



Original Research Paper

Impacts of Water Pollution on the Fecundity and Reproductive Physiology of Selected Freshwater Fishes in the Godavari River: A Systematic Review

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Abstract

The Godavari River is one of the most important freshwater ecosystems in peninsular India, supporting aquatic biodiversity, agricultural production, and inland fisheries. Increasing urbanization, industrial discharge, domestic sewage, agricultural runoff, and plastic contamination have raised concerns regarding the ecological condition of the river and the reproductive health of its fish populations. This review examines the relationship between water pollution and fish fecundity, with particular reference to *Labeo calbasu*, *Cirrhinus mrigala* and *Mystus seenghala*. Relevant evidence concerning river water quality, potentially toxic elements, microplastics, and pollutant-induced reproductive dysfunction is synthesized to identify plausible mechanisms and important research gaps. Reproductive endpoints considered include absolute and relative fecundity, gonadosomatic index (GSI), gonadal maturation, oocyte atresia, vitellogenin responses, oxidative stress, and egg viability. Published investigations have documented potentially toxic elements and microplastics in the Godavari system, while experimental studies in freshwater fishes demonstrate that certain contaminants can interfere with endocrine regulation and ovarian development. However, evidence directly linking measured pollution exposure to reduced fecundity in each of the five focal species within the Godavari remains limited. The available literature therefore supports concern about reproductive risk but does not establish a uniform, basin-wide decline in fish fecundity. Integrated monitoring of water, sediment, fish tissues, and reproductive biomarkers is needed to determine the extent of these effects and inform fisheries conservation.

Keywords: Godavari River, Water Pollution, Heavy Metals, Fecundity, Oocyte Atresia, Endocrine-Disrupting Chemicals, *Labeo calbasu*, *Cirrhinus mrigala* and *Mystus seenghala*.

Introduction

1.1 Background and context

The Godavari River is the largest river system in peninsular India and flows from the Western Ghats across several states before entering the Bay of Bengal. Its basin supports diverse freshwater habitats, commercially important fishes, irrigation, domestic water use, and livelihoods dependent on inland fisheries. Nevertheless, expanding settlements, industrial development, agricultural activities, and wastewater discharge create multiple pressures on river water and sediment quality (Das et al., 2022). These pressures may vary among upstream, urban-industrial, reservoir, and downstream locations.

Investigations have identified heavy-metal contamination and water-quality deterioration at selected locations in the Godavari basin. Hussain et al. (2023) reported spatial

variation in metal concentrations across sampled river and tributary stations, while Kharake and Raut (2021) assessed water quality in the Nashik stretch. More recently, Ganguly et al. (2026) examined potentially toxic elements in water and sediment across the main river channel, identifying urban-industrial and other sources of contamination. Research has also documented microplastics in water, sediment, and fish along the Godavari River (Choudhary et al., 2025). These findings establish the presence of environmental pressures, but pollutant detection alone does not demonstrate reproductive impairment in fish.

1.2 Fish fecundity as a biological bioindicator

Fecundity is the reproductive capacity of a fish, commonly expressed as the number of eggs produced or present in the ovaries during a reproductive period (Esa et al., 2023). Absolute fecundity refers to the total number of eggs

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estimated for an individual female, whereas relative fecundity expresses egg number in relation to body mass or another defined measure, such as eggs per gram of body weight. These measures provide information about reproductive potential but do not, by themselves, establish successful fertilization, hatching, or recruitment (Callet et al., 2022).

The gonadosomatic index is generally calculated as:

$$GSI = \frac{Gonad\ Weight}{Body\ Weight} \times 100$$

GSI is useful for evaluating reproductive development when fish of comparable species, sex, season, and maturity stage are compared. Fecundity and GSI should be interpreted alongside gonadal histology, maturity stages, egg quality, and environmental measurements because reproductive variation can also arise from age, body size, nutrition, temperature, flow conditions, and natural seasonal cycles (Xiang et al., 2025).

1.3 Problem statement and objectives

Pollution may affect fish reproduction through direct toxicity, endocrine disruption, altered energy allocation, and damage to reproductive tissues. However, the extent to which these mechanisms have reduced fecundity in wild Godavari fish remains insufficiently resolved. A critical synthesis is therefore required to distinguish measured environmental contamination from experimentally demonstrated toxic effects and from reproductive outcomes that remain unverified in the river (Khole, 2021). This review aims to assess documented water-quality pressures in the Godavari basin, explain plausible mechanisms linking pollutants with reproductive dysfunction, examine evidence relating to five representative fish species, and identify priorities for environmental monitoring and fisheries management.

2. Review methodology

This article uses a structured literature-synthesis approach, bringing together studies of Godavari River pollution, fish reproductive biology, and aquatic ecotoxicology. The literature search covered scholarly indexing and publisher platforms, including PubMed, Springer Nature, ScienceDirect, and journal websites. Search terms included combinations of “Godavari River,” “fish fecundity,” “gonadosomatic index,” “heavy metals,” “ovarian histopathology,” “vitellogenin,” “microplastics,” and “endocrine disruption.”

Studies were considered relevant when they provided evidence of river contamination, reproductive biology in the focal species, or pollutant-associated reproductive effects in freshwater fishes. Evidence was classified as-

- (i) directly obtained from the Godavari,
- (ii) obtained from the same species in another environment, or
- (iii) mechanistic evidence from other freshwater fish or controlled experiments.

This distinction is important because findings from one river or experimental exposure cannot automatically be applied to wild fish in another river.

This is a structured review of the literature identified for this article, rather than a fully reproducible PRISMA systematic review with a documented complete search yield, duplicate removal, and independent screening. Those steps would be required before describing the work as a formally registered or PRISMA-compliant systematic review.

3. Water quality dynamics and pollutant profile of the Godavari River

3.1 Physicochemical stressors

Dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), pH, electrical conductivity, and total dissolved solids are important indicators of aquatic environmental conditions. Elevated BOD and COD can indicate increased organic loading and oxygen demand, while reduced DO can constrain aerobic metabolism and increase physiological stress in aquatic organisms (Chakraborty et al., 2026). However, these indicators do not identify individual toxicants and should be interpreted alongside chemical analyses.

Water-quality assessments in the Nashik and Nanded stretches have reported concerns associated with human activities and local pollution sources (Ganeshkar et al., 2024 and Kharake & Raut, 2021). Conditions may also change seasonally. Monsoon flows can dilute certain dissolved contaminants while transporting suspended material, agricultural runoff, and plastic debris. During lower-flow periods, reduced dilution may increase the concentration of some pollutants. These effects are not universal: the outcome depends on discharge, rainfall, pollutant solubility, sediment interaction, and local sources (Tatavarthi et al., 2025).

For reproductive studies, seasonal water quality must be assessed alongside the natural breeding cycle. A low GSI recorded before spawning, for example, cannot be attributed to pollution without considering the fish's maturity stage and seasonal reproductive pattern (Siddique et al., 2026).

3.2 Heavy metals and potentially toxic elements

Lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), zinc (Zn), nickel (Ni), and other potentially toxic elements can enter freshwater systems through industrial discharge, urban runoff, mining-related activities, and agricultural inputs (Mukherjee & Bhowmick, 2024). Their toxicity depends on chemical form, concentration, duration of exposure, water chemistry, and the ability of organisms to regulate or eliminate them (Burande et al., 2026).

Hussain et al. (2017) documented spatial variation in metal contamination across selected Godavari basin stations. In a more recent investigation, Ganguly et al. (2026) measured nine potentially toxic elements in water and sediment at 17 sites along the main river channel. Their results identified different source contributions and highlighted the

importance of considering both dissolved and sediment-associated contamination. The study reported a downstream cadmium concern in the Maharashtra urban-industrial corridor. These results provide environmental context for investigating reproductive exposure, but they do not themselves demonstrate reduced egg production in the focal fish species.

Metals may affect fish through gill uptake, ingestion of contaminated food or sediment, and subsequent distribution to internal tissues. Some metals are essential at low concentrations but toxic at excessive levels, whereas others, such as cadmium and lead, have no established biological requirement in fish. Benthic and demersal species may encounter contaminated sediment and prey, although trophic position alone does not reliably predict exposure or reproductive toxicity (Oros, 2025).

3.3 Organic pollution, agrochemicals, and emerging contaminants

Domestic wastewater and industrial effluents can introduce organic matter, nutrients, detergents, pharmaceuticals, and other biologically active substances. Nutrient enrichment may promote excessive algal growth and subsequent oxygen depletion, while some chemicals can affect hormone signalling at concentrations that do not produce obvious external signs of toxicity. Pesticides and other agrochemicals may also influence fish reproduction, depending on their properties and exposure conditions (Rohani, 2023).

Microplastics are an additional concern. Choudhary et al. (2025) investigated their distribution in Godavari water, sediment, and fish tissues across the river system. Their study reported widespread contamination, with higher levels in urban areas and reservoirs, and identified the Vishnupuri reservoir near Nanded as a location of elevated microplastic accumulation. The finding establishes an exposure pathway requiring further investigation, but it does not prove that microplastics have reduced fecundity in Godavari fish.

Potential reproductive effects of microplastics may arise from physical interactions, particle-associated chemicals, or additives and co-contaminants. The magnitude of these effects in wild fish depends on particle size, polymer composition, exposure dose, ingestion, and physiological responses (Ullah et al., 2026). Field studies must therefore connect measured exposure with reproductive endpoints instead of treating microplastic detection as evidence of reproductive failure.

4. Mechanisms of pollution-induced reproductive impairment

4.1 Endocrine disruption and the hypothalamic–pituitary–gonadal axis

Fish reproduction is regulated by the hypothalamic–pituitary–gonadal (HPG) axis. Signals from the hypothalamus stimulate pituitary gonadotropin release, which regulates gonadal steroid production, gamete development, and spawning. Environmental contaminants

may interfere with hormone synthesis, receptor activity, steroid metabolism, or feedback regulation (Kadam et al., 2024).

In female teleosts, oestrogen stimulates the liver to produce vitellogenin, a precursor protein transported through the blood to developing oocytes. Uptake of vitellogenin contributes to yolk formation and normal oocyte development. Chemicals that disrupt oestrogen signalling or hepatic vitellogenin production may therefore interfere with reproductive development (Reading et al., 2018).

Rajalakshmi et al. (2023) reviewed evidence that cadmium can affect hormone regulation, gonadal development, and reproductive processes in freshwater fish. The authors also describe changes in vitellogenin-related responses and ovarian injury under particular exposure conditions. However, endocrine responses are chemical- and species-dependent; vitellogenin changes should not automatically be interpreted as a reduction in fecundity. In particular, elevated vitellogenin in male fish can indicate exposure to oestrogenic substances, whereas reduced production in females may indicate a different form of disruption.

4.2 Ovarian histopathology and oocyte atresia

Ovarian histology can reveal reproductive injury that is not apparent from external examination. Relevant changes include degeneration of developing oocytes, abnormal follicular structure, altered oocyte maturation, and increased atresia (Baldini et al., 2024). Atresia is a natural process through which unspawned or degenerating oocytes are resorbed; therefore, its presence alone is not proof of pollution. Evidence of an adverse effect requires appropriate comparisons among maturity stages, seasons, exposure levels, and reference sites.

A study of *Labeo calbasu* outside the Godavari basin, reported abnormal oocytes, reduced oocyte numbers, and impaired oogenesis in fish sampled from sites affected by heavy-metal pollution (Banerjee et al., 2022). This provides species-specific evidence that gonadal abnormalities can occur under polluted field conditions. It cannot, however, establish that identical lesions occur in *L. calbasu* from the Godavari without comparable local observations.

4.3 Oxidative stress and energetic trade-offs

Exposure to certain metals and organic contaminants can increase the production of reactive oxygen species. When antioxidant defenses cannot adequately control these species, oxidative stress may damage membrane lipids, proteins, and cellular structures. Biomarkers such as superoxide dismutase (SOD), catalase (CAT), and malondialdehyde (MDA) can help evaluate this response, provided that the tissue, analytical method, exposure conditions, and units are clearly reported (Li Pomi et al., 2026).

Chronic stress may also alter energy allocation. Maintenance, detoxification, and tissue repair require energy that might otherwise support growth and gamete production. Nevertheless, an oxidative-stress response

does not necessarily mean that fecundity has declined (Kaltsas, 2023). A convincing demonstration requires simultaneous assessment of contaminant exposure,

physiological biomarkers, gonadal development, and reproductive output (Goud et al., 2025).

5. Case studies: reproductive effects in selected fish species

The five focal species differ in feeding ecology, habitat use, and reproductive biology. These differences may influence their exposure to contaminants, but they should not be used to assign a pollution-sensitivity ranking without comparative data.

Fish species	Ecological characteristics	Evidence relevant to reproduction	Evidence limitation for the Godavari	Reference
<i>Labeo calbasu</i>	Freshwater carp; mainly water-column and bottom-associated feeding	Gonadal abnormalities have been reported in polluted habitats outside the basin	Direct pollution-linked fecundity reduction requires local confirmation	Gupta & Banerjee, 2015
<i>Cirrhinus mrigala</i>	Indian Major Carp	Fecundity and GSI have been measured in pond-reared fish and across Ganges-basin rivers	Studies outside the Godavari do not demonstrate a local pollution–fecundity relationship	Iqbal, 2009 and Dwivedi et al., 2021
<i>Mystus seenghala</i>	Freshwater catfish of fisheries importance	Published work describes breeding and early-life history	Direct evidence linking measured Godavari pollution to fecundity was not identified in the reviewed sources	Deshmukh et al., 2019

5.1 *Labeo calbasu* (Calbasu)

Labeo calbasu is an economically important Indian major carp and a useful species for investigating environmental effects on reproductive performance (Gupta & Banerjee, 2016). Its reproductive output can be influenced by body size, nutrition, seasonal conditions, and gonadal maturity, making careful matching of these variables essential when comparing fish from different river stretches (Mishra et al., 2024).

There is the possibility of pollutant-associated reproductive injury in the species. However, it is evidence from a different wetland and does not establish that Godavari populations exhibit the same lesions or a measurable reduction in fecundity. For Godavari populations, future studies should quantify absolute fecundity, relative fecundity, GSI, oocyte-stage distribution, and the proportion of atretic follicles while simultaneously measuring metal concentrations in water, sediment, and fish tissues. Seasonal and reference-site comparisons are necessary before attributing reproductive differences to contamination (Akanksha, 2023).

5.2 *Cirrhinus mrigala* (Mrigal)

Cirrhinus mrigala is an Indian major carp for which reproductive traits, including fecundity and gonadosomatic index, have been examined in riverine and aquaculture settings. Kumar et al. (2025) reported seasonal variation in GSI and fecundity in pond-reared fish, with reproductive activity peaking during the monsoon-period breeding season under the conditions studied. Sah (2017) also compared reproductive potential across six rivers of the Ganges basin and reported positive relationships between

fecundity and fish or ovary measurements. These studies provide useful reproductive-biology context, but they are not direct evidence of a pollution-induced decline in *C. mrigala* in the major rivers of India including Godavari (Dwivedi et al., 2017 and Wanjari et al., 2025). Local work should measure contaminants and reproductive endpoints in the same fish, with appropriate reference sites and seasonal controls.

5.3 *Mystus seenghala* (Giant River catfish)

Mystus seenghala is a freshwater catfish of fisheries importance, and earlier research has described its early life history, breeding, and hatchling rearing (Gupta et al., 2015). Such work provides background on reproduction and development but does not establish a relationship between pollution exposure and fecundity in the Godavari. In addition, taxonomic sources may use the combination *Sperata seenghala* for this species; the name used in a review should be checked against the taxonomic authority adopted by the journal (Kumar et al., 2021). A basin-specific investigation should record species identification, sex, body size, maturity stage, GSI, fecundity, and egg viability while measuring relevant contaminants in water, sediment, prey, and fish tissues (Ajibare & Loto, 2023).

6. Ecological and fisheries management implications

6.1 Population recruitment

A decline in the number of viable eggs, fertilization success, hatching rate, or larval survival can reduce the number of young fish entering a population (Cattelan & Valenzano 2025). Repeated reproductive failure may eventually affect population structure and fishery productivity. However, recruitment also depends on

spawning habitat, hydrological conditions, predation, food availability, and fishing pressure. Consequently, a decline in fish abundance cannot be attributed to pollution-related fecundity reduction without supporting evidence (Saima et al., 2026).

Long-term monitoring should link adult reproductive indicators to egg and larval abundance, juvenile recruitment, and catch data. This would help determine whether observed physiological effects translate into population-level consequences (Crane et al., 2010).

6.2 Socio-economic implications

Riverine fisheries contribute food, income, and employment to communities across the Godavari basin (Hon & Jagdale, 2026). Deteriorating water quality may affect fisheries through habitat degradation, altered food webs, and potential reductions in reproductive success. Contamination may also raise food-safety concerns when pollutants accumulate in edible tissues (Eli & Lelei, 2026). Nevertheless, the economic consequences of reproductive impairment should be quantified rather than assumed. Catch records, fish-market data, household dependence on fisheries, and longitudinal population surveys can help distinguish the effects of pollution from other pressures on inland fisheries.

7. Strategic recommendations and future research directions

7.1 Standardized reproductive and environmental biomarkers

A coordinated monitoring program should integrate physicochemical measurements with reproductive assessments. At each sampling site, water and sediment should be analyzed for relevant contaminants, while fish should be examined for tissue burdens, GSI, absolute and relative fecundity, gonadal maturity, ovarian histopathology, and egg viability.

Vitellogenin can be included as an endocrine biomarker, but results must be interpreted according to sex, maturity stage, season, and analytical method. SOD, CAT, and MDA measurements may provide complementary evidence of oxidative stress. No single biomarker should be treated as conclusive evidence of reproductive failure.

Sampling should cover upstream reference sites, urban-industrial stretches, and downstream locations, with repeated observations during pre-spawning, spawning, and post-spawning periods. This design would allow environmental exposure to be evaluated against natural reproductive variation.

7.2 Research gaps and ecotoxicological priorities

Three major gaps emerge from the literature. First, environmental contamination is better documented than direct relationships between pollutant exposure and fecundity in the five selected species. Second, reproductive studies frequently require stronger integration of water chemistry, sediment contamination, tissue burdens, and histological endpoints. Third, long-term evidence

connecting reproductive biomarkers with larval recruitment and fisheries production remains insufficient. Future work should combine field investigations with controlled experiments using environmentally relevant exposure concentrations. Molecular analyses of steroidogenesis, gonadotropin signalling, oestrogen receptors, and vitellogenin-related pathways may help explain mechanisms identified through field observations. Microplastic research should additionally distinguish particle-associated effects from the effects of additives and co-occurring pollutants.

7.3 Policy and conservation interventions

Pollution management should prioritise effective treatment of municipal sewage, compliance with industrial effluent standards, monitoring of agricultural runoff, and improved plastic-waste management. Urban and industrial stretches requiring particular attention should be identified through repeated, comparable monitoring rather than isolated measurements.

Spawning and nursery habitats should be mapped and protected where ecological assessments demonstrate their importance. Seasonal restrictions on fishing may be appropriate where supported by local breeding data. Environmental agencies and fisheries departments should coordinate water-quality monitoring with fish reproductive surveys so that changes in pollutant exposure can be evaluated against biological outcomes.

8. Conclusion

Water pollution in the Godavari River is an important environmental concern because documented contamination by potentially toxic elements and microplastics creates plausible exposure pathways for freshwater fishes. Evidence from freshwater ecotoxicology indicates that certain contaminants can interfere with endocrine regulation, ovarian development, cellular antioxidant defences, and reproductive performance. Research on *Labeo calbasu* outside the Godavari also demonstrates that gonadal abnormalities can occur in polluted habitats, while a study of *S. mrigala* at Nanded provides a locally relevant fecundity baseline.

However, the current evidence does not establish a uniform decline in fecundity across the five selected species or demonstrate a direct pollution–fecundity relationship for each species in the Godavari. Such conclusions require field studies that measure exposure and reproductive endpoints in the same fish populations while controlling for season, body size, maturity, and habitat conditions.

An integrated river-basin approach combining pollution control, standardized reproductive biomarkers, species-specific monitoring, and protection of spawning habitats is therefore essential. Establishing a clear connection between environmental contamination, reproductive impairment, and recruitment will provide the evidence needed for effective freshwater biodiversity conservation and sustainable fisheries management.

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