Review of Industrial Effluent-Induced Enzymatic Alterations in *Channa punctata* Across Various Freshwater River Ecosystems

Abstract

Freshwater ecosystems across India are under growing threat from industrial pollution, with effluents released into riverine environments adversely affecting the health of resident aquatic organisms. Among freshwater fishes, Channa punctata (spotted snakehead) has emerged as an important bioindicator species for ecotoxicological assessment owing to its widespread distribution, adaptability and sensitivity to physiological stress. Enzymatic biomarkers such as aspartate aminotransferase (AST), alanine aminotransferase (ALT), lactate dehydrogenase (LDH), alkaline phosphatase (ALP) and acid phosphatase (ACP) serve as reliable diagnostic tools for evaluating sub-lethal toxic effects in fish exposed to contaminants. This review synthesises peer-reviewed literature published between 2010 and 2024 on alterations in these biochemical enzymes in C. punctata inhabiting different industrially stressed freshwater river ecosystems across India. Emphasis is given to seasonal fluctuations in enzyme responses, and their association with various classes of industrial effluents including paper-mill wastewater, tannery discharges, textile dyes, pharmaceutical residues, and heavy-metal-laden mining run-off. Most studies report elevated levels of AST, ALT and LDH in serum or tissue of exposed fish—indicative of cellular damage, altered metabolism and hepatopancreatic dysfunction. Similarly, shifts in ALP and ACP suggest changes in membrane transport, ion regulation and lysosomal activity. Seasonal variation is noted, with heightened enzymatic disturbance generally observed during pre-monsoon and summer months due to increased pollutant concentration arising from lower river flow. Overall, these enzymatic disruptions highlight the susceptibility of C. punctata to industrial pollution, underscoring the value of enzyme biomarkers in biomonitoring. This review identifies major river systems investigated, compares biomarker responses among different effluent types, highlights research gaps, and proposes suggestions for the refinement of biomarker-based monitoring strategies in Indian aquatic ecosystems.

Keywords

Channa punctata, Industrial effluent, Enzymatic biomarkers, AST, ALT, LDH, ALP, ACP, Seasonal variation, Indian rivers.

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Introduction

Rapid industrial development in recent decades has intensified the release of partially treated or untreated effluents into freshwater ecosystems, a trend particularly evident in developing nations such as India. These discharges often contain complex mixtures of heavy metals, phenolic compounds, synthetic dyes, acids, alkalis and other xenobiotic substances. When such contaminants enter rivers and wetlands, they disrupt water chemistry, degrade habitat quality and pose serious risks to aquatic life. Freshwater fishes are among the most affected groups because they readily absorb pollutants through their gills, skin and dietary intake. As a result, they tend to accumulate toxic substances in their tissues and exhibit clear biochemical and physiological disturbances, making them reliable organisms for monitoring environmental contamination (Sarah, Jahan & Singh, 2019). Channa punctata, the spotted snakehead, is one of the most commonly studied species in Indian ecotoxicology due to its wide distribution, adaptability to variable water quality and economic value as a food fish. Its sensitivity to industrial pollutants, combined with its ability to survive in moderately stressed habitats, makes it an effective sentinel species for field-based assessments (Shukla & Prakash, 2022). In particular, enzyme-based biomarkers have gained importance because they provide early indications of metabolic stress and tissue impairment at relatively low cost and with high analytical sensitivity (Naz et al., 2023). Key enzymes such as Aspartate Aminotransferase (AST), Alanine Aminotransferase (ALT), Lactate Dehydrogenase (LDH), Alkaline Phosphatase (ALP) and Acid Phosphatase (ACP) are essential for energy metabolism, hepatopancreatic activity and lysosomal function in fish. Shifts in their activity levels can reveal early cellular injury, alterations in membrane integrity or disruptions in osmoregulatory balance (textile-effluent exposure study; see equalization-tank effluent of textile industry, 2023). Seasonal changes in rainfall, river flow and dilution capacity further influence the toxicity of industrial effluents, resulting in fluctuating biomarker responses throughout the year. The present review consolidates studies published between 2010 and 2024 that have examined enzymatic responses in C. punctata exposed to various industrial effluents across Indian river systems. It compares seasonal and regional trends, evaluates the influence of effluent type on biochemical alterations and identifies existing research gaps.

Methodology

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التعليق [u4]: industrial effluent-induced
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This review was undertaken with the objective of consolidating research on industrial-effluent-induced enzymatic alterations in *Channa punctata*, a freshwater teleost widely recognised as a sensitive indicator of aquatic contamination. The review period of 2010–2024 was selected to encompass both foundational studies and recent advancements in biomarker-based ecotoxicological assessment. Industrial expansion in South Asia has accelerated rapidly over the last decade, leading to intensified pollutant discharge into freshwater ecosystems, therefore a focused review window was necessary to evaluate metabolic responses within this evolving pollution landscape.

To ensure comprehensive coverage and reduce the risk of missing relevant data, literature was retrieved from multiple academic databases including ScienceDirect, Scopus, PubMed, SpringerLink, Web of Science and Google Scholar. Using several platforms enabled cross-matching of indexed articles, improved literature diversity and strengthened review reliability. The combined repositories represent the majority of global ecotoxicology publications, which supported the development of a scientifically inclusive dataset.

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A multi-layered keyword strategy was used involving Boolean operators to refine search accuracy. Primary search phrases included *"Channa punctata", "industrial effluents", "enzyme biomarkers", "AST", "ALT", "LDH", "ALP", "ACP", "river pollution", and "seasonal variation in fish physiology"*. These terms were used individually and in combination forms such as *ALT + effluent exposure* and *LDH + river contamination* to retrieve research directly examining biochemical responses under effluent stress. This targeted search format ensured thematic relevance across all selected sources.

التعليق [u8]: visualization

Beyond conventional keyword searches, advanced digital research tools were applied to expand retrieval depth and identify emerging publishing trends. Citation-network mapping in Scopus and topic-cluster visualisation in Web of Science allowed identification of interconnected research groups and recently published studies that may not surface through standard keyword algorithms alone. These enhancements were particularly useful for capturing post-2021 studies, strengthening temporal relevance.

Only peer-reviewed English-language studies were considered, and inclusion required direct exposure of *Channa punctata* to industrial effluent—either through field monitoring or laboratory assays using authentic wastewater. Eligible studies needed to report measurable changes in at least one core enzyme: Aspartate Aminotransferase (AST), Alanine Aminotransferase (ALT), Lactate Dehydrogenase (LDH), Alkaline Phosphatase (ALP) or Acid Phosphatase (ACP), because these biomarkers are globally accepted indicators of metabolic imbalance, hepatocellular leakage and physiological stress in fish (Van der Oost *et al.*, 2003; Kumar *et al.*, 2019).

Articles focusing solely on agricultural or pesticide toxicity without industrial effluent involvement were excluded to prevent thematic dilution. Research lacking biochemical enzyme data or presenting only qualitative observations without measurable endpoints was also removed. Studies centred exclusively on histological, antioxidant or genetic biomarkers were included only where enzymatic correlations were present, maintaining enzymatic response as the central analytical focus.

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A uniform extraction template was adopted for all retained studies, capturing essential details such as river location, dominant industry type, effluent characteristics, sampling season, exposure duration and magnitude of enzyme variation. Supporting physicochemical parameters including dissolved oxygen, pH, water temperature, conductivity and metal concentration were noted where available, as these factors influence enzyme fluctuations and toxicity severity. Oxidative stress markers such as SOD, CAT, GST and lipid peroxidation were also recorded to help interpret enzyme responses mechanistically (Fazio *et al.*, 2020).

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Field-based river monitoring studies were prioritised; however, laboratory trials using real industrial wastewater were incorporated to complement situations where seasonal or long-term field data were limited, particularly for critically polluted rivers like Yamuna, Damodar and Cooum (CPCB, 2022). Extracted information was synthesised using narrative review methodology to identify recurring enzymatic patterns, seasonal fluctuations, pollutant-specific alterations and mechanistic pathways. This structure followed accepted review principles for data integration (Xiao & Watson, 2019; Liberati *et al.*, 2009; Moher *et al.*, 2015), enabling a reliable assessment of effluent-driven biochemical disruption in *Channa punctata*.

Enzyme-wise Alterations in *Channa punctata* Under Industrial Effluent Exposure

Industrial effluents discharged into Indian freshwater systems contain a mixture of organic and inorganic pollutants, many of which exert considerable biochemical stress on resident fish populations. *Channa punctata*, a widely distributed air-breathing teleost, is frequently used as a

التعليق [u11]: organic , inorganic and biological sentinel species due to its ecological tolerance and measurable physiological responses. Among the various biomarkers employed in ecotoxicological assessments, enzymatic indicators remain some of the most sensitive and diagnostically relevant. The following sections summarize enzyme-wise alterations documented in *C. punctata* exposed to different types of industrial wastewaters, integrating findings from field investigations and controlled experimental studies conducted between 2010 and 2024.

Aspartate Aminotransferase (AST)

Aspartate Aminotransferase (AST) is a major transaminase enzyme responsible for amino-group transfer during protein metabolism in fish. Its distribution is highest in the liver but also extends to the kidney, myocardium and gill epithelium. Under healthy physiological conditions, AST is retained inside cells; however, when hepatocyte membranes lose stability due to heavy metals, phenolic compounds, oxidative radicals or hypoxic pressure, the enzyme diffuses into the bloodstream. This leakage makes AST a dependable biochemical indicator of hepatocellular disruption. Studies demonstrate that industrial effluents containing chromium, surfactants, azo dyes or phenolic compounds frequently correspond to AST elevation in freshwater teleosts. Elevated AST usually accompanies ALT and LDH changes and is strongly associated with hepatic necrosis, mitochondrial stress, membrane lysis and loss of metabolic homeostasis (Kumar *et al.*, 2019). In polluted river stretches, AST elevation is also commonly supported by histopathological symptoms such as cell vacuolation, swollen hepatocytes, and sinusoidal dilation, indicating that enzyme rise is an early and quantifiable marker of tissue damage (Fazio *et al.*, 2020). Seasonal hydrodynamics further modulate AST behavior summer and pre-monsoon low-flow periods intensify pollutant load, making enzyme elevation more distinct than in monsoon months. Evaluated collectively, AST serves as a robust biomarker for early-stage hepatotoxicity and is reliable for field-based water-quality diagnosis in *Channa punctata* along industrial river corridors (Xiao & Watson, 2019).

Alanine Aminotransferase (ALT)

Alanine Aminotransferase (ALT) is a key gluconeogenic transaminase and is highly liver-specific compared to AST. Elevation in ALT reflects direct hepatic injury or impaired carbohydrate metabolism. Consistent ALT activation has been reported in *Channa punctata* exposed to industrial pollutants, particularly under metal-rich, thermally altered wastewater discharge. In effluent-impacted environments, ALT and AST often rise concurrently, indicating compound hepatotoxic stress. ALT is considered the more selective index of hepatic integrity, as ALT response is largely restricted to liver damage whereas AST may reflect injury in additional tissues. Thus, simultaneous elevation in AST and ALT strongly suggests metabolic imbalance, membrane disruption and progressive hepatic inflammation in *C. punctata* populations exposed to industrial effluents (Kumar *et al*., 2019; Fazio *et al.*, 2020). Elevated ALT is therefore a reliable early-warning biomarker for hepatic necrosis, glucose imbalance and metabolic deterioration in polluted freshwater habitats.

Lactate Dehydrogenase (LDH)

Lactate Dehydrogenase (LDH) regulates the pyruvate-to-lactate shift in anaerobic respiration. LDH elevation indicates metabolic divergence from aerobic ATP production and reflects mitochondrial stress, hypoxia or chemical interference with respiratory enzymes. Documented increases in LDH activity in *C. punctata* from effluent-contaminated rivers demonstrate that the species frequently shifts toward glycolytic dependence when oxygen availability declines due to wastewater discharge. Pollutants such as dyes, phenolic complexes and surfactants limit gill oxygen diffusion capacity, forcing anaerobic compensation. Studies further indicate that LDH activity is seasonally structured peaking during summer when river flow is minimal and pollutant concentration increases, followed by partial reduction during winter dilution phases (Fazio *et al*., 2020). LDH can therefore be interpreted as a metabolic stress gauge, marking both pollutant intensity and respiratory adaptation intensity in *C. punctata* inhabiting contaminated waters.

Alkaline Phosphatase (ALP)

Alkaline Phosphatase (ALP) is a membrane-associated enzyme linked to ion transport, osmoregulation and bone mineralization. Changes in ALP activity reveal disturbances in membrane permeability or internal ion balance. Industrial effluents often elevate ALP in *C. punctata*, particularly under detergent- and surfactant-rich wastewater, where membrane leakage accelerates enzyme release into circulation. However, ALP does not always exhibit a uniform rise. Under high concentrations of heavy metals such as cadmium, nickel or lead, ALP may be suppressed due to catalytic-site inhibition and disruption of enzyme synthesis. This dual response pattern demonstrates that ALP can either act as a marker of membrane destabilization (moderate pollution) or metal-induced cellular inhibition (extreme contamination). Interpretation therefore requires consideration of pollutant class, concentration and exposure duration (Fazio *et al.*, 2020).

Acid Phosphatase (ACP)

Acid Phosphatase (ACP) is a lysosomal hydrolase involved in intracellular digestion, autophagy and immune responses. ACP elevation is widely associated with lysosomal destabilization, oxidative degradation and inflammatory signaling in effluent-exposed fish. Under chronic pollutant accumulation, ACP often increases due to enhanced turnover of cellular debris and activation of detoxification pathways. Industrial wastewater containing xenobiotics elevates ACP particularly during pre-monsoon concentration phases, when reduced flow amplifies chemical stress. Enhanced ACP activity therefore reflects lysosomal stress, cellular breakdown and progressive metabolic burden in *Channa punctata*, making ACP a valuable indicator of chronic toxicity and immune activation in polluted river systems (Kumar *et al.*, 2019; Fazio *et al.*, 2020).

Table 1: Reported enzymatic responses in *Channa punctata* from Indian rivers polluted by industrial effluents

River (State)	Major Industrial Effluent Type	Season Studied	Enzymes Affected	Direction of Change	Key Reference(s)
Ganga (Kanpur, UP)	Tannery	Pre-monsoon	AST, ALT, LDH	↑↑ (significant increase)	*Pandey et al., 2012*
Chambal (MP)	Thermal-power discharge	Summer	ALT, AST	↑ (52 %)	*Singh et al., 2014*
Bichhiya (MP)	Paper-mill	Monsoon/pre-monsoon	AST, LDH, ALP	↑↑	*Sharma & Verma, 2017*
Damodar (Jharkhand)	Textile dyes	Summer	LDH, ALT	↑↑ (up to 72 %)	*Saha et al., 2016*
Yamuna (UP)	Pharmaceutical	Pre-monsoon	ALP, ACP	↑	*Pathak et al., 2018*
Kshipra (MP)	Mixed effluent (metal-rich)	Summer	ACP, AST	↑	*Rathore & Jain, 2013*
Sabari (Odisha)	Mining run-off	Winter/summer	ALP, LDH	↓ ALP; ↑ LDH	*Mishra et al., 2021*
Hooghly (West Bengal)	Jute-mill/pulp wastewater	Monsoon	AST, ALT, ALP	↑	*Ghosh et al., 2022*

Rihand (Chhattisgarh)	Power-plant, coal-based effluent	Pre-monsoon	LDH, ALT, ACP	↑↑	*Gupta et al., 2023*

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SEASONAL VARIATION IN ENZYMATIC RESPONSES

Seasonality plays a defining role in shaping biochemical responses of *Channa punctata* inhabiting industrially impacted freshwater systems. In tropical rivers, summer and pre-monsoon months are typically characterised by elevated temperature, reduced discharge and higher evaporative concentration, conditions that increase pollutant retention and intensify toxic stress. Under such hydrological compression, wastewater becomes more chemically aggressive, and transaminases such as AST and ALT often rise markedly due to heightened hepatocellular permeability and intensified metabolic burden. LDH activity frequently mirrors this trend, reflecting respiratory strain and greater dependence on anaerobic glycolysis as dissolved oxygen decreases under organic and chemical load (Kumar *et al*., 2019). Alkaline phosphatase (ALP) also tends to increase during peak-pollution phases, indicating membrane leakage and osmoregulatory imbalance, although suppression may occur in extreme metal-dominated environments where catalytic inhibition occurs (Fazio *et al*., 2020).

In contrast, monsoon months bring substantial hydrological relief. Increased river flow enhances dilution, reduces conductivity and carries suspended material downstream, resulting in a temporary decline in overall toxicity. During such periods, enzyme values frequently reassume near-baseline states, suggesting partial metabolic recovery as pollutant concentration falls and oxygen availability improves. ACP, which responds strongly to chronic lysosomal stress, also shows seasonal responsiveness, generally peaking during pre-monsoon phases and declining during post-monsoon periods where environmental pressure is reduced. The cyclic elevation and regression of these biomarkers reflects the rhythmic nature of industrial stress on fish physiology and signifies the dynamic interplay between exposure intensity and detoxification capacity.

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Season-linked biochemical oscillation has broader ecological implications. Elevated summer-phase enzyme deviation often coincides with spawning season in *C. punctata*, meaning hepatic stress may translate into compromised reproductive investment, impaired gametogenesis and reduced offspring viability. Seasonal biomarker profiles therefore provide not only diagnostic insight into pollution patterns but also predictive value for population-level consequences. In this manner, AST, ALT, LDH, ALP and ACP serve as temporal indicators of effluent toxicity, revealing both acute and cyclic physiological pressure in river-dwelling fish (Xiao & Watson, 2019).

MECHANISTIC INSIGHTS AND INTEGRATED TOXICITY PATHWAYS

The enzymatic deviations observed in *Channa punctata* under industrial effluent exposure are best interpreted within a mechanistic toxicity framework. Industrial wastewater often contains complex mixtures of heavy metals, phenolics, surfactants, dyes and nitrates, each capable of generating excessive reactive oxygen species (ROS) within hepatocytes and gill tissues. This oxidative overload initiates lipid peroxidation, disrupts mitochondrial integrity and destabilises cellular membranes. Compromised membranes allow cytosolic enzymes such as AST, ALT and ALP to diffuse into plasma, producing quantifiable biochemical signatures of damage. LDH elevation reflects mitochondrial impairment and a metabolic shift toward anaerobic energy dependence, particularly under hypoxia where oxidative phosphorylation becomes energetically restricted (Kumar *et al.*, 2019).

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Simultaneously, lysosomal destabilisation activates Acid Phosphatase (ACP), signalling autophagic turnover of damaged organelles and protein aggregates. Prolonged ACP activation indicates chronic exposure, persistent oxidative pressure and sustained cellular degradation. Antioxidant enzymes including superoxide dismutase (SOD), catalase (CAT), glutathione-S-transferase (GST) and glutathione peroxidase (GPx) often increase initially as defence, but prolonged stress eventually exhausts antioxidant reserves, allowing ROS- mediated cytotoxicity to dominate (Fazio *et al.*, 2020). These overlapping pathways demonstrate that enzyme biomarkers reflect distinct segments of the same toxicity cascade: oxidative initiation → membrane disruption → metabolic shift → lysosomal degradation.

The relationship between effluent toxicity and biomarker deviation can be conceptualised as a progressive chain of events. Industrial pollutants induce oxidative stress, causing membrane leakage of transaminases, mitochondrial recession triggering LDH elevation and lysosomal activation signalled by ACP rise. This interconnected mechanism confirms that these enzymes do not change in isolation; rather, they collectively map the trajectory of cellular injury and provide an integrated picture of toxic impact intensity (Xiao & Watson, 2019). Such mechanistic insight strengthens the application of enzyme biomarkers as decision-tools for river health evaluation, impact forecasting and ecological risk management.

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Discussion

Industrial pollution is increasingly recognized as a major driver of biochemical stress in freshwater fishes, particularly in densely populated and industrially active regions of India. Across the studies synthesized in this review, *Channa punctata* displayed consistently elevated levels of AST, ALT, LDH, ALP and ACP in response to metals, dyes, acids, alkalis, and organic toxicants discharged into river systems after insufficient treatment. This pattern agrees with previous biomonitoring reviews suggesting that hepatic leakage enzymes and metabolic oxidoreductases serve as frontline biomarkers for detecting early sub-lethal tissue injury in fishes subjected to anthropogenic stress .Transaminases AST and ALT showed strong correlation with hepatic cell membrane integrity and are commonly upregulated in effluent-exposed fish due to cytoplasmic release caused by necrosis or apoptosis of hepatocytes (Gupta *et al.*, 2020). LDH also displayed a remarkable sensitivity, reflecting activation of anaerobic glycolysis under oxygen-stressed conditions induced by chemical insult. ALP and ACP illustrated membrane transport perturbations and lysosomal destabilisation, indicative of disrupted osmoregulation and increased autophagic activity. This agrees with the mechanistic hypothesis that effluent toxicity in fish initiates oxidative stress, ionic imbalance and mitochondrial dysfunction, eventually producing downstream enzyme disturbances .Seasonal variation played a critical role in modulating enzymatic responses. Pre-monsoon and summer months characterized by reduced river flow, higher temperatures and greater effluent concentration produced more severe enzyme deviations. During monsoon or winter when dilution was higher, partial recovery was often observed in liver and serum biomarkers. River-specific factors, such as the type of industry and pollutant load, further governed the magnitude of toxicity. Textile dyeing effluents from the Damodar region were rich in aromatic amines, whereas mining effluents in the Sabari contained predominantly heavy metals, producing differing effects suggesting effluent composition-specific responses. Overall, enzyme biomarkers provide a valuable window into real-time physiological disturbances in specimen fish such as *C. punctata*. However, integration with additional biomarkers (oxidative stress enzymes, histopathology, genotoxicity) is recommended to strengthen conclusions. Furthermore, application of molecular techniques for identifying isoenzyme patterns and gene-level regulation could broaden mechanistic understanding.Standardisation of field biomonitoring protocols would allow better comparison across river systems.

Conclusion and Future Perspectives

The present review, which synthesizes research published between 2010 and 2024, demonstrates that the enzymatic physiology of Channa punctata is highly responsive to contamination from industrial effluents in Indian freshwater systems. Across multiple river basins, consistent increases in AST, ALT, LDH, ALP and ACP activity were recorded in fish sampled downstream of industrial discharge zones. These elevations were particularly prominent during the summer and pre-monsoon periods, when reduced water flow and higher temperatures tend to concentrate pollutants. Such enzymatic shifts provide strong indications of hepatocellular injury, disturbed energy metabolism and compromised membrane integrity in exposed fish populations. The findings reinforce the utility of *C. punctata* as a practical and cost-efficient bioindicator for riverine pollution monitoring. Its wide distribution, ecological tolerance and measurable biochemical responses make it suitable for early-warning biomonitoring frameworks, especially in regions with limited resources for advanced chemical analysis. Despite these strengths, several gaps remain. Future studies should aim to establish river-specific baseline enzyme values that account for natural seasonal variability. Field-relevant dose–response models using actual effluent concentrations are also needed to translate biomarker changes into meaningful ecological risk assessments. Integrating enzymatic biomarkers with complementary endpoints such as histopathology, oxidative stress markers, gene expression profiles and population-level assessments will generate a more holistic understanding of pollutant impact. Moreover, long-term, multi-seasonal monitoring programmes incorporating modern “omics” technologies can help identify molecular pathways of toxicity and support scientifically informed river restoration, pollution mitigation and effluent regulation strategies.

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