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Diversity of Golden Mahseer: A Morphometric and Genetic Review

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Abstract

One of the freshwater fishes with the highest ecological value in India is the Golden Mahseer (Tor putitora), which is well known for its cultural significance and sensitivity to environmental changes. The species is rapidly declining despite its importance because of overexploitation, hydrological changes, habitat degradation, and genetic erosion. Conservation and fisheries management depend on an understanding of its genetic and phenotypic diversity. To assess the degree of diversity in T. putitora, this review summarizes previous research, including morphometric, meristic, and RAPD-based studies. Significant eco-morphological variation caused by habitat gradients, substrate type, and hydrodynamic conditions is revealed by morphometric analyses. The relative stability of meristic traits highlights their taxonomic dependability. High polymorphism and unique genetic structuring among riverine populations are revealed by RAPD studies, indicating limited gene flow and potential evolutionary divergence. The combination of genetic and phenotypic data emphasizes the necessity of population-specific conservation tactics. This review concludes that in order to guarantee the long-term sustainability of Golden Mahseer populations, multidisciplinary approaches combining morphology, ecology, and molecular genetics are crucial.

Keywords: Tor putitora, Mahseer, morphometric variation, meristic traits, RAPD, genetic diversity, population structure, conservation.

Introduction

The Golden Mahseer (Tor putitora) is recognized as a flagship species of Himalayan river systems due to its migratory patterns, cultural relevance, and ecological sensitivity (Nautiyal, 2013). However, the species' sharp population losses have been caused by habitat fragmentation, hydropower development, overfishing, sedimentation, and human pressure (Sarkar et al., 2015; Bhatt et al., 2016). Conservation requires an understanding of Mahseer's genetic structure, morphological adaptations, and population diversity.

While molecular tools like RAPD offer insights into genetic differentiation, morphometric and meristic techniques are commonly employed to evaluate fish stock structure. Previous research shows that while meristic traits frequently remain genetically canalized (Clayton, 1981; Helfman et al., 1997), morphometric traits can reflect ecological adaptation and phenotypic plasticity

(Mohd. Hussain, 2007; Solem& Berg, 2011). Therefore, comprehending divergence in Mahseer populations requires combining phenotypic and molecular analyses.

Mahseer taxonomy, distribution, morphological variability, meristic stability, genetic structure, ecological significance, and conservation challenges are all covered in this review.

General Literature on Mahseer

Morphometric Diversity and Environmental Adaptation

It is commonly known that morphometrics play a part in stock discrimination. Early studies showed how morphometric characteristics can distinguish between fish species and populations in terms of size and shape (Kendall Jr. et al., 2007; Mohd. Hussain, 2007). Morphometric divergence frequently reflects ecological adaptation, hydrological regimes, and selective pressures, according to research on cyprinids and other freshwater fishes (Bagherian&Rahmani, 2009; Manimegalai et al., 2010). In a number of species, significant correlations between morphometric characteristics and ecological gradients have been documented. For instance: Highly significant morphometric–length relationships were observed in Oreochromismossambicus (Muhd. Naeem et al., 2011). Significant morphological variations associated with river basin separation were observed in Garra spp. (Dhinakaran et al., 2011).Geographical distance was linked to mThese findings suggest that similar patterns exist in Mahseer populations inhabiting variable Himalayan river systems.orphological divergence in Atlantic salmon populations (Solem& Berg, 2011).

Meristic Traits and Taxonomic Reliability

Fish species have long been identified using meristic traits like vertebral counts, fin rays, lateral line scales, and gill rakers (Clayton, 1981; Helfman et al., 1997). Meristic characteristics are usually more consistent and genetically determined, whereas morphometric traits can be affected by environmental variability (Ihssen et al., 1981). Therefore, morphological evaluations in Mahseer taxonomy and stock identification are supported by meristics.

Taxonomy and Classification of Mahseer (Genus Tor

Due to inconsistent genetic markers and overlapping morphological traits, Mahseer taxonomy is still complicated. According to Khare et al. (2014), mtDNA sequences revealed previously unknown clades by resolving taxonomic ambiguities among Tor, Neolissochilus, and Naziritor.

The lack of thorough taxonomic clarity was highlighted by Pinder et al. (2019), who pointed out that many species are still listed as Data Deficient on the IUCN Red List. According to Jaafar et al. (2021), there are only ten legitimate Tor species in Southeast Asia due to discrepancies in morphological and molecular identification.

Based on mitochondrial variation and unique morphological traits, recent molecular analyses have even reclassified Indian Mahseer species, including Tor mahanadicus (Johnson et al., 2023)

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Global and Indian Distribution

Mahseer are found throughout the Indus, Ganges, and Brahmaputra basins, among other Himalayan and sub-Himalayan River systems. According to Sarma et al. (2022), there are 47 known species of Mahseer in the world, 15 of which are found in India. However, habitat degradation, climate change, and hydrological changes pose a threat to numerous species.

Hydropower projects change ecological conditions and interfere with river connectivity (Baruah, 2023). In areas with significant dam construction and uncontrolled fishing pressure, population declines are severe (Sarkar et al., 2015).

Ecological and Economic Importance

Mahseer are valued for:

- High nutritional value (Sarma et al., 2022).
- Recreational and sport fishing (Nautiyal, 2013)
- Support for livelihoods and ecotourism (Bhatt et al., 2016)

An important factor in Mahseer physiology is temperature. Research on T. putitora shows:

- 19°C is ideal for growth (Rathod et al., 2022).
- Different stress and antioxidant reactions in different temperature ranges (Dash et al., 2023)
- Mahseer's sensitivity to ecological disruptions makes them bioindicators of river health as well.

Genetic Diversity and RAPD-Based Studies

Long-term species survival, adaptive potential, and population resilience are all significantly influenced by genetic diversity. Understanding genetic variation is especially crucial for a migratory, slow-growing, and ecologically sensitive species like the Golden Mahseer (Tor putitora). Population declines, habitat fragmentation, and uncontrolled hatchery practices can quickly reduce genetic diversity, which eventually hinders growth, adaptability, and reproductive success. In this regard, molecular markers have become useful instruments for evaluating genetic variation in Mahseer populations, particularly Random Amplified Polymorphic DNA (RAPD) markers.

Genetic Diversity's Significance in Mahseer

Evolutionary adaptability is based on genetic diversity. Natural riverine barriers, hydrological fragmentation, localized adaptation, and limited gene flow all contribute to population differentiation in widely distributed species such as T. putitora (Sarma et al., 2022). Different evolutionary lineages are present in related Tor and Neolissochilus species, according to several studies (Khare et al., 2014; Jaafar et al., 2021). Long-term geographic and ecological isolation may cause even morphologically similar Mahseer populations to differ genetically, according to molecular evidence (Johnson et al., 2023).

The connectivity between Mahseer habitats in India has been significantly diminished by hydropower dams, barrages, and changed flow regimes (Baruah, 2023). Genetic evaluation is crucial for conservation planning since this has led to smaller, isolated units.

RAPD Markers as a Fish Genetics Tool

RAPD (Random Amplified Polymorphic DNA) markers use short, arbitrary primers to amplify random regions of the genome. The method has been applied extensively to freshwater fish because of its

Simple, inexpensive, and requiring no prior genomic knowledge.

Both coding and non-coding regions are sensitive to polymorphism.

Efficacy in differentiating populations, even in cases where morphological differences are negligible.

RAPD has been effectively used to uncover hidden genetic variation and population structure in a number of freshwater species and cyprinids (Bagherian&Rahmani, 2009; Mohd. Hussain, 2007). According to Mahseer, RAPD analysis is particularly helpful when baseline molecular data is scarce and quick evaluation is necessary for conservation decision-making.

Genetic Polymorphism and Population Differentiation

Different banding profiles that reflect genetic variation are usually produced by RAPD-based studies. Rich genetic diversity is indicated by high levels of polymorphism, whereas shared bands among populations indicate shared ancestry or historical connectivity.

Despite the paucity of published research on T. putitora RAPD characterization, findings from related studies and several Mahseer taxa indicate:

- Substantial genetic variation among river basins.
- Local adaptation is reflected in population-specific RAPD bands.
- River fragmentation is associated with genetic differentiation.
- Greater similarity between populations that are closer together geographically

The validity of RAPD markers for population studies has been confirmed by similar patterns found in other freshwater fishes, including Garra spp. (Dhinakaran et al., 2011), Oreochromismossambicus (Muhd. Naeem et al., 2011), and Mugilidae species (El-Zaeem, 2011).

Mahseer populations probably retain unique genetic signatures shaped by their microhabitats due to the high habitat heterogeneity of Himalayan rivers, which range from slow-moving tailwaters to torrential upstream stretches.

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RAPD and Taxonomic Clarification

Mahseer research has long been hampered by taxonomic ambiguity. Identification of species is frequently complicated by morphological overlap between Tor, Neolissochilus, and Naziritor (Pinder et al., 2019). Clarity is improved by incorporating molecular markers like RAPD and mtDNA in:

- Verifying species with cryptic morphology.
- Distinguishing between taxa that are closely related.
- Identifying hybridization, particularly in hatchery environments.

Khare et al. (2014) demonstrated that Tor putitora, Tor mosal, and Tor mussullah can be distinguished by sequences from COI and D-loop regions; however, RAPD can supplement these results by providing more extensive genome coverage at a lower cost.

Hatchery Implications and Genetic Risks

Uncontrolled hatchery breeding is one of the main risks to Mahseer genetic integrity. Multiple, genetically unrelated river systems are frequently the source of broodstock, increasing:

- Genetic uniformity
- Loss of regional adaptations
- Possibility of introgression
- Decrease in the size of the effective population
- RAPD fingerprinting can assist in determining:
- The genetic purity of hatchery stocks
- The genetic separation between populations in hatcheries and the wild
- Appropriate combinations of broodstock
- Effects of genetic drift across generations

Similar issues for Malaysian Tor species are raised by Khudamrongsawat et al. (2021), who point out that molecular screening must direct broodstock development in order to preserve strain purity.

Combining Genetic and Morphometric Diversity

Distinguishing genuine genetic divergence from environmentally induced phenotypic plasticity is a major advantage of integrating RAPD data with morphometric analysis. Mahseer body shape varies with the following, according to numerous morphometric studies:

- Velocity of flow
- The temperature
- Type of substrate

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- Nourishing ecology

(Manimegalai et al., 2010; Solem& Berg, 2011; Kendall Jr. et al., 2007)

Nevertheless, genetic differentiation is not always indicated by such variation. RAPD data is used to verify whether:

Genetic divergence is reflected in morphological differences.

Different conservation units are represented by populations.

Observable characteristics are adaptable reactions to the surroundings.

Morphometric divergence without corresponding genetic differentiation has been observed in numerous freshwater species, including Mahseer relatives (El-Zaeem et al., 2012). Therefore, conservation accuracy is strengthened by an integrated approach.

1. **Conservation Challenges**

In South and Southeast Asia, the conservation of Golden Mahseer (Tor putitora) and related Tor species has emerged as a crucial ecological and management priority. Due to a complex mix of anthropogenic pressures, Mahseer populations are rapidly declining despite their high ecological, cultural, and recreational value. Using ecological studies, taxonomic investigations, hydrological analyses, and physiological research from the literature, this section offers a thorough overview of the main conservation issues affecting Mahseer diversity**.**

Habitat Fragmentation and River Connectivity Loss

One of the biggest dangers to Mahseer populations is habitat fragmentation. Mahseer need long, unobstructed river segments for spawning, feeding, and juvenile dispersal because they are potamodromous migratory fishes (Nautiyal, 2013). River connectivity has been drastically changed by the building of hydropower dams, barrages, and water diversion structures.

Hydroelectric Projects' Effects

According to Baruah (2023), hydroelectric projects in the Indian Himalayan Region (IHR) disrupt rivers' natural continuity, which results in:

- Changes in flow patterns
- Physical-chemical water parameter changes
- disturbance of planktonic and benthic environments
- Absence of spawning areas
- **Limitations on upstream migration**

Mahseer are extremely sensitive to temperature gradients, dissolved oxygen levels, and flow velocity, all of which are altered by impoundments.

Migration Obstacles

The following are adversely affected when migratory routes are blocked:

- Successful reproduction
- Interpopulation genetic exchange
- Recruitment of young people
- Adaptability

Mahseer populations may experience similar fragmentation-driven differentiation, as salmonids have shown similar patterns of geographic isolation driving morphological and genetic divergence (Solem& Berg, 2011).

Overexploitation and Unsustainable Fisheries

One of the main reasons for the decline in the Mahseer population is overfishing. Mahseer have historically faced intense fishing pressure despite being valued as a trophy fish and a significant sport species.

Broodstock Harvest

According to Sarkar et al. (2015), breeding populations in many Indian rivers have significantly decreased as a result of the careless capture of broodstock and juveniles. Eliminating large adults, which are essential to preserving genetic diversity, leads to:

- Decreased size of the effective population
- Rare allele loss
- Reduced fertility
- Heightened susceptibility to inbreeding

Harmful Fishing Methods

Typical unsustainable behaviors include:

- Tiny-mesh nets
- Toxicology
- The process of electrofishing
- Explosives or blasting

Long-term population instability results from these methods' disproportionate effects on juveniles and spawning adults.

Pollution and Environmental Degradation

Mahseer Rivers frequently flow through areas that are rapidly becoming more industrialized, urbanized, and agricultural. Aquatic habitats are significantly degraded as a result.

Siltation and Sedimentation

Construction and deforestation in catchments raise sediment loads, which

- Eggs that are smothered in gravel beds
- Limit the amount of oxygen available to embryos
- Modify the preferred substrates

Water Quality Changes

Effluents and agricultural runoff alter:

- pH
- Temperature
- Heavy metal concentration
- Nutrient load

Studies demonstrating temperature-dependent physiology and stress responses have shown that mahseer larvae and juveniles are especially sensitive to such changes (Rathod et al., 2022; Dash et al., 2023).

Climate Change and Temperature Stress

Temperature and Mahseer physiology are closely related. Strong thermal sensitivity is indicated by recent studies:

T. putitora grows best at about 19°C (Rathod et al., 2022).

Under extreme temperature conditions, antioxidant and heat shock protein responses change dramatically (Dash et al., 2023).

- Climate change may therefore:
- Seasonal shifts in spawning
- Modify the timing of migration
- Decrease the suitability of lower-altitude Rivers as habitats
- Boost the level of metabolic stress

Population imbalance results from the disruption of natural life cycles caused by rising water temperatures and changed monsoon patterns.

Genetic Hazards Associated with Stocking and Hatchery Practices

For Mahseer conservation, artificial propagation and stocking programs have become popular. But a lot of hatchery operations are unregulated and can make genetic issues worse.

Local Adaptations Are Lost

The introduction of non-local or genetically unrelated broodstock results in:

- Decrease in characteristics unique to a population
- Hybridization
- Genetic uniformity

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- Evolutionary identity loss

Genetic Drift and Inbreeding

Similar issues are raised by Khudamrongsawat et al. (2021) in the Malaysian Tor species, where poor broodstock management increased the risk of inbreeding and decreased genetic variability. Hatchery programs may unintentionally jeopardize wild stocks in the absence of genetic screening

Molecular Tools' Function

Microsatellite markers, mtDNA, and RAPD can:

- Check the purity of the stock.
- Prevent inappropriate mixing
- Track genetic diversity across generations
- The ability of mtDNA to resolve species boundaries in Tor was shown by Khare et al. (2014), highlighting the necessity of incorporating genetics into stocking programs

Misidentification and Taxonomic Ambiguity

Taxonomic uncertainty is one of the main challenges to Mahseer conservation. Research by Jaafar et al. (2021) and Pinder et al. (2019) demonstrates:

- Morphological characteristics that overlap
- Inaccurate species identification
- Confusion between other species and Tor putitora, Tor tor, and Tor mosal

Tor mahanadicus was recently reclassified by Johnson et al. (2023), demonstrating that several species had been incorrectly identified for decades.

The Significance of Taxonomy in Conservation

Inaccurate identification results in:

- Inappropriate conservation priorities
- Inappropriate stocking
- Loss of unique ancestry
- Not protecting endangered species
- To address these uncertainties, molecular tools are crucial.

Insufficient Research and Monitoring

Mahseer species are still poorly understood despite their ecological significance. According to Nautiyal (2013), there are still gaps in:

- Long-term demographic information
- Knowledge of the biology of migration
- Modeling of habitats
- Breeding in captivity

- Hydropower projects' effects
- Genetic surveillance

According to the IUCN, many Tor species are still "Data Deficient" (Pinder et al., 2019), which makes conservation efforts more difficult.

Conclusion

To provide a comprehensive understanding of the Golden Mahseer (Tor putitora), the current study combines morphometric, meristic, and genetic analyses with a thorough review of ecological, taxonomic, and conservation literature. The Golden Mahseer, one of the most recognizable freshwater fish in the Himalayan region, has great cultural, nutritional, and recreational value throughout South and Southeast Asia in addition to its high ecological value. The synthesis of the available data, however, shows that the species is under previously unheard-of pressure from genetic erosion, habitat fragmentation, overexploitation, environmental degradation, and climate instability. The study confirms that morphometric and meristic traits continue to be essential instruments for stock discrimination, population evaluation, and species identification. Significant character variation is a result of both genetic and environmental influences, including hydrological gradients, river flow, and substrate composition. Previous research on freshwater fishes and cyprinids (Mohd. Hussain, 2007; Bagherian&Rahmani, 2009; Manimegalai et al., 2010; El-Zaeem, 2011) confirms the accuracy of these instruments while emphasizing the necessity of combining shape analysis with molecular methods. The need for population-specific conservation strategies is further supported by the fact that morphological plasticity in Mahseer frequently reflects local adaptation. Genetic analyses—in particular, RAPD and mitochondrial DNA markers—have become effective methods for revealing cryptic diversity. The Tor–Neolissochilus–Naziritor complex is still rife with taxonomic ambiguities, as evidenced by the literature (Khare et al., 2014; Pinder et al., 2019; Jaafar et al., 2021). Recent reclassifications (Johnson et al., 2023) suggest that the true diversity of Indian Mahseer remains unresolved. The implementation of policies, stocking programs, and conservation efforts are all directly impacted by this ambiguity. To differentiate between environmental variation and true genetic divergence, morphometric results must be integrated with RAPD-based genetic insights. Combining these methods makes it possible to identify Evolutionarily Significant Units (ESUs), which is essential for creating conservation initiatives with biological significance. Golden Mahseer is extremely sensitive to environmental changes, as evidenced by the ecological and physiological literature reviewed in this study. Research on oxidative stress, metabolic reactions, and temperature tolerance (Rathod et al., 2022; Dash et al., 2023) shows limited thermal optima and considerable susceptibility to extreme weather. Climate change is a significant long-term threat to Mahseer survival due to its rapid warming and altered monsoon dynamics. According to

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Baruah (2023), hydropower development worsens habitat fragmentation, interferes with migration routes, modifies flow regimes, and reduces spawning success. Population structure, genetic connectivity, and recruitment are all negatively impacted by these disruptions.

Overfishing is still a problem in all Mahseer habitats. According to Sarkar et al. (2015), the removal of juveniles and broodstock from rivers, frequently prior to spawning, has accelerated local population collapse, decreased effective population sizes, and increased susceptibility to genetic drift. While hatchery-based stocking programs run the risk of hybridization, inbreeding, and loss of local adaptations if they are not genetically informed, uncontrolled fishing practices further erode conservation gains (Khudamrongsawat et al., 2021). When taken as a whole, these elements highlight the necessity of developing scientifically managed broodstock programs and genetic screening.

Effective conservation is still hampered by a lack of long-term monitoring, a lack of data, and a lack of integration between scientific disciplines, despite the substantial body of research that is currently available. There is an urgent need for improved research infrastructure, molecular laboratories, species inventories, and transboundary cooperation because many Mahseer species are still poorly studied and some populations are classified as "Data Deficient" (Pinder et al., 2019).

Recommendations and Future Directions

Improvement Taxonomy with Molecular Techniques

Resolve species-level ambiguities within Tor by integrating morphometric, meristic, and genetic markers (RAPD/mtDNA) to guarantee accurate identification, which is crucial for conservation planning.

Incorporate Genetic Screening into Hatchery Initiatives

To avoid hybridization and preserve regional adaptations, choose broodstock based on genetic knowledge. It is only appropriate to release genetically confirmed juveniles into natural rivers.

Reestablish River Communication

In order to support Mahseer's natural migration routes, hydropower projects must guarantee ecological flows and include fish passageways.

Preserve Vital Habitats It is important to map, keep an eye on, and prevent pollution, sedimentation, and habitat degradation in spawning and nursery areas.

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