

Assessment of Heavy Metal and Agricultural Pesticide Bioaccumulation in Freshwater Fish Species of South Dinajpur District, West Bengal

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ABSTRACT

Freshwater fish occupy a critical position at the intersection of aquatic ecology, rural livelihoods, and food security in eastern India. In agrarian districts such as South Dinajpur in West Bengal, fish are embedded within floodplain rivers, kharis, beels, ponds, and culture-based systems that are increasingly exposed to agricultural runoff, sediment-bound contaminants, and diffuse anthropogenic inputs. Although substantial literature documents heavy metal contamination and pesticide residues in freshwater fishes across India, and several studies from the lower Gangetic and wider West Bengal region demonstrate measurable contaminant burdens in edible species, the evidence remains fragmented. Most published studies examine either heavy metals or pesticides, focus on a restricted set of species, or neglect the ecological and landscape processes that mediate contaminant uptake. A district-focused synthesis for South Dinajpur is lacking.

This review critically synthesizes peer-reviewed literature and relevant policy documents to examine how heavy metals and agricultural pesticides may accumulate in freshwater fish species inhabiting the fluvial and wetland mosaic of South Dinajpur District. The article is guided by a landscape ecotoxicology framework that links land use, hydrological connectivity, sediment dynamics, fish ecology, and human dietary exposure. It argues that South Dinajpur represents a high-priority but under-studied freshwater risk landscape because it combines intensive agriculture, floodplain hydrology, river-beel connectivity, and dependence on locally harvested fish. Evidence from India and the lower Gangetic region indicates consistent patterns of species-specific, tissue-specific, and site-specific bioaccumulation; recurrent concern for Pb, Cd, Cr, Hg, DDT derivatives, HCH isomers, endosulfan, and organophosphate residues; and growing relevance of human health risk metrics such as estimated daily intake, target hazard quotient, and carcinogenic risk.

The article contributes to knowledge in three ways. First, it integrates metal and pesticide literatures that are often treated separately. Second, it develops a district-sensitive conceptual model for understanding contaminant movement from agricultural landscapes to fish tissues and, ultimately, to human consumers. Third, it proposes a research agenda for South Dinajpur that prioritizes mixed-contaminant surveillance, species ecology, seasonality, sediment linkage, and food safety governance. The review provides a basis for journal publication, field study design, and policy discussion on freshwater fish safety in eastern India.

Keywords- bioaccumulation, heavy metals, pesticide residues, freshwater fish, South Dinajpur, West Bengal, food safety, landscape ecotoxicology.

I. INTRODUCTION

Freshwater ecosystems in South Asia are increasingly shaped by the convergence of agricultural intensification, hydrological instability, and diffuse chemical contamination. Among the organisms inhabiting these systems, fishes are especially important because

they integrate contaminant exposure over time, occupy different trophic levels, and serve simultaneously as ecological indicators and food items for local populations. For this reason, the study of bioaccumulation in freshwater fish is not a narrow toxicological problem. It is also a question of environmental governance, rural nutrition, livelihood security, and public health.

Heavy metals and pesticide residues are of particular concern because they behave differently in aquatic systems yet may ultimately converge in fish tissues. Metals such as lead, cadmium, chromium, mercury, nickel, copper, and zinc may enter aquatic systems through natural weathering, fertilizer impurities, sewage, traffic emissions, industrial discharge, and contaminated irrigation return flows. Unlike many organic contaminants, heavy metals do not biodegrade and may persist in sediments, undergo remobilization during flooding, and enter aquatic food webs through water, particulate matter, benthic feeding, and trophic transfer (Ray & Vashishth, 2024; Panda et al., 2023). Pesticides follow a somewhat different pathway. Their ecological behavior depends on chemical class, persistence, lipid solubility, formulation, timing of application, and landscape hydrology. Organochlorines are notable for persistence and lipophilicity, while organophosphates and some newer compounds may display shorter environmental persistence but still pose acute or chronic toxicological risks, especially under repeated agricultural use (Kashyap et al., 2024; Ghafarifarsani et al., 2024).

The South Dinajpur context makes this discussion particularly important. The district lies within the lower Gangetic plain and is characterized by an agrarian landscape with flood-prone conditions, river channels, kharis, beels, ponds, and aquaculture-linked water bodies. Official district documentation identifies the area as part of the old alluvial zone and notes both flood contingencies and fisheries-aquaculture vulnerabilities within district planning (Government of India, 2011). Earlier ichthyological work documented the district's riverine fish diversity across major rivers such as the Atrai, Punarbhaba, Tangan, and Jamuna, as well as kharis and beels, identifying forty-nine fish species in surveyed waters and noting potential breeding habitats in Danga Beel and Gochina Beel (Chakraborty & Bhattacharjee, 2008). These features are ecologically significant because complex river-wetland connections can increase contaminant heterogeneity rather than reduce it. Flood pulses may dilute pollutants during some periods while also redistributing contaminated sediments and runoff into wetlands and marginal waters during others.

The wider literature already shows that fish contamination is not hypothetical. In freshwater systems across India, heavy metals and pesticide residues have been detected in edible fishes, sometimes at concentrations that raise concern for non-carcinogenic or carcinogenic health risk, depending on species, site, and exposure assumptions (Maurya et al., 2019; Aktar et al., 2009; Kaur et al., 2008; Samidurai et al., 2019). Studies from eastern India and the lower Gangetic system are especially relevant because they offer evidence from comparable hydrological and socio-agricultural settings. Dutta et al. (2022), for example, found measurable burdens of Pb, Cd, Cr, and Hg in edible fishes from the East Kolkata Wetlands and showed that accumulation

differed across species. A more recent wetland study from Murshidabad in West Bengal likewise reported marked metal enrichment in fish relative to ambient water and flagged lead and arsenic as contaminants of concern (Uddin et al., 2025). Kumar et al. (2024) further demonstrated that lower Gangetic food fish can accumulate potentially toxic elements at levels that warrant continued dietary risk scrutiny. This body of work suggests that South Dinajpur should not be treated as an uncontaminated blank space merely because district-specific residue data remain scarce.

The problem, however, is that the literature is analytically fragmented. First, many studies isolate one contaminant class from another, thereby obscuring the cumulative implications of mixed exposure. Second, numerous papers privilege concentration reporting over ecological interpretation, treating fish as passive containers rather than biological actors with species-specific feeding habits, habitat use, lipid content, and metabolic characteristics. Third, there is a persistent spatial problem. Strong evidence exists for selected rivers, wetlands, industrial regions, or sanctuaries, but district-level agrarian landscapes such as South Dinajpur remain understudied even though they may face substantial diffuse contamination from agriculture, aquaculture inputs, and seasonal hydrological connectivity. Fourth, the literature often privileges human health risk assessment at the expense of fisheries governance, biodiversity implications, and landscape management.

This review addresses these gaps by asking six interrelated questions. First, what does current literature reveal about the major pathways through which heavy metals and agricultural pesticides enter freshwater food webs in agrarian aquatic landscapes? Second, how do bioaccumulation patterns vary across fish species, tissues, trophic guilds, and seasons? Third, what forms of evidence from West Bengal, the lower Gangetic basin, and India more broadly are most relevant to interpreting risks in South Dinajpur? Fourth, what conceptual framework best explains contaminant transfer from agricultural landscapes to fish tissues and human consumers? Fifth, what is the principal research gap in relation to South Dinajpur District? Sixth, what kind of district-level research design is needed to move from fragmented knowledge to robust evidence?

The central argument advanced here is that South Dinajpur should be understood as a likely mixed-contaminant freshwater landscape in which hydrological connectivity, agricultural intensification, and fish species ecology interact to shape uneven bioaccumulation patterns. The originality of the article lies not in presenting new laboratory results, but in constructing an integrated, district-sensitive framework that draws together toxicology, fisheries ecology, landscape processes, and food safety. In doing so, the article lays the conceptual and evidentiary groundwork for a future empirical study that could be designed around species

selection, tissue-specific analysis, sediment linkage, seasonal hydrology, and health risk assessment.

II. LITERATURE REVIEW

2.1 Theoretical framework: landscape ecotoxicology and trophic transfer

A useful way to understand fish contamination in agrarian freshwater systems is through a landscape ecotoxicology perspective. This framework does not treat contamination as a point-source event alone. Instead, it emphasizes how land use, hydrological pathways, sediment transport, habitat structure, and species ecology mediate contaminant exposure and retention. Under this perspective, agricultural land is not simply adjacent to aquatic habitat; it is functionally connected to it through runoff, drainage channels, inundation, irrigation return flow, and sediment deposition. Fish are therefore exposed not only to contaminants dissolved in water, but also to contaminants adsorbed to suspended particles, settled in sediments, concentrated in prey items, or remobilized during hydrological disturbance.

Within this framework, bioaccumulation refers to the net uptake of contaminants by an organism from all sources relative to elimination, while biomagnification describes increasing concentration along food chains. The two are related but not identical. Metals may accumulate strongly in internal organs associated with detoxification or exchange, such as liver and gills, while some persistent pesticides tend to concentrate in lipid-rich tissues and may be important in muscle from a food-safety perspective. Fish are therefore both sentinels of environmental quality and vectors of dietary exposure.

Recent reviews reaffirm the continuing relevance of this framework. Ray and Vashishth (2024) argue that heavy metal bioaccumulation in fish should be interpreted across organs, aquatic media, and human exposure routes, rather than as an isolated measurement problem. Emon et al. (2023) similarly synthesize evidence that fish acquire metals through water, sediment, and food pathways, while physiological factors such as age, species, and tissue function mediate accumulation. Panda et al. (2023) extend the discussion to public health, showing how fish contamination can serve as a key indicator of both ecological contamination and carcinogenic risk. Together, these works suggest that district-level studies should move beyond reporting concentrations and instead explain the mechanisms that produce contamination gradients.

2.2 Major scholarly debates

The first major debate concerns source attribution. Heavy metal contamination is often associated with industrial discharge, but this framing can obscure the significance of non-industrial sources in agrarian districts. Fertilizers, pesticides, livestock waste, vehicular deposition, household sewage, and contaminated groundwater used for irrigation all contribute to metal mobility in agricultural landscapes. Pesticide residues

also present attribution challenges because residues may reflect current application, historical persistence, or legacy contamination. Kashyap et al. (2024) show that pesticide pollution in India is spatially widespread and shaped by regulatory, agricultural, and environmental factors rather than by a single pathway.

The second debate concerns which fish tissues should be prioritized. From a toxicological standpoint, liver and gills often show higher burdens because of metabolism, detoxification, and direct interface with water. From a public health standpoint, however, muscle is the principal edible tissue and therefore the most policy-relevant. Studies repeatedly show that internal organs may accumulate higher metal concentrations than muscle, yet public health risk cannot be dismissed simply because muscle concentrations are lower, especially where fish consumption is frequent (Bawuro et al., 2018; Hashim et al., 2014). In other words, tissue choice is not a technical detail; it structures the meaning of contamination results.

A third debate involves species differences. Omnivorous, benthic, predatory, and detritivorous fishes may experience different exposure routes, and accumulation also varies by size, age, growth rate, lipid content, and habitat use. Dutta et al. (2022) found species-specific ordering in East Kolkata Wetlands, with higher overall metal bioaccumulation in tilapia relative to rohu and catla. Other studies likewise show that accumulation is shaped by species ecology rather than contaminant concentration alone (Maurya et al., 2019; Balzani et al., 2021). This debate matters for South Dinajpur because district fish assemblages are heterogeneous and may include both cultured and wild-caught species.

A fourth debate concerns temporal and hydrological variability. Seasonal comparisons are not always straightforward. Monsoon and flood conditions may dilute dissolved concentrations while increasing sediment disturbance, catchment wash-in, and habitat connectivity. Dry seasons may concentrate contaminants in reduced water volumes. For this reason, single-season sampling often underestimates ecological complexity. In a district like South Dinajpur, where flood contingencies and aquaculture vulnerabilities are institutionally recognized (Government of India, 2011), seasonal design is central to credible interpretation.

The fifth debate concerns how to interpret risk. Traditional contaminant studies often stop at concentration values relative to guideline thresholds. More recent work incorporates estimated daily intake, target hazard quotient, hazard index, and carcinogenic risk calculations to link fish contamination to food safety. Maurya et al. (2019), Panda et al. (2023), and Kumar et al. (2024) demonstrate the value of this approach. Yet risk assessment still depends on species consumed, portion size, local dietary patterns, edible tissue analyzed, and the assumption that contaminants act independently. Mixed exposure from metals plus pesticide residues is rarely incorporated in an integrated fashion.

2.3 Evidence from India and eastern India

The Indian literature provides several important lessons for a South Dinajpur-focused article. First, both metals and pesticide residues are detectable in freshwater fish from non-marine systems across multiple states. Kaur et al. (2008) reported organochlorine pesticide residues in five freshwater fish species in Punjab, with DDT-related compounds dominating the residue profile. Samidurai et al. (2019) detected varying levels of organochlorine pesticides in freshwater fishes from bird sanctuaries in Tamil Nadu, reinforcing that even protected aquatic settings are not immune to legacy pesticide burdens. Aktar et al. (2009) documented pesticide residues in fish from the Ganga around Kolkata, including HCH, DDT, endosulfan, dimethoate, and malathion, and observed that total HCH most frequently exceeded maximum residue limits.

Second, lower Gangetic and eastern Indian studies show that the regional context is highly relevant. The lower Gangetic basin is densely populated, agriculturally active, hydrologically dynamic, and socially dependent on fish. Kumar et al. (2024) examined commercially important food fish from the lower Gangetic stretch and found measurable burdens of potentially toxic elements, highlighting the need for continued human health evaluation. Dutta et al. (2022) demonstrated metal contamination in edible fishes from the East Kolkata Wetlands, an ecosystem that, despite its ecological importance, receives multiple pollutant inputs. These studies make it difficult to assume that river-connected districts in West Bengal are insulated from contamination simply because they are less industrialized.

Third, Indian research frequently reports a disconnect between contamination evidence and governance response. Regulatory standards exist, but residue surveillance remains uneven, and local fish markets rarely operate with species-specific contaminant labeling or district-level contaminant advisories. This gap is especially concerning in a state where fisheries are recognized as nutritionally and economically important. The West Bengal Fisheries Policy highlights the value of inland fisheries, the importance of scientific culture methods, and the need to protect productivity in beels, reservoirs, and other water bodies (Government of West Bengal, 2015). Yet productivity and food safety cannot be treated as separate agendas.

2.5 Conceptual model for South Dinajpur

The conceptual model proposed in this review can be summarized as a source-pathway-receptor framework with feedbacks. At the source level, contaminants enter the landscape through crop inputs, legacy residues in soils and sediments, household sewage, aquaculture chemicals, and trace metal-bearing amendments. At the pathway level, contaminants move through irrigation return flow, overland runoff, embankment breaches, channel transport, flood inundation, sediment deposition, and trophic incorporation into lower food-web components. At the

receptor level, fish receive contaminants through branchial uptake, ingestion of suspended particles, benthic feeding, omnivorous diet, and contact with contaminated sediments or prey organisms. Human consumers then become the final receptor through repeated dietary exposure, while governance systems act as a mediating layer that can either interrupt or amplify risk through surveillance, extension, and market regulation.

This conceptual model is useful because it avoids two common analytical errors. The first is reductionism, in which contaminant burden is attributed only to chemical use on fields without accounting for hydrological redistribution. The second is compartmentalization, in which fish contamination is discussed without considering how fisheries management, household nutrition, and local marketing practices shape human exposure. In South Dinajpur, where capture fisheries, pond aquaculture, and local consumption overlap, such compartmentalization would be particularly misleading.

2.6 Regulatory context and surveillance deficit

A sixth major finding concerns regulation. India possesses food-safety and contaminant regulations, and food contamination is not an unregulated field. The Food Safety and Standards framework recognizes the importance of controlling contaminants, toxins, and residues in foods, including limits for metal contaminants and residue-related monitoring in food systems (Food Safety and Standards Authority of India, 2020). However, the regulatory existence of limits does not automatically translate into district-level surveillance capacity. Residue regulation is strongest when linked to active testing, clear commodity mapping, traceability, and laboratory access. These conditions are often uneven in inland fish systems, particularly where fish move through informal or semi-formal marketing channels.

This regulatory deficit has two consequences. First, contamination remains under-detected until an academic or targeted monitoring study is conducted. Second, consumers and fishers are left without species- or site-based guidance. In practice, the burden of proof falls on researchers rather than on continuous surveillance systems. This is precisely why district-level studies remain valuable even when general regulations exist. A South Dinajpur study would not duplicate national policy; it would operationalize it in a locally relevant form.

2.7 Comparison with wider scholarship

The argument advanced here is consistent with, but also extends, wider scholarship on freshwater contamination. Existing reviews already show that heavy metal accumulation in fish has become a global concern because aquatic organisms integrate environmental exposure and transfer contaminants into human diets (Ray & Vashishth, 2024; Emon et al., 2023). Likewise, Indian pesticide scholarship shows that pesticide contamination reflects both environmental persistence and gaps in agricultural governance (Kashyap et al., 2024). What the

present review adds is a district-sensitive ecological reading of these literatures. Rather than treating contamination as a generalized Indian problem, it asks how contaminant behavior should be interpreted in a specific floodplain-agricultural district where rivers, kharis, beels, ponds, and aquaculture systems coexist.

This move from national generalization to district interpretation is important. National-scale discussions often flatten ecological diversity and imply that contamination risk is uniformly distributed. Yet the literature itself suggests the opposite. Species differ, tissues differ, aquatic habitats differ, and hydrological regimes differ. A district-scale framework therefore does not narrow the field of view; it sharpens it.

2.8 Implications for empirical PhD design

Because the present manuscript is positioned as a review article, its most immediate practical value lies in informing empirical design. A PhD study emerging from this review should ideally be structured around a mixed-methods environmental toxicology design. The quantitative core would include contaminant analysis of fish tissues, water, and sediment. The contextual component would include local interviews or survey work with fishers, aquaculture practitioners, input dealers, or agricultural households to understand fish sourcing, chemical-use calendars, and consumption frequency. Such triangulation would greatly improve interpretation of laboratory results.

A further design implication concerns sample framing. The title phrase "freshwater fish species from South Dinajpur District" should not be operationalized solely as fish purchased from one market. Market samples are useful, but they detach fish from habitat. A stronger design would pair habitat-linked sampling with market-linked sampling. The first clarifies ecological exposure. The second clarifies actual consumer exposure. Taken together, they would generate a much stronger journal paper than either source alone.

2.9 Limits of current knowledge

The present review also reveals where caution is necessary. It would be methodologically unsound to claim that South Dinajpur fish are already proven unsafe in the absence of district-specific analytical data. The accessible literature does not justify that conclusion. What it does justify is a more careful claim: given district ecology, regional contamination evidence, and mixed exposure pathways, the absence of integrated data should be treated as a research and governance gap rather than as evidence of safety. This distinction is crucial in scholarly writing. It prevents both overstatement and complacency.

2.10 The South Dinajpur research gap

A critical finding of this review is not merely what is known, but what remains unstudied. The accessible district-specific literature located for this review includes fish biodiversity and habitat accounts, but not a peer-reviewed integrated assessment of heavy metals and agricultural pesticide residues in edible freshwater fish species from South Dinajpur. Chakraborty

and Bhattacharjee (2008) documented species diversity and identified breeding grounds, which is an essential ecological baseline. District planning documents confirm the district's agrarian and flood-sensitive character and include fisheries and aquaculture contingencies (Government of India, 2011). However, these materials do not substitute for contaminant data. Conversely, contamination studies from nearby or comparable systems in West Bengal and the lower Ganga reveal that fish in the region can indeed carry ecotoxicologically and public-health-relevant contaminant burdens (Aktar et al., 2009; Dutta et al., 2022; Kumar et al., 2024). The resulting gap is therefore sharply defined: South Dinajpur has ecological and hydrological characteristics that make contamination plausible, but lacks an integrated district-level evidence base.

This gap is scientifically important for four reasons. First, the district's river-khari-beel mosaic likely creates fine-scale variability in exposure. Second, fish species used by local consumers may differ from those examined in existing studies elsewhere. Third, agricultural contamination in a largely agrarian district is likely to be diffuse and seasonally mobile rather than point-source and static. Fourth, the coexistence of capture fisheries, pond culture, and household consumption creates a direct pathway from environmental contamination to dietary exposure.

III. METHODOLOGY

Given the absence of a district-specific integrated empirical dataset, the most defensible article type for the present manuscript is a critical review article rather than an empirical research paper. The review was organized as a thematic narrative synthesis informed by principles of transparent source selection and analytical comparison. The objective was not to generate pooled effect sizes, but to identify conceptual patterns, regional relevance, research gaps, and an actionable agenda for future empirical work in South Dinajpur District.

3.1 Source selection strategy

The review prioritized three categories of material: first, peer-reviewed journal articles on heavy metal bioaccumulation, pesticide residues, fish contamination, and human health risk in freshwater fishes; second, studies from India, especially West Bengal, the lower Gangetic basin, and ecologically comparable freshwater systems; and third, official policy or district planning documents relevant to fisheries, agriculture, and food safety. Preference was given to peer-reviewed papers that addressed at least one of the following: tissue-specific accumulation, species-specific differences, spatial variation, residue classes, health risk assessment, or aquatic contaminant pathways.

The review deliberately included both heavy metal and pesticide studies because real-world fish exposure in agrarian landscapes is rarely mono-contaminant. It also included selected review articles to

clarify conceptual debates and identify methodological lessons. District-level ecological context for South Dinajpur was drawn from published ichthyological work and official planning documents.

3.2 Analytical framework

The synthesis was structured around five analytical lenses:

1. Source-to-water pathways: how agricultural and landscape processes deliver contaminants into freshwater systems.
2. Species and tissue differentiation: how feeding ecology, habitat, and tissue function shape accumulation.
3. Spatial and seasonal variability: how contamination varies across sites and hydrological conditions.
4. Human health and food safety relevance: how concentration studies translate into risk discourse.

5. District applicability: how broader findings can be used to identify South Dinajpur's likely vulnerability and research priorities.

3.3 Strengths and limitations of the review approach

The strength of the review lies in integration. It brings together toxicology, fisheries ecology, food safety, and district geography, which are often treated separately. The main limitation is that the article does not report original laboratory measurements from South Dinajpur. Consequently, the article should be read as a high-level evidence synthesis and research agenda rather than a substitute for field or laboratory investigation. That limitation is not a weakness to be concealed. Rather, it clarifies why South Dinajpur now requires a full empirical study.

IV. RESULTS AND THEMATIC ANALYSIS

Table 1: Representative studies relevant to a South Dinajpur contaminant framework

Study	Location	Main focus	Key relevance
Aktar et al. (2009)	Ganga around Kolkata, West Bengal	Pesticide residues in fish	Demonstrates residue occurrence in West Bengal river fish, including HCH, DDT, endosulfan, dimethoate, and malathion
Dutta et al. (2022)	East Kolkata Wetlands, West Bengal	Pb, Cd, Cr, Hg in edible fish	Shows species-specific metal accumulation in a major wetland system of West Bengal
Kumar et al. (2024)	Lower Gangetic stretch	Potentially toxic elements in food fish	Establishes lower Gangetic relevance and importance of health-risk framing
Maurya et al. (2019)	River Ganga basin	Metal bioaccumulation and human health risk	Useful for risk metrics and source interpretation
Kaur et al. (2008)	Punjab, India	Organochlorine pesticide residues in freshwater fish	Confirms persistence of legacy pesticide residues in Indian food fish
Samidurai et al. (2019)	Tamil Nadu, India	Organochlorine pesticides in freshwater fishes	Shows variability by species and site even in non-industrial settings
Panda et al. (2023)	Freshwater systems review/meta-evidence	Metal contamination and carcinogenic risk	Provides risk-oriented interpretive framework
Ray and Vashishth (2024)	Review	Heavy metal bioaccumulation in fish and food chain	Useful for conceptual integration from water to plate

4.1 South Dinajpur as an exposure landscape

The first major finding of this review is that South Dinajpur should be treated as an exposure landscape rather than as a mere geographic backdrop. The district's old alluvial setting, flood contingencies, and fisheries-aquaculture sensitivity indicate a landscape in which agricultural chemicals, sediment transport, and water-body connectivity can interact in complex ways (Government of India, 2011). Earlier ichthyological surveys documented major rivers, smaller channels,

khari, and beels, including Atrai, Punarbhaba, Tangan, Jamuna, and beels such as Danga and Gochina, confirming that the district's freshwater habitats are hydrologically diverse rather than uniform (Chakraborty & Bhattacharjee, 2008).

This matters because contaminant behavior is rarely homogeneous across such systems. River channels may receive catchment runoff and upstream inputs. Beels may function as sinks for sediment-bound contaminants during low-flow conditions, but may also exchange water



and biota during seasonal inundation. Kharis and marginal waters may be especially vulnerable to agrochemical inflow from adjacent fields. Pond and culture systems can accumulate contamination through feed, liming agents, aquadugs, source water, and local sediment conditions. Recent work on freshwater aquaculture systems in West Bengal shows that farms use a wide range of chemicals and biological products, while farmers often have limited knowledge of dose and residue implications (Singha et al., 2021). This widens the exposure framework beyond field pesticides alone and reinforces the need to consider aquaculture management chemicals alongside agriculturally derived residues.

A South Dinajpur study would therefore need to reject the assumption that contamination enters fish through one dominant route. Instead, the likely pathway is multi-scalar: agrochemical application in cropland, transport through runoff and minor channels, deposition in ponds and wetlands, remobilization under flood conditions, uptake by plankton or benthos, trophic transfer to fish, and human consumption through local markets or household harvest.

4.2 Heavy metals: patterns of uptake, storage, and significance

The second major finding is that heavy metal bioaccumulation in freshwater fish is best understood as a patterned biological process rather than a simple reflection of water concentration. The literature shows that the distribution of metals across tissues is shaped by both environmental exposure and organ function. Liver often records high burdens because of its role in metabolism, detoxification, and storage. Gills may accumulate metals because they are in direct contact with water and mediate ion exchange. Muscle generally accumulates less for many metals, but remains the most important tissue from a human exposure perspective (Bawuro et al., 2018; Hashim et al., 2014).

Studies from India reinforce these distinctions. Maurya et al. (2019) assessed fish species from the Ganga basin and emphasized both accumulation patterns and human health implications. Dutta et al. (2022) found that overall metal burden in edible fishes from East Kolkata Wetlands followed a species-specific pattern, with tilapia showing higher overall bioaccumulation than rohu and catla. Kumar et al. (2024) further confirm that lower Gangetic food fishes can carry measurable burdens of potentially toxic elements, even if not all individual metal concentrations exceed standard limits in every case. The implication is not that all fish are unsafe, but that safety cannot be assumed without species-specific evidence.

A recurring trend in the broader literature is concern for Pb, Cd, Cr, and Hg because of their toxicological significance and their capacity for chronic health effects at relatively low concentrations. Essential metals such as Cu and Zn may also become problematic at elevated levels, though they are often interpreted differently because of their biological functions. This difference matters analytically. South Dinajpur studies

should not collapse all metals into a single contamination narrative. Distinguishing toxic non-essential elements from essential but potentially excessive trace metals is crucial for both ecological interpretation and food safety communication.

Another important issue is size and trophic ecology. Some studies indicate that bottom-feeding or omnivorous species may exhibit higher accumulation of certain contaminants because of greater sediment contact or broader dietary uptake. Others show size-dependent differences that may be linked to age, exposure duration, growth dilution, or habitat choice (Balzani et al., 2021). For South Dinajpur, where local consumption may include multiple species classes and size ranges, this implies that market sampling should not rely exclusively on one dominant carp species if the goal is to understand actual dietary exposure.

4.3 Agricultural pesticides: persistence, legacy, and contemporary risk

The third major finding is that the pesticide literature adds a different but equally important dimension to the contamination problem. Compared with heavy metals, pesticide residues often reflect a mixture of legacy and contemporary exposure. Older organochlorines such as DDT-related compounds and HCH isomers may persist in sediment or food webs long after formal restrictions, while other compounds can enter fish through recurrent contemporary agricultural use, runoff, and aquatic drift.

Indian evidence strongly supports continued concern. Kaur et al. (2008) found that DDT-related compounds predominated among organochlorine residues in freshwater fish species from Punjab. Samidurai et al. (2019) reported variable levels of organochlorine pesticide residues in freshwater fishes from Tamil Nadu bird sanctuaries, illustrating that ecological protection status does not prevent contaminant entry. Most relevant for West Bengal, Aktar et al. (2009) examined fish from the Ganga around Kolkata and reported residues of total HCH, total DDT, total endosulfan, dimethoate, and malathion, with total HCH most frequently above the maximum residue limit. This is especially significant because the study links residue detection to a major river system in the same state and suggests that fish contamination by agricultural or sewage-linked pesticide inputs is already a documented regional problem.

Pesticides raise at least four analytical issues for South Dinajpur. First, pesticides differ widely in persistence and tissue behavior. Lipophilic compounds can accumulate in muscle and adipose-rich tissues, raising direct food-safety concerns. Second, residue profiles may vary seasonally depending on crop cycles, rainfall events, and application timing. Third, fish contamination may not mirror current-use lists alone because historical residues can remain in sediments. Fourth, some contemporary aquaculture practices may introduce additional chemical burdens through pond management, ectoparasite control, or therapeutic inputs, complicating attribution.

These issues are rarely addressed together in freshwater contamination studies. Many papers report residues without linking them to land use calendars, hydrological timing, or fish ecology. For a district such as South Dinajpur, where agricultural cycles are central to landscape functioning, this is a serious omission. A robust district study should therefore integrate fish sampling with crop seasonality, sediment analysis, and local pesticide-use surveys.

4.4 Why single-contaminant studies are no longer enough

A fourth major finding is conceptual: the traditional separation between heavy metal studies and pesticide studies is increasingly inadequate for real-world freshwater risk assessment. Fish in agrarian landscapes are exposed to contaminant mixtures, not isolated compounds. Sediments may carry metals, persistent pesticide residues, and nutrient-derived changes in water chemistry at the same time. Floodplain systems may redistribute these mixtures seasonally. Local consumers do not eat a "metal fish" or a "pesticide fish"; they eat fish carrying whatever complex burden the landscape has produced.

This matters methodologically and theoretically. Metal analyses often emphasize ICP-based laboratory determination and risk metrics linked to target hazard quotient or carcinogenic risk. Pesticide studies often rely on chromatographic methods and compare residue burdens to maximum residue limits. Yet both streams are part of the same food-safety problem. Integrated district research should therefore pair metal and pesticide analyses on the same fish specimens wherever feasible. Without such integration, one contaminant class may appear manageable while the other remains undetected, producing a false sense of safety. Recent work on aquatic biota also shows that metal-pesticide mixtures can generate ecotoxicological interactions that are not adequately captured by single-contaminant designs (Gu et al., 2022).

The mixed-contaminant perspective also aligns with broader environmental health thinking. Kashyap et al. (2024) emphasize that pesticide pollution in India is both environmental and public-health relevant. Ray and Vashishth (2024) frame heavy metal transfer explicitly from water to plate. When these two arguments are read together, the logical next step is a unified food-chain perspective for districts like South Dinajpur.

4.5 Human health, food safety, and livelihood implications

The fifth major finding is that fish contamination in South Dinajpur should not be interpreted only as an environmental issue. It is equally a food-safety and livelihood issue. Fish are nutritionally important in West Bengal, and state policy explicitly recognizes the importance of fish for nutrition, small indigenous species, and rural well-being (Government of West Bengal, 2015). Therefore, contamination that affects edible fish does not simply threaten biodiversity or market reputation; it may

also affect household protein intake, micronutrient access, and trust in local food systems.

Human health risk studies in India have increasingly moved beyond concentration reporting to exposure metrics. Maurya et al. (2019), Panda et al. (2023), and Kumar et al. (2024) demonstrate that public health interpretation requires attention to fish consumption rates, body weight assumptions, reference doses, and the distinction between carcinogenic and non-carcinogenic effects. Such methods are highly relevant to South Dinajpur, but they must be localized. National or international consumption assumptions may not reflect district dietary practices, and locally preferred species may differ in contaminant burdens.

There is also a communication challenge. If contamination is reported without context, fishers and local markets may be stigmatized. If contamination is ignored, public-health protection is weakened. The solution is not alarmism but targeted surveillance, species-based advisories where needed, and transparent residue monitoring that distinguishes between relatively safer and more concerning species or harvest locations.

Table 2: Proposed variables for a district-level empirical study in South Dinajpur

Domain	Recommended variables
Fish ecology	species, trophic guild, habitat type, size class, body weight, lipid content
Tissue analysis	muscle, liver, gills; optional kidney and gut where feasible
Metals	Pb, Cd, Cr, Hg, As, Ni, Cu, Zn, Mn, Fe
Pesticides	DDT and metabolites, HCH isomers, endosulfan, selected organophosphates, pyrethroids based on local use profile
Environmental media	water, sediment, aquatic macrophytes or benthos where possible
Spatial design	rivers, kharis, beels, ponds, aquaculture sites, market samples
Temporal design	pre-monsoon, monsoon, post-monsoon, crop-season linked sampling
Human health	estimated daily intake, target hazard quotient, hazard index, carcinogenic risk, local consumption survey
Governance context	pesticide use history, aquaculture chemical use, local fish marketing channels, regulatory awareness

V. DISCUSSION

The evidence synthesized in this article supports a clear interpretation: South Dinajpur is not simply a data-poor district, but a conceptually important district for freshwater contamination research in eastern India. Its significance lies in the combination of agrarian land use,

hydrological connectivity, fish diversity, floodplain habitat heterogeneity, and dependence on freshwater fish for food and livelihood. These are precisely the conditions under which both heavy metals and pesticides may display strong spatial and temporal variation.

The landscape ecotoxicology framework helps explain why. In heavily engineered or point-source dominated systems, contamination studies can sometimes focus on a single discharge route. In a district such as South Dinajpur, however, contamination is likely to be distributed across multiple pathways and storage compartments. Flooding can redistribute contaminants. Beels can retain sediment-bound residues. Kharis can act as transport corridors. Ponds may receive both agricultural runoff and aquaculture chemicals. Fish species move across or between habitat types, and consumers may purchase or catch fish from multiple sources. Thus, the district should be analyzed as an interconnected mosaic.

This interpretation also clarifies the limits of extrapolation. Evidence from East Kolkata Wetlands, the Ganga near Kolkata, the wider Ganga basin, Punjab, or Tamil Nadu cannot be mechanically transferred to South Dinajpur. The point is not that South Dinajpur necessarily replicates those contamination levels. Rather, those studies establish three propositions that are highly relevant: first, freshwater fish in India and West Bengal do accumulate both metals and pesticide residues; second, accumulation is highly species- and site-dependent; third, food-safety implications become meaningful once local dietary habits are considered. These propositions justify district-level investigation.

Another important implication concerns the relationship between fisheries development and contamination surveillance. State fisheries policy understandably emphasizes productivity, scientific culture practices, inland water development, and nutritional contribution (Government of West Bengal, 2015). Yet productivity without residue surveillance is incomplete governance. The policy recognition of inland fisheries, small fish nutrition, and scientific management could be strengthened by a parallel contaminant-monitoring agenda. In practical terms, this means integrating fisheries departments, agricultural extension, food safety agencies, and local laboratories rather than treating each domain separately.

The review also suggests that future research in South Dinajpur should resist the temptation to focus only on marketable major carps. While carps are important, they may not capture the full contaminant story. Small indigenous species, benthic feeders, omnivores, and species harvested from beels or kharis can reveal exposure routes that commercial aquaculture species may not. This is particularly important because state policy itself recognizes the nutritional role of small fish, and district biodiversity work indicates a wider fish assemblage than commonly sampled in market-based

contaminant studies (Government of West Bengal, 2015; Chakraborty & Bhattacharjee, 2008).

A further implication concerns methodology. The next generation of South Dinajpur research should be explicitly mixed-contaminant and mixed-media. Fish muscle data alone are insufficient for ecological interpretation. Water data alone are insufficient for food safety. Sediment data alone cannot capture dietary exposure. Instead, a robust district design should combine fish tissue analysis, sediment analysis, limited water chemistry, and land-use-informed site selection. Seasonal sampling is not optional; it is central. Equally, species ecology should be built into sample design from the start, not added as an afterthought.

Finally, the article contributes conceptually by reframing the district not as peripheral, but as analytically revealing. Large rivers and iconic wetlands often dominate contamination scholarship, but smaller agrarian districts may expose the cumulative effects of diffuse pollution, weak residue governance, and localized food dependence more clearly than metropolitan systems do. South Dinajpur is therefore a strong case for district-scale freshwater toxicology in India.

VI. CONCLUSION

This review set out to examine the likely bioaccumulation patterns of heavy metals and agricultural pesticides in freshwater fish species from South Dinajpur District, West Bengal, through a critical synthesis of available literature and policy materials. The evidence supports four broad conclusions.

First, the district's ecological and agricultural structure makes contaminant transfer to fish plausible and worthy of urgent study. South Dinajpur contains a connected mosaic of rivers, kharis, beels, ponds, and aquaculture-linked waters within an agrarian and flood-sensitive landscape. Such systems are highly conducive to diffuse contaminant movement.

Second, the wider Indian and lower Gangetic literature demonstrates that fish contamination by both metals and pesticides is a documented reality rather than a hypothetical risk. Studies from West Bengal and comparable freshwater systems show measurable residues and species-specific accumulation patterns, with clear implications for edible tissues and food safety.

Third, the current knowledge base is fragmented. Heavy metal and pesticide studies are often separated. Human health risk is frequently assessed without sufficient ecological interpretation. District-scale agrarian systems are underrepresented in the literature. For South Dinajpur specifically, the accessible literature does not yet provide an integrated district-level assessment of metals plus agricultural pesticide residues in edible freshwater fish.

Fourth, the most important scholarly and practical contribution now lies in designing that missing study. A strong South Dinajpur research program would

combine species ecology, tissue-specific analysis, seasonal sampling, sediment linkage, and localized dietary risk assessment. It would also connect environmental science to fisheries governance and food-safety policy.

The contribution of the present article is therefore twofold. Substantively, it establishes why South Dinajpur matters in the geography of freshwater contamination research in eastern India. Conceptually, it offers an integrated framework linking agricultural landscape processes, aquatic pathways, fish bioaccumulation, and human consumption. This makes the article suitable not only as a review manuscript but also as the intellectual foundation for a future empirical PhD paper.

FUTURE RESEARCH DIRECTIONS

Future research on South Dinajpur should proceed along seven lines.

First, district-scale baseline surveillance is required for both heavy metals and pesticide residues in edible fish species. Second, sample design should include rivers, kharis, beels, ponds, and culture systems to capture habitat heterogeneity. Third, species selection should cover major carps, omnivores, benthic feeders, and small indigenous species. Fourth, sampling should be seasonal and aligned with agricultural calendars and monsoon hydrology. Fifth, environmental media, especially sediment, should be analyzed alongside fish tissues to improve source interpretation. Sixth, local fish consumption surveys should accompany laboratory work so that health-risk calculations reflect district dietary practice. Seventh, policy translation should be built into the research design from the outset through collaboration with fisheries, agriculture, and food-safety institutions.

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