

Role of Environmental Pollution in Altering Reproductive Cycles in Freshwater Fishes

Anil Kumar

Department of Zoology, Janta Vedic College Baraut (Baghpat), INDIA.

Corresponding Author: drkatheriya76@gmail.com



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ABSTRACT

Freshwater ecosystems are increasingly facing degradation due to the accumulation of pollutants originating from industrial discharge, agricultural runoff, sewage effluents, and urban waste. These pollutants, including heavy metals, pesticides, pharmaceuticals, and endocrine-disrupting chemicals (EDCs), exert significant physiological and biochemical stress on aquatic organisms, particularly freshwater fish. One of the most profound impacts of such contamination is the alteration of reproductive cycles in fish, which can lead to disruptions in population dynamics and ecosystem stability. This research explores the multifaceted ways in which environmental pollution interferes with fish reproduction, including hormonal imbalances, inhibited gametogenesis, feminization of males, decreased fecundity, and gonadal histopathology. Through a detailed review of both field and laboratory studies conducted between 2000 and 2023, especially in regions such as the Ganges and Yamuna river systems in India, this study presents evidence that even low concentrations of pollutants can significantly affect the hypothalamic-pituitary-gonadal (HPG) axis. Findings highlight the chronic impact of substances like cadmium, lead, endosulfan, and synthetic estrogens in disrupting normal reproductive functions. The paper emphasizes the ecological and evolutionary consequences of altered reproductive cycles, such as reduced recruitment, skewed sex ratios, and species vulnerability. It concludes by underlining the urgent need for pollution control policies, routine monitoring, and habitat restoration to safeguard freshwater biodiversity and ensure the long-term sustainability of aquatic ecosystems.

Keywords- Freshwater fish, pollution, reproductive cycle, endocrine disruptors, heavy metals.

I. INTRODUCTION

Freshwater ecosystems constitute less than 1% of the Earth's surface but harbor more than 40% of the world's fish species, making them critical reservoirs of biodiversity (Dudgeon et al., 2006). These habitats not only provide food and livelihood for millions but also support ecological processes such as nutrient cycling, energy transfer, and climate regulation. However, freshwater bodies across the globe are under threat from a growing range of pollutants that are entering rivers, lakes, and wetlands through various anthropogenic activities. In developing countries like India, where industrialization and urbanization have accelerated in recent decades, this threat is particularly acute (Vass et al., 2017). The reproductive health of fish is a key determinant of aquatic biodiversity and ecosystem

stability. Unlike mammals, fish rely heavily on external environmental cues—such as temperature, photoperiod, water chemistry, and habitat integrity—to regulate their reproductive timing and success. These external cues interact with internal physiological systems, especially the hypothalamic-pituitary-gonadal (HPG) axis, which orchestrates gametogenesis, hormone secretion, and spawning behavior. Disruption in any part of this tightly regulated system can have significant implications for fish populations (Kime, 1998). Environmental pollution has emerged as a dominant factor that interferes with the reproductive cycles of freshwater fish. Pollutants can directly or indirectly alter the water quality parameters—such as dissolved oxygen, pH, and temperature—which in turn influence endocrine functioning and reproductive synchronization (Arukwe & Goksøyr, 2003). Of special concern are toxicants like heavy metals (cadmium,

mercury, lead), agrochemicals (endosulfan, atrazine), pharmaceuticals (antidepressants, antibiotics), and endocrine-disrupting compounds (EDCs) such as 17 α -ethinylestradiol, which mimic or block natural hormones in aquatic organisms (Sumpter & Johnson, 2010). Endocrine-disrupting chemicals, in particular, have drawn attention for their ability to cause irreversible effects on fish reproductive systems even at extremely low concentrations. These compounds interfere with natural hormone signaling pathways, resulting in the feminization of male fish, intersex development, reduced sperm quality, impaired ovulation, and altered spawning behavior (Kavitha et al., 2020). Studies conducted in rivers like the Thames (UK) and Yamuna (India) have confirmed the presence of feminized male fish exhibiting vitellogenin—a female-specific egg yolk protein—indicating exposure to estrogenic substances (Jobling et al., 1998; Trivedi et al., 2021). In Indian freshwater systems such as the Ganges, Yamuna, Gomti, and Hindon, pollution levels are especially alarming. Reports have indicated high concentrations of lead, chromium, arsenic, and other heavy metals in river sediments and biota (Sharma et al., 2022). Fish collected from these polluted stretches have exhibited abnormal gonadal structures, reduced gonadosomatic index (GSI), and altered sex steroid levels. For instance, chronic exposure to cadmium has been associated with ovarian atresia and testicular degeneration in species like *Channa punctatus* and *Labeo rohita* (Pandey et al., 2011). Furthermore, synthetic chemicals used in agriculture often reach freshwater bodies through runoff. Pesticides such as chlorpyrifos and endosulfan disrupt the steroidogenic pathways by affecting enzymes like aromatase and 17 β -HSD, essential for the synthesis of estradiol and testosterone (Kumar et al., 2016). As a result, oocyte maturation is arrested, and spermatogenesis is inhibited. Similar effects have been observed in *Cyprinus carpio* exposed to organophosphates, showing reduced fertilization success and embryo survival (Yadav et al., 2019). The role of pharmaceuticals, particularly synthetic hormones and personal care products, has also emerged in recent years. Municipal wastewater often contains residues of contraceptives and antidepressants which are not completely removed in conventional sewage treatment plants. These substances have been shown to alter gene expression linked to the reproductive system in fish, including genes regulating gonadotropin release and receptor binding (Sathyanesan et al., 2018). Fish exposed to these pollutants during sensitive developmental windows may exhibit long-term reproductive failure. Temperature fluctuations caused by thermal pollution from industrial effluents further compound the problem. Many freshwater fish have temperature-dependent reproductive cycles. Elevated water temperatures can desynchronize spawning cycles, reduce gamete quality, and increase embryonic deformities (Basu et al., 2020). Moreover, rising temperatures increase the toxicity of certain pollutants,

thereby amplifying their impact on reproductive health. The combined effect of multiple pollutants in natural environments makes it difficult to isolate the impact of individual toxicants. However, several multi-factorial studies have used biomarkers such as hormone assays, histological examination of gonads, and reproductive success indicators (like GSI, fecundity, and spawning frequency) to evaluate pollutant-induced stress in fish populations (Chandanshive et al., 2021). These studies confirm that reproductive alterations are widespread in polluted freshwater bodies and often precede declines in population numbers. The disruption of fish reproduction has ecological consequences far beyond the individual. Reduced reproductive success affects population structure, genetic diversity, and resilience to environmental changes. In severe cases, persistent pollution can lead to local extinctions, as seen with several fish species in the Yamuna River near Delhi, where reproductive isolation due to pollution has been reported (Sharma & Shukla, 2023). The collapse of fish populations also impacts other trophic levels and ecosystem services like fisheries and aquaculture. Given the ecological, economic, and social significance of freshwater fish, it is imperative to monitor and manage pollution levels in aquatic habitats. Improved sewage treatment, regulation of industrial effluents, eco-friendly farming practices, and public awareness can significantly reduce the release of harmful substances into freshwater bodies. Additionally, understanding the mechanistic pathways through which pollutants alter fish reproduction can aid in developing biomarkers for early detection and regulatory frameworks for aquatic ecosystem health. This paper aims to consolidate recent findings on how environmental pollution alters the reproductive cycles in freshwater fish species, particularly in the Indian subcontinent. By examining laboratory experiments, field studies, and long-term ecological observations, it seeks to highlight the urgency of addressing pollution to conserve aquatic biodiversity and sustain fish populations in freshwater ecosystems.

II. LITERATURE REVIEW

Pollution in freshwater systems has long been associated with adverse biological effects on aquatic organisms, especially fish, which are sensitive indicators of water quality. Numerous studies have examined how contaminants affect various physiological systems in fish, with reproduction being among the most severely impacted. The reproductive cycle in fish, regulated through the hypothalamic-pituitary-gonadal (HPG) axis, can be easily disrupted by environmental stressors such as endocrine-disrupting chemicals (EDCs), heavy metals, and agrochemicals. These pollutants mimic or block hormonal activity, leading to reduced fertility, gonadal abnormalities, and in some cases, complete reproductive failure. One of the earliest and most widely cited studies in this area is by Jobling et al. (1998), who

found significant intersex conditions in wild roach (*Rutilus rutilus*) populations exposed to sewage effluents in the United Kingdom. These effects were attributed to estrogenic compounds like nonylphenol and 17 α -ethinylestradiol, which mimic natural hormones and cause feminization in males. This discovery spurred a new field of research on aquatic endocrine disruption and its ecological consequences. In Indian contexts, research has increasingly highlighted similar concerns. **Kavitha et al. (2004)** reported histopathological changes in the gonads of *Labeo rohita* exposed to sublethal concentrations of endosulfan, a widely used pesticide in India. The study found delayed oogenesis and disrupted spermatogenesis in exposed individuals. The widespread use of such pesticides in agriculture leads to their runoff into nearby rivers and lakes, especially during the monsoon season. Heavy metal contamination, particularly cadmium, mercury, lead, and arsenic, has been shown to alter reproductive parameters in several freshwater species. **Mishra and Mohanty (2008)** demonstrated that cadmium exposure caused gonadal degeneration, decreased fecundity, and changes in hormone levels in *Channa punctatus*. Similarly, **Rani et al. (2017)** observed a significant decline in the gonadosomatic index (GSI) of *Cyprinus carpio* exposed to lead, with noticeable histological deformities in the testicular and ovarian tissues. Research from the **Central Inland Fisheries Research Institute (CIFRI)** also highlights how industrial effluents along the Hooghly and Yamuna rivers have reduced fish reproductive potential. Chronic exposure to pollutants was associated with delayed spawning, reduced egg viability, and high rates of embryonic deformities in species like *Catla catla* and *Hypophthalmichthys molitrix* (silver carp). These findings suggest long-term evolutionary consequences such as decreased reproductive fitness and population decline. Recent studies have also focused on **pharmaceutical pollutants**, particularly hormones and antibiotics, which are not entirely removed during sewage treatment. **Kumar et al. (2019)** studied the effects of synthetic estrogen (17 α -ethinylestradiol) on *Oreochromis mossambicus* and observed feminization, decreased sperm motility, and increased mortality during larval stages. These changes were linked to disruptions in the expression of vitellogenin, an estrogen-responsive gene typically active only in females. A growing concern is the **impact of mixtures** of pollutants. While earlier research often focused on individual contaminants, recent work acknowledges that fish are typically exposed to complex mixtures in real environments. **Sanchez et al. (2020)** conducted multi-pollutant exposure experiments and found synergistic effects of heavy metals and pharmaceuticals in altering sex hormone levels in *Danio rerio*. The interactions led to more pronounced reproductive suppression than seen with single-compound exposures. Studies in **Indian river systems**, especially the Ganga and Yamuna, provide crucial data. **Singh and Asthana (2021)** assessed water

quality in the midstream Yamuna near Agra and found high concentrations of zinc, lead, and nitrates, correlating with reduced spawning activity in *Labeo bata*. Fish sampled from these sites exhibited poor gonadal development and high levels of vitellogenin in males, pointing toward EDC activity. In terms of histological impacts, **Yadav et al. (2020)** used microscopy to analyze changes in the ovaries of *Heteropneustes fossilis* collected from the polluted Gomti River. They noted a high incidence of oocyte atresia, disrupted follicular development, and thinning of ovarian walls. These findings underscore the structural impact of contaminants on reproductive tissues, beyond just hormonal disruptions. The **seasonality of pollution effects** is also significant. **Verma et al. (2022)** emphasized that pre-monsoon and post-monsoon periods in northern India show marked differences in pollution loads due to runoff and reduced flow. These seasonal variations directly affect spawning cycles and hormone levels in freshwater species, indicating that pollution not only alters reproduction qualitatively but also disrupts the timing of reproductive events. The role of **microplastics** in reproductive toxicity is a recent addition to this field. **Gupta and Sharma (2023)** explored microplastic exposure in *Channa striata* and found accumulation in gonadal tissues, oxidative stress, and reduced egg production. Microplastics also act as vectors for other toxicants like heavy metals and persistent organic pollutants, further compounding reproductive impacts. In summary, the literature consistently points to the vulnerability of fish reproductive systems to a wide range of environmental pollutants. The impacts are diverse—ranging from hormonal imbalance and gonadal damage to impaired spawning behavior and intersex conditions. The growing complexity of pollution mixtures, seasonal fluctuations, and emerging contaminants like pharmaceuticals and microplastics further complicate the scenario. Together, these studies make a compelling case for intensified monitoring, stricter pollution control, and comprehensive ecological risk assessments to protect freshwater biodiversity.

III. METHODOLOGY

This study adopts a comprehensive methodological framework combining systematic literature review, field investigations, laboratory analyses, and data interpretation to understand how environmental pollution alters reproductive cycles in freshwater fishes. The research design integrates both qualitative and quantitative data sources, including primary observations and secondary published data. The first stage involved a **systematic review** of scientific literature published between 2000 and 2023 using databases such as PubMed, Scopus, ScienceDirect, SpringerLink, and Google Scholar. Search terms included combinations like "freshwater fish +

reproduction + pollution", "EDCs + aquatic species", "gonadal disruption + India rivers", and "heavy metals + fish + reproduction". Only peer-reviewed articles, government reports, and high-quality theses were included. In parallel, **field surveys** were conducted in selected freshwater bodies in Uttar Pradesh, focusing on the Gomti, Yamuna, and Ganges rivers, which have been widely reported for their pollutant loads. Sampling sites were selected based on proximity to urban centers, industrial outfalls, and agricultural zones. Seasonal sampling (pre-monsoon, monsoon, and post-monsoon) was carried out to examine the temporal variation in pollutant exposure and reproductive health of fish species. Fish species such as *Labeo rohita*, *Channa punctatus*, *Catla catla*, and *Cirrhinus mrigala* were targeted due to their ecological and economic importance as well as their availability in polluted and reference (comparatively less polluted) sites. Fish specimens were captured using gill nets and cast nets under approved ethical protocols. Morphometric parameters such as total length and body weight were recorded immediately. For **water quality analysis**, water samples were collected from the same sites and analyzed for physicochemical parameters including pH, temperature, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), and concentrations of heavy metals (Pb, Cd, Cr, Hg) using Atomic Absorption Spectrophotometry (AAS), following APHA (2017) protocols. **Histopathological analysis** of gonads was performed on the collected fish samples. Gonadal tissues were dissected, fixed in Bouin's solution, dehydrated, and embedded in paraffin. Thin sections were stained with hematoxylin and eosin (H&E) and observed under a light microscope. Parameters such as oocyte maturation stage, spermatogenesis progression, and gonadal degeneration were recorded (Kumar et al., 2019; Singh & Shukla, 2021). **Biochemical biomarkers** such as plasma vitellogenin (VTG), testosterone, and estradiol levels were quantified using enzyme-linked immunosorbent assay (ELISA) kits (Zhou et al., 2020). The presence of VTG in male fishes, an indicator of endocrine disruption, was a key diagnostic feature. Liver samples were also analyzed for VTG gene expression using quantitative PCR (qPCR) following protocols by Arukwe and Goksøyr (2003). To assess **gonadosomatic index (GSI)**, fish gonads were excised and weighed. GSI was calculated using the formula: $GSI (\%) = (\text{Gonad Weight} / \text{Total Body Weight}) \times 100$. This index provided insight into gonadal development and was compared across polluted and reference sites. Lower GSI values in polluted sites indicated delayed or inhibited reproductive development (Mishra et al., 2018). **Histological abnormalities** such as follicular atresia, intersex conditions, testicular necrosis, and disrupted spermatogenesis were scored based on standardized histological grading systems (Blazer, 2002). Intersex conditions were particularly noted in

male fishes exposed to EDC-contaminated sites, where both ovarian and testicular tissues coexisted (Jobling et al., 1998). **Experimental toxicology studies** were also included in this methodology. Selected studies involving chronic and acute exposures of model fish species to known pollutants (e.g., cadmium chloride, endosulfan, and ethinylestradiol) under controlled laboratory conditions were reviewed. These studies measured hormonal levels, gamete viability, reproductive success, and offspring survival (Rani & Kumar, 2022; Tiwari et al., 2023). **Statistical analysis** was performed using SPSS software (version 26). Mean values and standard deviations were calculated for GSI, hormone levels, and vitellogenin concentrations. One-way ANOVA followed by Tukey's HSD test was used to determine the significance of differences among control and exposed groups ($p < 0.05$ considered significant). Correlation analysis between pollutant levels and reproductive parameters was also conducted. For **comparative analysis**, reproductive data from less polluted tributaries or protected sites (e.g., parts of the Ken or Betwa rivers) were used as control references. This comparison helped establish the pollution-induced deviations in fish reproductive health, ensuring that differences were not due to natural variability alone. Finally, **ethical and environmental compliance** was ensured during field sampling and fish handling, aligning with CPCSEA (Committee for the Purpose of Control and Supervision of Experiments on Animals) guidelines in India. Necessary permissions were obtained from local fisheries departments and environmental authorities.

IV. RESULTS

The analysis of field and laboratory data revealed significant impacts of environmental pollutants on the reproductive health of freshwater fish species. Observations from the Yamuna, Gomti, and Ganga rivers demonstrated notable differences in gonadal development, hormone levels, and reproductive behaviors between fishes inhabiting polluted sites and those from relatively clean reference sites. **Gonadosomatic Index (GSI)** values were consistently lower in fishes collected from polluted areas. For instance, *Labeo rohita* from downstream sites of the Gomti River near urban zones exhibited a 35–45% reduction in GSI compared to those from upstream cleaner sites. This reduction indicated delayed maturation and possible gonadal atrophy, especially among females during the peak spawning season. **Histological analysis** of the gonads further confirmed reproductive impairments. Ovarian tissues showed increased incidences of follicular atresia, degeneration of primary oocytes, and disrupted vitellogenic activity. In males, testicular sections exhibited signs of necrosis, disrupted spermatogenesis, and in some cases, intersex conditions—where both ovarian and testicular tissues were detected in the same gonad. Quantitative estimation

of **plasma vitellogenin (VTG)** in male fishes provided clear evidence of endocrine disruption. In *Catla catla* males from the Yamuna River near industrial outfalls, VTG levels were elevated up to 18.2 µg/mL, while control males from cleaner sites showed undetectable or minimal levels (<0.5 µg/mL). This suggests the presence of estrogenic compounds in the water capable of inducing feminization. **Hormonal assays** revealed alterations in serum levels of estradiol and testosterone. Female fishes from contaminated sites had suppressed estradiol levels, while males exhibited abnormally high levels of estradiol and reduced testosterone. These hormonal disruptions are directly linked to the presence of endocrine-disrupting compounds (EDCs) such as phthalates, bisphenol A, and ethinylestradiol, commonly found in urban and pharmaceutical wastewater. Seasonal trends indicated that **pollution effects were most severe during the pre-monsoon and post-monsoon periods**, when water flow was low and pollutant concentrations were relatively high. During these periods, spawning frequency was reduced, and a smaller proportion of the population was found in full reproductive maturity. **Species-specific sensitivity** was also observed. *Channa punctatus* and *Oreochromis mossambicus* exhibited higher resilience with partial reproductive activity even in moderately polluted zones, whereas *Labeo rohita* and *Cirrhinus mrigala* were more vulnerable, showing complete suppression of reproductive markers under similar conditions. **Water quality analysis** confirmed high levels of pollutants at affected sites. The

concentration of lead (Pb) ranged from 0.12–0.28 mg/L, cadmium (Cd) from 0.01–0.05 mg/L, and total pesticides up to 0.04 mg/L—all exceeding permissible limits prescribed by the Central Pollution Control Board (CPCB). These levels showed strong negative correlation ($r = -0.71$ for Pb, $r = -0.78$ for Cd) with reproductive health indices. The **reproductive success**, measured by the number of fertilized eggs and hatchling survival in laboratory-controlled spawning trials, was significantly lower in fish collected from polluted sites. Egg fertilization success in *Labeo rohita* dropped from 88% in reference sites to 46% in polluted zones. Hatchling survival rates declined by over 50%. **Behavioral changes** were also observed. Fishes from polluted environments showed reduced courtship behaviors, sluggish spawning responses, and in some cases, complete absence of spawning activity. These behavioral anomalies are likely due to neurological or hormonal interference caused by pollutants. **Multivariate statistical analysis (PCA and correlation)** revealed that among the environmental variables tested, cadmium and EDC concentrations had the highest loadings and were most strongly associated with negative reproductive outcomes. The first two principal components accounted for 78.4% of the total variance in reproductive parameters across sites. The compiled data is summarized in the table below, representing average reproductive health parameters of four fish species across different pollution gradients:



V. DISCUSSION

The findings from both field observations and laboratory studies consistently demonstrate that environmental pollution severely disrupts the

reproductive health of freshwater fish. One of the most alarming outcomes is the presence of endocrine-disrupting chemicals (EDCs) in aquatic environments, which mimic or block natural hormones and interfere with the hypothalamic-pituitary-gonadal (HPG) axis.

The detection of vitellogenin—a female-specific protein—in male fish across several studies, particularly in polluted stretches of the Yamuna and Gomti rivers, is a clear indicator of hormonal imbalance caused by estrogenic pollutants. This feminization effect impairs reproductive viability, reduces male fertility, and potentially leads to population decline over time. Heavy metals such as cadmium, lead, and mercury, commonly found in industrial and urban effluents, exhibit strong gonadotoxic effects. These metals disrupt steroidogenesis, reduce the gonadosomatic index (GSI), and lead to histological abnormalities like follicular atresia, necrosis, and delayed gametogenesis. Such conditions not only compromise the reproductive output but also result in structural damage to gonadal tissues, which may be irreversible in chronic exposures. In fish species like *Labeo rohita* and *Channa punctatus*, exposure to these metals has shown a direct correlation with reduced fecundity, impaired spawning behavior, and lower larval survival rates, affecting recruitment success in natural populations. Pesticides, especially organochlorines and organophosphates, also contribute significantly to reproductive disruption in fish. They interfere with hormonal receptors, impair oocyte development, and result in ovotestis formation, an indicator of intersex conditions. In laboratory experiments, long-term exposure to sub-lethal concentrations of pesticides like endosulfan or chlorpyrifos led to reduced egg production, altered sex steroid levels, and abnormal mating behavior. Such alterations have ecological consequences, as they may lead to asynchronous spawning, poor fertilization success, and eventually affect fish biodiversity, especially in rivers with continuous pesticide runoff from agricultural fields. Overall, the disruption of reproductive cycles in freshwater fish due to pollution has broad ecological implications. Reproductive failure in fish populations can lead to a decline in genetic diversity, skewed sex ratios, and loss of native species, thereby destabilizing aquatic ecosystems. These findings emphasize the urgency of pollution mitigation, improved wastewater treatment, and routine biomonitoring of sentinel species. Additionally, integrating molecular and histopathological markers into environmental assessment frameworks can provide early warning signals for reproductive stress in fish, enabling proactive conservation strategies.

VI. CONCLUSION

Environmental pollution, particularly in freshwater ecosystems, poses a severe threat to the reproductive health of aquatic species. The presence of pollutants such as heavy metals, pesticides, industrial effluents, and endocrine-disrupting chemicals (EDCs) has been shown to interfere with the hormonal regulation of reproductive cycles in fishes. These substances disrupt the delicate balance of the hypothalamic-

pituitary-gonadal (HPG) axis, impairing gametogenesis, delaying maturation, and reducing overall fertility rates in various fish species, as observed in multiple field and laboratory studies. The findings from polluted river systems in India, especially the Ganges, Yamuna, and Gomti, confirm that long-term exposure to contaminants leads to gonadal histopathologies, altered sex ratios, and declining gonadosomatic index (GSI) values in native species like *Labeo rohita* and *Channa punctatus*. The occurrence of intersex conditions in male fishes, along with suppressed levels of key reproductive hormones such as testosterone and estradiol, indicates the strong estrogenic or anti-androgenic effects of many pollutants present in the water. These reproductive impairments not only affect the individual fitness of fish but also threaten the long-term survival of populations, potentially leading to a loss of biodiversity and the destabilization of aquatic ecosystems. As fish are crucial components of aquatic food webs and human food security, their declining reproductive health could have serious ecological and economic consequences. Therefore, urgent steps must be taken to monitor and mitigate pollution levels in freshwater bodies. Implementing stricter waste treatment regulations, promoting eco-friendly agricultural practices, and enforcing environmental legislation are essential. In addition, regular biomonitoring using fish reproductive biomarkers should be prioritized to assess the health of aquatic ecosystems and inform conservation strategies aimed at protecting freshwater biodiversity.

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