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Review Article

Climate Change Effects on Hatching Success, Embryonic Development and Larvae Survival of Freshwater Fish: A Critical Review

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Abstract: Climate change presents a complex challenge to aquatic ecosystems, profoundly affecting fish populations, especially during their critical early life stages. The embryonic and larval phases are particularly vulnerable, drawing increased attention from those seeking to understand the factors contributing to higher mortality rates. Notably, environmental variables, particularly water temperature, emerge as crucial determinants of early fish life survival. This comprehensive review explores the intricate interplay between rising water temperatures due to climate change and the processes governing fish embryonic development, hatching success, and larvae survival. It synthesizes existing research, elucidating diverse responses among fish species to this environmental stressor and delving into the physiological and molecular mechanisms at play, including growth, development, and gene expression. The review also addresses potential ecological and economic implications, underscoring the pressing need for ongoing research, conservation initiatives, and adaptive management strategies. A nuanced understanding of the relationship between climate change and early fish life stages is imperative for ensuring the resilience and sustainability of fish populations amid ongoing environmental transformations.

Keywords: Climate Change, Fish Embryonic Development, Growth and Development, Gene Expression, Ecological Impacts, Management Strategies

1. Introduction

Climate change significantly impacts fisheries, posing challenges to both marine and freshwater ecosystems [1]. Rising temperatures influence the distribution and abundance of fish species [2]. These changes often result in shifts in migration patterns, affecting the availability of fish for commercial and subsistence fisheries. Additionally, warming waters can lead to changes in fish physiology, growth rates, and reproductive patterns [3].

Water temperature plays a pivotal role in influencing various aspects of fish breeding [4]. Many fish species exhibit temperature-dependent spawning behaviors, with specific temperature ranges serving as cues for courtship and the initiation of reproductive activities [4]. The developmental stages of fish eggs are highly sensitive to temperature, and warmer conditions accelerate embryonic development, shortening incubation periods [4]. However, extremes in temperature, whether too high or too low, can be detrimental to egg and larval survival [5]. Additionally, water temperature contributes to sex determination in some species, with variations influencing the sex ratio of offspring [6]. The timing of crucial reproductive events, including migrations and spawning, intricately aligns with temperature fluctuations, and suitable temperature conditions are pivotal for habitat selection during breeding [7]. Overall, a nuanced understanding of the relationship between water temperature and fish breeding is crucial for effective fisheries management and conservation efforts, particularly in the context of climate change-induced temperature shifts.

In this review, we summarized the effects of temperature on early developmental stages in fish. Nonetheless, it's crucial to highlight that there is a notable scarcity of data about the effects of environmental conditions on the early stages of larval development arising from natural spawning. Of the various environmental factors at play, temperature emerges as a particularly significant driver impacting the development of fish embryos and larvae. Understanding the intricate relationship between temperature variations and the success of early fish life stages is of paramount importance, as it can have substantial implications for the overall health and sustainability of fish populations in the context of ongoing climate change.

2. Effects of Temperature on Fish

2.1. Embryonic Development and Hatching Success

Fish embryonic development is a complex process marked by external fertilization, cleavage leading to a blastula, and subsequent stages of gastrulation, neurulation, and organogenesis, ultimately resulting in the formation of major organs and structures [8, 9]. The specific developmental timeline and strategies, such as parental care or external incubation, vary among fish species, with diverse reproductive behaviors like laying eggs in nests or releasing them into the water. The ultimate goal is the hatching of well-developed embryos, a critical factor for the continuation of the species. However, the impact of rising water temperatures on fish embryos introduces a layer of complexity. While higher temperatures may expedite embryonic development, potentially causing premature hatching, this acceleration might not align with the availability of external resources, affecting overall hatching success [10]. Elevated temperatures can disrupt the balance of gene expression and essential biochemical processes in embryonic development, leading to deformities or diminished survival rates [11]. Body malformations in embryos, including damaged zygotes, cellular deformities, damaged yolk sac, coagulated organs, dark yolk sac, irregular segmentation, and pustules, have been observed under temperature stress [12]. Microscopic examination reveals that eggs are more influenced by high temperatures in the early stages, with observable effects from the Blastodisc to the morula stage. After the gastrula stage, temperature effects are evident but not critical [13]. These findings underscore the intricate relationship between environmental factors and the early life stages of fish, highlighting the potential consequences of increased water temperature on embryonic development. The impact of temperature on freshwater fish embryo development is summarized in Table 1.

Table 1. *Effects of temperature on freshwater fish embryo.*

Fish species	Temperature (°C)	Hatching success	Reference
Common Carp (*Cyprinus carpio*)	T-20	No eggs survived	[14]
	T-27	Fertilized eggs 59%	
	T-30	Fertilized eggs 77%	
	T-38	No eggs survived	
Siamese mud carp (*Henicorhynchus siamensis*)	T-26	Not successfully hatch	[15]
	T-28	Hatching success 73.76±2.37%	
	T-30	Hatching success 73.90±1.44%	
	T-32	Hatching success 61.42±11.19%	
	T-34	Not successfully hatch	
Zebra Fish (*Brachydanio rerio*)	T-13-22	100% fatality	[16]
	T-23-32	Embryo mortality <1%	
	T->34	100% fatality	
Bream (*Abramis brama*)	T-9.8	Hatching success 86.5%	[17]
	T-10.5	Hatching success 89.7%	
	T-15.1	Hatching success 94.3%	
	T-15.7	Hatching success 97.6 %	
	T-16.2	Hatching success 97.8 %	
Killfish (*Cynopoecilus melanotaenia*)	T-20±1	Hatching success 97.7%	[18]
	T-25±1	Hatching success 74.9%	
Rohu (*Labeo rohita*)	T-30	Hatching success 80.4%	[12]
	T-32	Hatching success 70.60%	
	T-34	Hatching success 27.60%	
	T-36	Hatching success 0.00%	
Common barbel (*Barbus barbus*)	T-12	Hatching success 11.2%	[19]
	T-14	Hatching success 90%	
	T-18	Hatching success 90%	
	T-20	Not detected	
	T-22	Hatching success 14.3%	
European eel (*Anguilla anguilla*)	T-16-24	Development was delayed when embryos were reared in cold temperatures while accelerated in warm temperatures.	[20]

Fish species	Temperature (°C)	Hatching success	Reference
Tilapia (*Oreochromis mossambicus)*	T-11	Hatching success 0.00%	[21]
	T-17	Hatching success 0.00%	
	T-20	Hatching success 25.5%	
	T-24	Hatching success 84%	
	T-28	Hatching success 94.5%	
	T-30	Hatching success 90%	
	T-34.5	Hatching success 48.5%	
Mrigel (*Cirrhinus mrigala*)	T-26	Hatching success 86.86±0.11	[13]
	T-29	Hatching success 91.30±0.48	
	T-31	Hatching success 79.98±0.49	
	T-34	Hatching success 63.48± 0.57	

*Here, T=Temperature

2.2. Survival of Larvae

Elevated water temperatures significantly impact fish larvae, affecting their development and survival [12]. Increased temperatures accelerate metabolic rates, leading to higher energy demands and influencing feeding efficiency and prey availability. This disturbance in metabolic activity affects overall growth and development. Furthermore, elevated temperatures disrupt crucial physiological processes like respiratory and cardiovascular functions, essential for larval survival. Previous studies indicate developmental deformities and minimal survival rates in fish larvae under elevated temperatures, emphasizing the urgency of addressing these challenges [12]. The effects of temperature on malformation in freshwater fish larvae are outlined in Table 2.

Table 2. *Effects of temperature on Freshwater fish larvae.*

Fish species	Developmental deformities/Mortality	Reference
Common Carp (*Cyprinus carpio*)	The volume of the yolk in newly hatching larvae demonstrated an inverse relationship with the rise in water temperature.	[14]
Siamese mud carp (*Henicorhynchus siamensis)*	An increase in water temperature results in a significant decrease in the survival of newly hatched larvae.	[15]
Zebra Fish (*Brachydanio rerio)*	Not studied	[16]
Bream (*Abramis brama)*	Not studied	[17]
Killfish (*Cynopoecilus melanotaenia)*	Not studied	[18]
Rohu (*Labeo rohita*)	Developmental deformities, such as fusion in the eye, axial curvature, yolk sac ulceration, blood coagulation, tail shortening, and ulceration, are observed alongside minimal survival.	[12]
Common barbell (*Barbus barbus)*	The most frequently observed types of larval deformation were curvature of the spine and yolk sac deformation.	[19]
European eel (*Anguilla anguilla*)	Survival, deformities, growth rate, yolk utilization, and yolk utilization efficiency are key parameters considered in the assessment of developmental outcomes.	[20]
Tilapia (*Oreochromis mossambicus)*	Not studied	[21]
Mrigel (*Cirrhinus mrigala*)	Not studied	[13]

3. Physiological and Molecular Mechanisms

3.1. Physiological Mechanisms

Fish facing higher water temperatures adapt their bodies in intricate ways to handle the resulting thermal stress [22]. When temperatures rise, their metabolism increases, demanding more energy for vital bodily functions. At the same time, these fish may change how they use oxygen, adjust their heart rate, and enhance blood circulation to meet their higher metabolic needs, ensuring effective delivery of oxygen and nutrients [21]. Their response to elevated temperatures includes additional aspects such as increased stress hormone production, shifts in enzyme activity, and behavioral changes like altered feeding habits and habitat preferences [23]. This complex response extends to their reproductive processes, influencing the development of eggs and spawning behaviors [24]. Moreover, the thermal stress experienced by these fish could weaken their immune system, making them more vulnerable to diseases [25]. Fully grasping these complex physiological adaptations is crucial for accurately predicting and effectively managing the various impacts of climate-induced temperature changes on fish populations and the overall health of aquatic ecosystems.

3.2. Molecular Mechanisms

Fish exposed to high water temperatures activate intricate molecular mechanisms to cope with thermal stress. One key response involves the induction of heat shock proteins (HSPs), particularly HSP70 and HSP90, acting as molecular chaperones to facilitate proper protein folding and prevent denaturation [26]. Concurrently, fish regulate oxidative stress by upregulating antioxidant enzymes like superoxide dismutase and catalase to counteract the increased production of reactive oxygen species [27]. The orchestration of apoptosis-related genes ensures a delicate balance between cell survival and death in response to elevated temperatures [28]. Metabolic pathways, including glycolysis and lipid metabolism, are adjusted to meet heightened energy demands, and some fish species exhibit genetic adaptations with the expression of thermal tolerance genes [29]. Furthermore, the modulation of RNA and protein synthesis ensures the production of essential cellular components for stress response [30]. These molecular insights into thermal adaptation are crucial for understanding the resilience of fish species to climate-induced temperature changes and inform conservation strategies for sustainable aquatic ecosystems.

4. Potential Adaptive Management Strategies

To protect fish embryos and larvae from the harmful impacts of rising water temperatures and climate change, it's vital to implement a range of adaptive management strategies. Targeted approaches, such as selective breeding programs focusing on traits linked to thermal resilience, can be effective. Controlled environments in temperature-regulated hatcheries support optimal early-stage development. Installing artificial shading, habitat structures, and restoring riparian vegetation in natural environments helps create microhabitats that shield against extreme temperatures. Assisted migration and flow augmentation facilitate the movement of fish populations to cooler habitats, ensuring they remain in suitable thermal conditions. Engaging communities and stakeholders through early warning systems, aquaculture techniques, and educational initiatives promotes proactive conservation efforts. Ongoing research and adaptive learning are crucial for refining strategies and sustaining the resilience of fish embryos and larvae amid changing environmental conditions.

5. Conclusion

In conclusion, climate change significantly impacts fish populations during their early life stages, with water temperature emerging as a crucial determinant. The review emphasizes the urgent need for ongoing research and adaptive management to address these challenges and underscores the importance of proactive conservation initiatives. Ensuring the resilience and sustainability of fish populations requires a nuanced understanding of the interplay between rising temperatures and early life stages in the face of environmental transformations.

Conflicts of Interest

The authors declare no conflicts of interest.

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