Review

Ecological Adaptations and Conservation Challenges of Schizothoracids in High Altitude Environments: A Mini Review

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Review

Ecological Adaptations and Conservation Challenges of Schizothoracids in High Altitude Environments: A Mini Review

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Abstract: The fish found in the Tibetan Plateau and the Himalayas are referred to as schizothoracids, and they have evolved unique biological adaptations to high elevations. These adaptations include changes in the shape of the mouth, size, and length of gill rakers according to the prey size, sucking attachment organs to cope with fast currents, and genetic differences due to hypoxia and UV light. Nevertheless, there are recent threats like destruction of natural habitats, pollution, overfishing, and global warming that have posed serious conservation issues for numerous species. Conservation measures have been initiated even though well-articulated management techniques or other protective measures are absent from several protected areas for freshwater fisheries located in India. To resolve these issues, Schizothoracid population rescue, rehabilitation and restocking in safe water bodies should be implemented. For achieving their sustainability, scientists, conservationists, and legislators need to coordinate with each other.

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Introduction

Schizothoracids, also known as snow trouts, are a group of fishes in the Cyprinidae family that inhabit high-altitude environments like the Himalayan region and Qinghai-Tibetan Plateau. Researchers have identified new species within this group (Yang, 2009; Arunakumar, 2016), providing insights into their phylogenetic relationships, and also discussing the conservation status of endangered species within this genera (Liu, 2020). The origin and evolution of these fishes has mostly been influenced by environmental changes particularly the uplift of the Tibetan Plateau (Dekui, 2009; He, 2007). Studies on different species of schizothoracids offer valuable insights into their biology, reproductive biology, and morphometric traits.R esearch on *Schizothorax esocinus*, a species found in the River Jhelum in Kashmir, has provided insights into its physical traits (Shafi et al., 2021). *Schizothorax labiatus*, another snow trout species in Kashmir, has also been studied for its reproductive and breeding biology, contributing to its conservation and management (Farooq et al., 2019). In addition, studies on male and female Himalayan snow trout, *Schizothorax richardsonii* (Ciji et al., 2020), have investigated intra-annual changes in reproductive indices to understand sex steroid hormone profiles and gonadal histology variations. These studies provide a holistic understanding of the unique characteristics and adaptations of these fishes to high-altitude environments. Overall, these studies contribute to our understanding of the diversity, evolution, and conservation of schizothoracid fishes.

High altitude environments play a crucial role in the evolution and adaptation of schizothoracid fishes. The genetic basis for these adaptations has been emphasized (He, 2007; Li, 2013), with positive selection identified in the mitochondrial genomes of a specialized clade. This adaptation is particularly important due to the vulnerability of these fishes to climate change (Sharma, 2021). The unique genetic structure and high genetic diversity of these fishes, particularly in endorheic populations has also been studied (Liang, 2017). The evolutionary history of these fishes is intricately linked to the geological and climatic events of the Qinghai-Tibetan Plateau, which have also influenced the phylogeography of the Yellow River schizothoracine fishes in China (Duan, 2009).

Schizothoracid fishes exhibit accelerated evolution in response to high-altitude environments, with transcriptomic analyses revealing insights into their physiological adaptations (Wang, 2015). The genomic basis of adaptation in fishes to highland regions has been explored, shedding light on the genetic mechanisms underlying their ability to thrive in such environments (Mo *et al.*, 2016). Research has also highlighted the importance of rapidly evolving immune genes in schizothoracine fish adaptation to high-altitude extreme aquatic environments, providing valuable information on their immune responses to diversified pathogen challenges (Tong and Li, 2020). Furthermore, the evolutionary history of schizothoracine fish indicates polyphyletic origins and adaptive evolution in their mitochondrial genomes, suggesting a gradual adaptation to high altitudes over time (Yonezawa *et al.*, 2014). Environmental factors influence the evolutionary rate of vertebrate mitochondrial DNA protein-coding genes (Wang *et al.*, 2021).

The aim of the review is to highlight the importance of understanding high-altitude fish communities and the need for long-term data collection in alpine areas. It also discusses the impact of climate change on these ecosystems and provides insights into the morphology, anatomy, and adaptations of these fishes. The review also emphasizes the need for a comprehensive study of the ecological adaptations and conservation challenges of Schizothoracids in high-altitude environments taking into account the impact of climate change in such ecosystems.

Taxonomy and Diversity of Schizothoracids

The origin of schizothoracids has been closely related to the rise of the Tibetan Plateau (Yang, 2018). They are not a monophyletic group but are similar to genera Gymnocypris and Schizogypsis (Dekui, 2007; He, 2007). Their molecular phylogenetic relationships reflect their geographical and historical associations with drainages. The divergence of Schizothorax species in the Yunnan-Guizhou Plateau began in the Pliocene, and their phylogenetic history is congruent with events caused by the uplift of the Tibetan Plateau and the YGP (Yang, 2012). These are classified within the Cyprinidae family and the Schizothoracinae subfamily and are primarily found in the Jinsha River and its tributaries in the upper regions of the Yangtze River (Li *et al.*, 2023). Understanding their natural swimming behavior in turbulent flows provides insights into their ecological interactions and habitat preferences.

The study of schizothoracid species diversity in high altitude environments is a significant area of research. Researchers have explored the genetic diversity and evolutionary history of schizothoracids, suggesting a connection between their origin and the global climate shift at the Eocene-Oligocene transition (Yang, 2018; Chen, 2022). The diversity of schizothoracids in high altitude environments is also explored in the Central Himalayas, Tibet Plateau, Ladakh, and Alpine sites (Regmi, 2019).

To understand the diversity patterns of schizothoracids in high-altitude regions, it is crucial to consider the altitudinal gradient and its impact on biodiversity. Research on plant communities along altitudinal gradients has shown changes in species composition and diversity, with different dominant species occurring at varying altitudes (Gao and Zhang, 2006; Perillo *et al.*, 2017). Investigations on epiphytic orchids along altitudinal gradients have demonstrated a decrease in species diversity with increasing altitude due to environmental harshness at higher altitudes (Timsina *et al.*, 2021). Similar studies on zooplankton diversity in high altitude tropical lakes have identified gaps n understanding biodiversity in such environments (Eskinazi-Sant Anna *et al.*, 2020). Long-term studies are needed to assess diversity efficiently in such environments. Based on the interpretation of results, it may be concluded that schizothoracids may have distinct species compositions and adaptations to survive in harsh environments in high altitude settings.

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These fishes have evolved unique adaptations to high altitude environments due to a combination of genetic, physiological, and biochemical factors. These adaptations are influenced by positive selection in the mitochondrial genome and the rapid evolution of genes in response to high altitude conditions. The earliest fossil schizothoracine, *Paleoschizothorax qaidamensis*, was discovered in the Oligocene of the Tibetan Plateau (Yang, 2018). Morphological variations among different species suggest a diverse range of adaptations (Nie, 2014). Landscape features, such as waterfalls, also play a role in shaping the genetic structure of schizothoracids.

Studies on high-altitude adaptations in other species provide valuable insights into the unique features of schizothoracids in such challenging habitats. Research on Tibetan populations has highlighted genetic adaptations related to circulatory, respiratory, and hematological systems, which are crucial for coping with low oxygen levels and harsh environmental conditions (Bigham *et al*., 2010). Studies on yaks have revealed stable genetic characteristics that facilitate physiological, biochemical, and morphological adaptations to high altitudes, enhancing their survival and fitness (Ayalew *et al*., 2021). Key miRNAs and genes involved in hypoxic responses have also been identified in high-altitude adaptations in Tibetan chickens (Chen, 2022). Additionally, studies on yaks have shown increased expression of specific proteins related to mitochondrial capacity, supporting metabolic rates under high-altitude conditions (Xin *et al*., 2020). Furthermore, research on Tibetan pigs has revealed unique expression patterns in lung tissue, indicating hypoxia-sensitive pathways that contribute to their adaptation to high-altitude hypoxia(Yang *et al*., 2021). Therefore, schizothoracids likely possess a combination of genetic, physiological, and biochemical adaptations that enable them to thrive in extreme high-altitude environments.

Ecological Role and Importance

Schizothoracids have a complex evolutionary history linked to the geological and climatic events of the Qinghai-Tibetan Plateau. Their genetic diversity and evolutionary mechanisms in the Lancang River are closely related to orogenesis and stable populations during Pleistocene glacial cycling. The divergence of Schizothorax species in the Yunnan-Guizhou Plateau is also linked to the uplift of the Tibetan Plateau and the YGP. These findings suggest that these unique aquatic animals play a crucial role in the ecosystem functions of their habitats, particularly in relation to the geological and climatic processes that have shaped their evolution (Chen, 2016; Yang, 2012).

Ecosystem functioning of Schizothoracids in high-altitude environments is influenced by various factors that shape the biodiversity and ecological dynamics of these unique habitats. Studies on microbial diversity, soil physiochemical characteristics, and carbon storage in high-altitude ecosystems provide insights into the intricate relationships between biotic and abiotic components in these environments. The presence of diverse microbial communities plays a crucial role in nutrient cycling, soil health, and overall ecosystem functioning in high-altitude environments (Kumar *et al*., 2019). Climate change impacts species richness in small temperate water bodies, affecting the ecological balance and functioning of aquatic ecosystems in high-altitude regions (Zhu *et al*., 2010; Zhang *et al*., 2021; Rosset *et al*., 2012). Understanding these complex relationships is essential for effective conservation and management strategies to preserve the biodiversity and ecological integrity of high-altitude environments.

The trophic interactions and food web dynamics of Schizothoracids are influenced by various factors, including insect-dominated food webs, freshwater pelagic food webs, mixotrophs, trophic interactions, soil structure, and below-ground food webs (Schoenly, 1991; Mills, 1988; Jost, 2004). These interactions shape the ecology of Schizothoracids and provide a comprehensive understanding of their complex interactions. To understand their trophic interactions and food web dynamics in high-altitude environments, it is essential to consider the intricate relationships between these fishes and other organisms within their ecosystems. The studies on convergent evolution of rumen microbiomes in high-altitude mammals, mercury levels in wild fish from high-altitude aquatic ecosystems in the Tibetan Plateau, and shifts in phytoplankton assemblages in sentinel lakes gives a comprehensive understanding of their trophic interactions and food web dynamics (Zhang *et al*.,

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2016; Zhang *et al*., 2014; and Dory *et al*., 2022). This includes understanding the bioaccumulation of mercury in the aquatic food web, the primary productivity and energy flow within high-altitude aquatic ecosystems, and the interactions between phytoplankton and food web components.

Understanding how climate change affects invasive species can offer insights into potential interactions involving Schizothoracids and invasive species in high-altitude environments (Rahel and Olden, 2008). Additionally, the role of biomarkers in evaluating aquatic ecosystem health can help identify species at risk from environmental contaminants (Hook *et al*., 2014). By synthesizing information from these studies, we can gain insights into how Schizothoracids interact with their environment, respond to stressors like climate change and pollution, and contribute to the overall health and functioning of aquatic ecosystems in high-altitude environments.

Physiological Adaptations to High Altitude

Schizothoracids have adapted to extreme conditions through various metabolic and respiratory mechanisms. These adaptations involve complex genetic, physiological, and biochemical mechanisms that enable these fishes to thrive in extreme conditions. Studies have shown that high-altitude Schizothorax nukiangensis have different metabolite concentrations, which are involved in oxidative stress, energy, carbohydrate, and lipid metabolism (Xu, 2023). The metabolic rate of juvenile *Schizothorax prenanti* juveniles increases with temperature and flow velocity, consistent with the broader literature on high-altitude adaptation. However, the specific respiratory and metabolic adaptations of schizothoracids to high-altitude environments require further investigation. Research on the yak genome provides insights into the genetic adaptations of animals living in high-altitude environments, as well as the physiological adaptations of Schizothoracine fishes to hypoxia and low oxygen conditions (Wang *et al*., 2022, Qi *et al*., 2018)). Understanding these adaptations provides valuable information on the respiratory and metabolic strategies of Schizothoracine fishes in high-altitude environments.

Research on the behavioral responses of schizothoracids to altitude stress is also limited, but can be explored through studies such as the EPO H131S mutation in *Gymnocypris dobula*, which reveals physiological adaptations compared to other species (Qi et al., 2018). Analyzing the adaptive responses to hypoxia in *Gymnocypris eckloni* highlights biochemical, physiological, and molecular adaptations to low oxygen conditions. The genetic adaptations of the Eda gene and scales loss in Schizothoracine fishes in response to the uplift of the Tibetan Plateau provides insights into the genetic adaptations of Schizothoracine fishes to high altitudes.

Schizothoracids are known to have adapted to high altitude environments through genetic adaptations exhibiting a high degree of spawning synchronicity, with a short spawning period and a linear increase in fecundity with body size (Ma, 2012; Zhou, 2014). Autogeny, a form of asexual reproduction, may also be employed by these fish (Raastad, 1989). The discovery of a new Oligocene genus and species of schizothoracine fish in response to the uplift of the Tibetan Plateau provides further insight into their reproductive strategies (Yang, 2018). A transcriptomic analysis of the Tibetan Schizothoracinae fish Gymnocypris przewalskii provides valuable information on its adaptation to high-altitude aquatic life (Tong *et al*., 2017). Understanding the trophic morphologies and adaptations of Schizothoracine fishes can offer insights into their reproductive strategies and ecological roles in high-altitude environments. Additionally, integrating mRNA and microRNA transcriptome analyses can reveal the regulation of thermal acclimation in Gymnocypris przewalskii, a Tibetan Schizothoracine fish (Zhang et al., 2017). By synthesizing these studies, a comprehensive understanding of the reproductive strategies and adaptations of Schizothoracine fishes in high-altitude environments can be gained.

Conservation Challenges and Strategies

Schizothoracine fish populations in high altitude environments face various threats, primarily due to climate change and human activities. Climate change is causing a shift in the distribution of snow trout, a key species in the Himalayas, leading to a loss of suitable habitat (Sharma, 2023). The genetic basis for high altitude adaptation in schizothoracine fishes is poorly understood, but positive selection has been identified in the mitochondrial genomes of some species (Li, 2013). High altitude endemic species, including schizothoracins, are vulnerable to habitat loss due to climate change (Dirnbock, 2011). Human activities such as overfishing, habitat fragmentation, and the introduction of exotic species further threaten these populations.Threats to Schizothoracine fish populations in high-altitude environments are influenced by various factors that can impact their survival and abundance. Despite these challenges, there is potential for conservation through measures such as the establishment of fish conservation zones and the prohibition of exotic species stocking.

The conservation status and endangered species of schizothoracids in high altitude environments are a significant concern, especially in the context of climate change. Highland species are vulnerable to climate change, with local extinction risking a 2-3°C increase in temperature (Wilson, 2007; Yang, 2018). Factors such as water conservancy facilities, overfishing, and the introduction of living things have caused significant destruction to the survival of *Schizothorax biddulphi* (Wu, 2007). The phylogenetic diversity and evolutionary history of schizothoracids have been studied in the context of Cenozoic aridification (Abrams, 2019). The impact of historical and contemporary factors on genetic variation in *Schizothorax kozlovi* populations has also been explored (He, 2022). These studies underscore the urgent need for conservation efforts to protect these unique and vulnerable species.

Schizothoracids are highly vulnerable to climate change. The age and growth of schizothoracids in high-altitude environments indicate their vulnerability to overfishing. Landscape features like waterfalls also influence their phylogeography. To safeguard these fish populations, conservation initiatives and management practices are essential. Strategies include devolving responsibility for resource management to local communities, stakeholder management, marine protected areas, sustainable harvest practices, community-based enforcement efforts, educational campaigns, research, and conservation partnerships (Najera-Medellin, 2023). Habitat restoration, stock transfer, captive breeding, and cryopreservation are also crucial for the long-term sustainability and biodiversity of these fish populations (Maitland and Lyle, 1992).

Conclusion

The study of schizothoracids in high altitude environments is a field that requires further research. The recent discovery of a new Oligocene genus and species in the Qaidam Basin (Yang, 2018), identification of two phylogroups in *Schizothorax o'connori* (He, 2009), work on *Schizopygopsis stoliczkai* (Wanghe, 2017), study on the population genetic structure of three schizothoracines from the Nujiang River (Ming *et al*., 2010) and molecular phylogeny (He, 2004), provide a broader context for understanding the evolutionary history of these fish. However, there are still research areas such as genetic adaptations, behavioral ecology, conservation strategies, population dynamics, and ecosystem interactions which can help researchers enhance their knowledge of Schizothoracine fishes and contribute to their conservation and management in high-altitude environments.

Moreover integrating traditional knowledge with scientific research in Schizothoracine studies is essential for a comprehensive understanding of these fishes in high-altitude environments (Huntington *et al.,* 2004). By exploring these areas researchers can enhance their understanding of these fishes, promote sustainable conservation practices, and foster collaboration between indigenous communities and scientific experts (Fraser *et al*., 2006; Gagnor and Berteaux, 2009). Despite the challenges faced by this group of fishes, their adaptive skills, such as their ability to sustain fecundity, provide some hope for their survival (Thapliyal, 2019). However, the decline and isolation of these fish due to environmental pollution and habitat degradation underscore the urgent need for conservation efforts (Da-qing, 2010).

To improve conservation efforts, a comprehensive approach that integrates traditional knowledge, scientific research, and community engagement is essential. This approach can be tailored to the specific needs of Schizothoracine fishes in high-altitude environments. Possible steps include community involvement, habitat restoration, genetic conservation, monitoring and research, and raising awareness about the importance of Schizothoracine conservation among local communities, policymakers, and the general public. By integrating traditional knowledge with scientific research and implementing targeted conservation strategies, it is possible to enhance conservation efforts and ensure the long-term sustainability of these unique fishes in high-altitude environments (Zimmerer, 2000).

The conservation and management of Schizothoracids in high altitude environments is a complex issue with implications for climate change, habitat destruction, and overfishing. These fish are vulnerable to local extinction with even a small temperature increase, and their distribution is negatively impacted by factors like water conservancy facilities, overfishing, and the introduction of living things. Their origin and evolution are linked to the rise of the Tibetan Plateau, and their slow growth and long life make them susceptible to overfishing. Conservation efforts should focus on addressing these threats.

Besides genetic methods can be helpful to identify gene pools and their connectivity, providing insights into the genetic structure of Schizothoracine populations. Genomic resources can also aid in understanding evolutionary adaptation, genetic diversity, and resource conservation of Schizothoracine fishes, informing conservation strategies. Population genetic structure analysis can inform conservation management decisions by determining appropriate conservation units and spatial scales for effective management of Schizothoracine populations. Understanding patterns of adaptive differentiation and gene flow is crucial for prioritizing populations for conservation and focusing management efforts on preserving genetic diversity. Conservation and management efforts can be tailored to address the specific needs of Schizothoracine populations, ensuring their long-term survival and biodiversity conservation.

Highlights

- Schizothoracid fishes in high-altitude environments exhibit physiological adaptations to cope with hypoxia and cold, such as reduced critical swimming speeds and specialized metabolite profiles.
- Their streamlined body shapes and sucker-like adaptations enable Schizothoracids to navigate rapid currents, facilitating their survival in the turbulent waters of high-altitude rivers.
- Endemic Schizothoracid species face threats from habitat fragmentation, pollution, overfishing, and climate change-induced alterations to their habitats, highlighting the urgent need for conservation efforts to protect these unique fish fauna.

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