutritional composition of fish eggs is modified by seasonal and environmental stressors such as salinity, temperature and pollution, and this may affect recruitment success and, ultimately, fish stock sustainability. The studies mentioned above consistently have shown that the biochemical variability of fish eggs responds to environmental quality and demands close attention.

These fundamental studies can be expanded in future research that combines molecular approaches, including environmental DNA (eDNA) and genetic sequencing, to provide qualitative and quantitative metrics of fish egg viability and the contribution of dormant stages to assess adaptation under climate change. Furthermore, species-specific effort is required for work on fish eggs in the Arabian Gulf to fill knowledge gaps relating to reproductive biology, recruitment processes, and stock assessments

Declarations

Ethical Approval: This study has been granted by the research Committee.

Competing interests: The authors declare that there is no conflict of interest.

Author's Contributions: I confirm that I carried out all aspects of work presented in this manuscript, including it’s conception, methodology, data collection and analysis. The writing, and revision of the final draft was also done solely by myself

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