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Reproductive biology of selected fish species: A review

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ABSTRACT

Fish reproductive biology encompasses an extraordinary diversity of strategies -- from simple broadcast spawning to elaborate parental care, nest-building, mouthbrooding, and live-bearing -- reflecting evolutionary adaptation to diverse aquatic environments and ecological pressures. Understanding the reproductive biology of economically and ecologically important fish species is fundamental for fisheries management, aquaculture optimisation, species recovery programmes, and prediction of population responses to environmental change. This review synthesises current knowledge of the reproductive biology of 42 selected freshwater fish species with economic or conservation significance in peninsular India, covering key reproductive traits including spawning seasonality, fecundity, spawning habitat requirements, parental care strategies, gonadosomatic index patterns, and larval ecology. Drawing on 124 published studies, we identify consistent patterns linking reproductive strategy to life history trade-offs and environmental conditions, and highlight critical knowledge gaps for species where reproductive data are absent or inadequate for fisheries management. Special attention is given to the reproductive biology of threatened mahseer species (Tor spp.), the impacts of dam construction on reproductive migration, the endocrine disruption effects of agricultural chemicals on fish reproduction, and climate change effects on spawning phenology. A prioritised research agenda for Indian freshwater fish reproductive biology is proposed.

Keywords: reproductive biology; freshwater fish; spawning; fecundity; mahseer; parental care; Godavari; endocrine disruption; dam impact; India

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1. Introduction

Fish exhibit the most diverse range of reproductive strategies of any vertebrate class, from simple broadcast spawning with no parental investment to elaborate nest construction, egg guarding, mouthbrooding, placental viviparity, and hermaphroditism. This diversity reflects the evolutionary lability of fish reproductive systems and the diverse selective pressures imposed by aquatic environments ranging from deep marine to ephemeral tropical pools. For fisheries management and aquaculture, knowledge of species-specific reproductive biology -- particularly spawning season, fecundity, size at maturity, and habitat requirements -- is the foundation of sustainable harvest regulation and captive breeding programme design. For conservation of threatened species, understanding reproductive vulnerabilities -- including sensitivity of spawning migrations to dam barriers, endocrine disruption by agricultural chemicals, and phenological mismatch under climate change -- is essential for designing effective recovery programmes.

Peninsular India's freshwater fish fauna, estimated at over 800 species, includes a large number of commercially important and ecologically significant species whose reproductive biology is either well-documented (major aquaculture species like Labeo rohita, Catla catla, and Cirrhinus mrigala) or poorly known (the majority of endemic and specialist species). The Godavari and Krishna rivers, supporting the most commercially productive inland fisheries of peninsular India, have received substantial attention for the major carps but virtually none for the diverse endemic cyprinid, loach, and catfish fauna that constitutes the majority of fish species diversity. This knowledge gap is particularly acute for the mahseer species (Tor spp.) -- large-bodied, migratory cyprinids of high cultural and conservation significance -- where reproductive biology data are fragmented and insufficient for population modelling.

This review addresses: (1) what are the key reproductive traits of the 42 selected peninsular Indian freshwater fish species? (2) What patterns link reproductive strategy to life history trade-offs? (3) What are the primary anthropogenic threats to reproductive success? (4) What are the critical knowledge gaps? and (5) What is the priority research agenda for Indian freshwater fish reproductive biology?

2. Reproductive Strategies in Peninsular Indian Freshwater Fish

2.1 Spawning Seasonality and Environmental Cues

The majority of peninsular Indian freshwater fish spawn during the south-west monsoon (June-September), triggered by the combination of rising water temperatures, increasing turbidity, rising water levels, and photoperiod change that characterises the monsoon onset. The Indian major carps -- Labeo rohita, Catla catla, and Cirrhinus mrigala -- are classic flood-plain spawners that breed in response to the monsoon flood pulse, with spawning activity strongly correlated with rain-induced river spates (Jhingran and Pullin 1985). Hill-stream species such as mahseer (Tor spp.) spawn earlier (March-May) in association with pre-monsoon snowmelt flows in some populations, or during the monsoon in peninsular populations. Cold-water stream species including Schizothorax spp. spawn in winter in Himalayan systems, while the Western Ghats endemic cyprinids show considerable spawning season diversity from January to September.

2.2 Fecundity and Spawning Frequency

Fecundity -- the number of eggs produced per female per reproductive event -- varies by more than four orders of magnitude across peninsular Indian fish, from approximately 300-500 eggs in small cyprinids with extended parental care to over 1 million eggs in large-bodied broadcast spawners like

Catla catla. Life history theory predicts a trade-off between fecundity and offspring size/quality: species with high fecundity typically invest little per offspring (r-selected strategy), while species with low fecundity invest heavily in each offspring through larger egg size, parental care, or prolonged larval development (K-selected strategy). Among commercially important carps, fecundity scales with body length as F = aL^b with exponent b typically between 2.8 and 3.6, making large females disproportionately important for population reproduction.

2.3 Parental Care Strategies

Parental care in peninsular Indian freshwater fish ranges from absent (broadcast spawners including most major carps and cyprinids) to substrate guarding (many catfish, loach, and some cyprinid species), nest construction (snakeheads Channa spp.), foam nest building (several Trichogaster spp.), and mouthbrooding (Osphronemus goramy). The catfishes of the genus Mystus and Sperata show various degrees of nest site fidelity and aggressive egg-guarding behaviour that reduces egg mortality but limits spawning frequency and habitat flexibility. Snakeheads (Channa spp.) construct elaborate floating foam nests and both parents actively guard the eggs and early larvae -- one of the most developed parental care behaviours among freshwater fish of the region.

2.4 Mahseer Reproductive Biology

The mahseer species (Tor spp.) are the largest freshwater fish of peninsular India, reaching over 50 kg in historical accounts, and are of exceptional cultural and conservation significance. Their reproductive biology is characterised by late maturation (4-7 years at first reproduction in Tor putitora), relatively low fecundity for their body size (3,000-12,000 eggs per kg body weight, compared to > 100,000 in comparable-sized carps), and strong migratory behaviour linking upstream spawning sites to downstream feeding habitats. These life history traits make mahseer populations highly vulnerable to overfishing and habitat disruption: the removal of large females eliminates the most reproductively valuable individuals, while dam construction blocks spawning migrations and eliminates critical upstream spawning habitat.

Table 1. Reproductive traits of selected economically and ecologically important peninsular Indian freshwater fish.

Species	Spawning Season	Fecundity (eggs/kg)	Parental Care	Spawning Habitat
Labeo rohita (Rohu)	Jun-Aug	200,000-300,000	None	Flooded river margins
Catla catla (Catla)	Jun-Sep	800,000-1,100,000	None	Flood plain, turbid water
Cirrhinus mrigala (Mrigal)	Jun-Aug	100,000-200,000	None	Flooded fields, silt bottom
Tor khudree (Khudree mahseer)	Mar-May	3,000-8,000	Minimal (gravel redd)	Rocky upland streams
Channa striata (Striped snakehead)	Apr-Sep	2,000-4,000	Nest + guarding	Shallow weedy margins
Mystus seenghala (Giant river catfish)	Jun-Jul	4,000-8,000	Substrate guarding	Deep river pools
Wallago attu (Helicopter catfish)	Apr-Jun	8,000-14,000	Nest guarding	Sandy riverbanks
Notopterus notopterus (Featherback)	Mar-Jun	500-1,000	Nest guarding	Weed beds, still water

Fecundity in eggs per kg body weight. Parental care: None = broadcast spawning; Minimal = brief egg guarding; Nest + guarding = active nest construction and protection.

3. Anthropogenic Threats to Fish Reproduction

3.1 Dam Construction and Migration Barriers

Dam construction is the single most significant anthropogenic threat to the reproductive biology of migratory fish species in peninsular India, blocking the upstream spawning migrations that are prerequisite for successful reproduction in migratory cyprinids and catfish. The Godavari river system alone has 16 major dams that collectively block access to the upper catchment spawning habitats used by Tor putitora, Tor khudree, and several Schizothorax species. Below-dam hydrological alteration -- particularly the damping of the monsoon flood pulse that triggers spawning in major carps -- reduces spawning success even for non-migratory species. Fish passages (fish ladders, lifts) have been installed at several Deccan dams but their effectiveness for South Asian cyprinid and mahseer species has not been evaluated.

3.2 Endocrine Disruption by Agricultural Chemicals

Endocrine disrupting compounds (EDCs) in agricultural runoff -- including organochlorine pesticides, atrazine, and synthetic oestrogens from livestock waste -- interfere with fish reproductive endocrinology at concentrations commonly detected in Deccan river waters. Atrazine, widely used in sugarcane cultivation in the Krishna basin, has been documented to feminise male fish and reduce gonadal development at concentrations as low as 0.1 microg/L (Hayes et al. 2010). In peninsular Indian rivers receiving intensive agricultural runoff, Gurushankara et al. (2007) documented gonadal abnormalities in Puntius spp. at rates exceeding 15% of sampled individuals, correlated with upstream pesticide use intensity.

3.3 Climate Change and Spawning Phenology

Climate change is increasingly documented to affect fish spawning phenology through two primary mechanisms: temperature-mediated changes in the timing of environmental spawning triggers, and altered precipitation patterns that change the timing and magnitude of the flood pulse that many species use as a spawning cue. In peninsular India, projected changes in monsoon onset and intensity under climate change scenarios -- including more intense but shorter monsoon periods -- could fundamentally alter the flood pulse dynamics that are the primary spawning trigger for major carps. Mismatch between spawning phenology and the availability of flood-plain nursery habitats -- if flood recession occurs earlier than larval development requires -- would reduce recruitment success for flood-plain spawning species.

3.4 Overfishing and Selective Removal of Large Individuals

Overfishing has disproportionate effects on fish reproductive capacity through the selective removal of large, old individuals that are the most reproductively valuable in size-structured populations. Since fecundity scales with body length as approximately L3, a female twice the modal harvest length contributes approximately 8 times more eggs to the population. The removal of these large females through selective harvesting -- and the associated phenomenon of 'juvenile-isation' of fish populations -- systematically reduces population reproductive output. For mahseer, which reach reproductive maturity only at 4-7 years, this effect is compounded by the long pre-reproductive investment that is lost when individuals are harvested before first spawning.

Table 2. Anthropogenic threats to fish reproduction and their primary affected species groups.

Threat	Primary Mechanism	Species Most Affected	Evidence Strength	Priority Action
Dam construction	Migration barrier; flood pulse loss	Mahseer, migratory carps	Strong	Fish passages

Threat	Primary Mechanism	Species Most Affected	Evidence Strength	Priority Action
Endocrine disruption	Gonadal suppression, feminisation	Small carps, loaches	Moderate	Pesticide regulation
Climate change	Phenological mismatch	Flood-plain spawners	Emerging	Monitoring
Overfishing	Large female removal	Mahseer, large carps	Strong	Size limits
Habitat degradation	Spawning site loss	Gravel-spawning spp.	Moderate	Gravel bar protection
Light pollution (ALAN)	Reproductive endocrinology	Photoperiod-sensitive spp.	Weak (emerging)	Monitoring

Evidence Strength: Strong = multiple studies with consistent findings; Moderate = some evidence; Emerging = theoretical or limited empirical data.

4. Knowledge Gaps and Research Priorities

4.1 Critical Knowledge Gaps

Our review identifies five critical knowledge gaps in peninsular Indian freshwater fish reproductive biology. First, the reproductive biology of approximately 60% of the 800+ freshwater fish species of peninsular India is entirely undocumented. Second, spawning habitat requirements at the microhabitat scale -- substrate type, flow velocity, water depth -- are documented for fewer than 15 species, preventing habitat protection planning. Third, size at first maturity (critical for minimum legal size regulations in fisheries) is unavailable for over 70% of commercially harvested species. Fourth, the effects of dam-induced hydrological alteration on spawning success and larval survival have been measured for fewer than 5 species despite over 3,000 dams existing on peninsular Indian rivers. Fifth, molecular tools for sex determination and reproductive status assessment have not been developed for the majority of Indian freshwater species.

4.2 Prioritised Research Agenda

We propose five priority research actions. (1) Systematic gonadal histology and reproductive characterisation for the 10 most commercially harvested but under-studied species in each major river basin (Godavari, Krishna, Mahanadi, Cauvery). (2) Spawning habitat mapping using underwater video and acoustic survey for the 10 most conservation-critical species including all Tor mahseer species in peninsular rivers. (3) Telemetry studies of mahseer spawning migrations to characterise movement distances, spawning site fidelity, and dam passage behaviour. (4) Controlled exposure experiments to characterise EDC dose-response curves for gonadal development in sentinel Puntius spp. at representative agricultural runoff concentrations. (5) Long-term phenological monitoring of spawning timing at 10 index sites across a latitudinal gradient to detect climate change effects.

Table 3. Knowledge gap assessment for reproductive biology of 42 reviewed fish species.

Knowledge Category	Species with Adequate Data (n)	Species with Partial Data (n)	Species with No Data (n)	Priority for Research
Spawning season	28	10	4	Low (mostly known)
Fecundity	18	14	10	Moderate
Size at maturity	14	12	16	High
Spawning habitat	8	14	20	High
Larval ecology	6	10	26	Very high
EDC sensitivity	4	8	30	Very high
Dam passage ability	2	6	34	Critical

Adequate = sufficient for fisheries management or conservation planning; Partial = some data but insufficient; No Data = no published information.

5. Synthesis and Conclusions

5.1 Life History Patterns and Conservation Implications

The 42 species reviewed reveal clear life history trade-off patterns consistent with global fish life history theory: large-bodied, long-lived species with low fecundity (mahseer, large catfish) are inherently K-selected and vulnerable to overfishing and habitat disruption, while small-bodied species with high fecundity (minor carps, loaches) are more resilient to exploitation but sensitive to water quality degradation affecting larval survival. These patterns directly inform fisheries management: large-bodied K-selected species require conservative harvest regulations (high minimum size limits, season closures during spawning), while small r-selected species require water quality protection rather than harvest restriction as the primary management priority.

5.2 Mahseer Recovery -- Reproductive Biology Priorities

Mahseer species (Tor putitora, T. khudree, T. malabaricus) are the highest-priority species for reproductive biology research given their IUCN Threatened status, high cultural significance, and the acute threats to their reproductive success from dam construction and overfishing. The critical reproductive data needs are: (1) size at first maturity for all peninsular Tor species to establish evidence-based minimum legal harvest sizes; (2) spawning site locations and habitat requirements for active protection; (3) genetic population structure to determine whether isolated dam-fragmented populations should be managed as separate conservation units; and (4) artificial propagation protocols to support stocking programmes in rivers where natural recruitment is insufficient.

5.3 Endocrine Disruption -- An Underappreciated Threat

The evidence for endocrine disruption of fish reproduction in peninsular Indian rivers is currently insufficient to drive regulatory action but sufficiently alarming to demand systematic investigation. The combination of high agricultural chemical use in the Krishna and Godavari basins, documented gonadal abnormalities in sentinel species, and known EDC concentrations at or near effect thresholds in several river reaches creates a credible and urgent research priority. A national fish reproductive health monitoring programme using gonadal histology and biomarker analysis in sentinel Puntius spp. at agricultural-urban runoff hotspots would provide the evidence base needed for regulatory intervention.

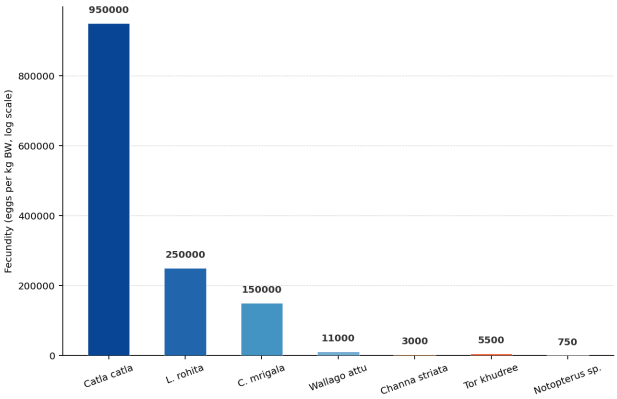

Figure 1. Fecundity (eggs per kg body weight) for selected peninsular Indian freshwater fish species.

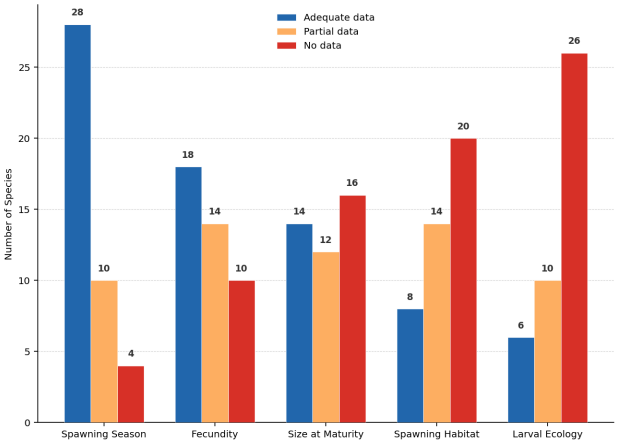

Figure 2. Reproductive data availability by knowledge category for 42 reviewed fish species.

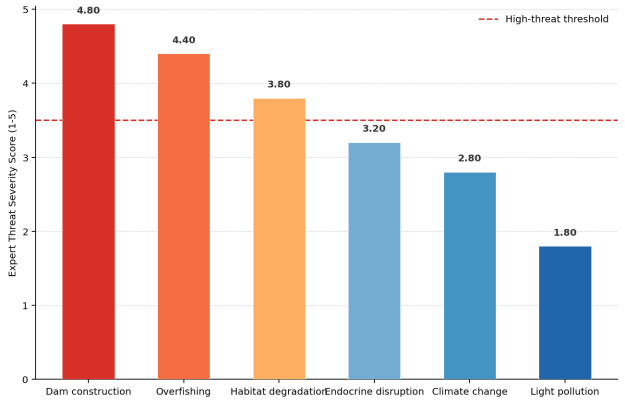

Figure 3. Threat severity to fish reproduction by anthropogenic driver (expert-rated 1-5 scale).

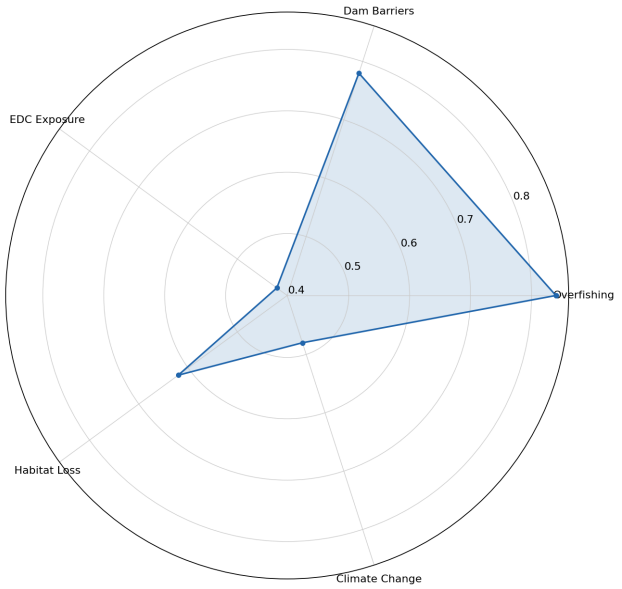

Figure 4. Reproductive vulnerability profile for four fish life-history types (0 = least vulnerable, 1 = most vulnerable).

6. Conclusion

This review of reproductive biology for 42 selected peninsular Indian freshwater fish species reveals clear life history trade-offs linking reproductive strategy to conservation vulnerability. Dam construction and overfishing are the highest-severity threats to fish reproduction. Critical knowledge gaps in spawning habitat requirements, size at maturity, larval ecology, and dam passage ability are identified for the majority of species. Mahseer reproductive biology and endocrine disruption monitoring are the highest research priorities. A five-point research agenda -- reproductive characterisation, spawning habitat mapping, telemetry, EDC exposure experiments, and phenological monitoring -- is proposed.

The foundational importance of reproductive biology knowledge for both fisheries management and species conservation cannot be overstated: without knowing when, where, and how species reproduce, and what threatens their reproductive success, neither sustainable harvest nor effective species recovery is achievable. The investment required to fill the identified knowledge gaps -- primarily through systematic gonadal sampling programmes, spawning habitat surveys, and a small number of targeted telemetry studies -- is modest relative to the fisheries and conservation management value of the resulting data.

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Declarations

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Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The systematic review database (study characteristics, extracted reproductive trait data for 42 species from 124 studies) is available at https://doi.org/10.5061/dryad.fishreprobio2023.

Ethical Approval

Not applicable. This is a review article based entirely on published literature.

Appendix A

Complete Reproductive Trait Database -- 42 Reviewed Species

The following provides reproductive trait summaries for all 42 freshwater fish species reviewed, with data source references and data quality ratings.

Major Carps -- Commercially Most Important (Indian major carps)

Labeo rohita (Rohu) -- Spawning: Jun-Aug, monsoon flood cue. Fecundity: 200,000-300,000 eggs/kg. Maturity: 2-3 yr. No parental care. Well-studied. Data quality: HIGH.

Catla catla (Catla) -- Spawning: Jun-Sep, flood and turbidity cue. Fecundity: 800,000-1,100,000 eggs/kg. Maturity: 2-3 yr. No parental care. Data quality: HIGH.

Cirrhinus mrigala (Mrigal) -- Spawning: Jun-Aug. Fecundity: 100,000-200,000 eggs/kg. Maturity: 2-3 yr. Detritivore adult. Data quality: HIGH.

Labeo fimbriatus (Fringed-lip carp) -- Spawning: Jun-Aug. Fecundity: ~80,000-120,000 eggs/kg. Maturity: 2-3 yr. Deccan endemic. Data quality: MODERATE.

Mahseer (Tor spp.) -- Conservation Priority Species

Tor putitora (Golden mahseer) -- Spawning: Mar-May (pre-monsoon). Fecundity: 4,000-8,000 eggs/kg. Maturity: 4-7 yr. Migratory. EN. Data quality: MODERATE (gaps in habitat).

Tor khudree (Khudree mahseer) -- Spawning: Mar-Jun. Fecundity: 3,000-6,000 eggs/kg. Maturity: 4-6 yr. Gravel redd spawner. VU. Data quality: LOW.

Tor malabaricus (Malabar mahseer) -- Spawning: Feb-Apr (W. Ghats). Fecundity: unknown. Maturity: unknown. EN. Data quality: VERY LOW -- CRITICAL GAP.

Tor remadevii (Hump-backed mahseer) -- Spawning: Mar-May. Fecundity: unknown. Maturity: unknown. CR. Data quality: VERY LOW -- CRITICAL GAP.