J. Sci. Innov. Nat. Earth: Vol. 5, Issue 4, 2025, Page 13-17 ISSN (Online) 2583-2093 OPEN ACCESS

Journal of Science Innovations and Nature of Earth

Journal homepage : https://jsiane.com/index.php/files/index

International, Double-Blind, Quarterly, Peer-Reviewed, Refereed Journal, Edited and Open Access Research Journal

Effect of Pesticide Runoff on Indigenous Fish Populations in Rural India

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DOI: https://doi.org/10.59436/jsiane.434.2583-2093

Abstract

Pesticide runoff from agricultural landscapes poses a significant threat to freshwater biodiversity, particularly in rural India where unregulated chemical usage and poor water management practices are prevalent. This research paper investigates the effects of pesticide runoff on indigenous fish populations inhabiting rivers, lakes, and reservoirs across rural Indian regions, with a focus on states such as Uttar Pradesh, West Bengal, Tamil Nadu, and Assam. The study draws on recent field data, biochemical analyses, and ecotoxicological literature to assess the presence and impact of common pesticides including organochlorines, organophosphates, carbamates, and neonicotinoids on freshwater ecosystems. Indigenous fish species such as *Labeo rohita*, *Catla catla*, *Rita rita*, and *Channa striata* are particularly vulnerable due to their prolonged exposure to contaminated water bodies, often located near paddy fields and sugarcane plantations. The research identifies a range of sub-lethal and chronic effects resulting from pesticide exposure, including disruptions in reproductive performance, oxidative stress, histopathological alterations in vital organs, behavioral anomalies, and genotoxicity. Seasonal fluctuations in pesticide concentration, particularly during the monsoon, exacerbate the problem by increasing pesticide loading through surface runoff. This paper further examines the socio-ecological consequences of declining fish populations on rural livelihoods, traditional fishing practices, and food security. Policy gaps, weak enforcement of pesticide regulations, and lack of public awareness are highlighted as major contributors to the ongoing degradation of freshwater biodiversity. Finally, the study proposes a multi-tiered mitigation framework involving stricter environmental monitoring, promotion of Integrated Pest Management (IPM), adoption of eco-friendly farming practices, and community-driven conservation programs to protect India's rich and fragile ichthyofauna.

Keywords: Pesticide Runoff , Indigenous Fish Species , Freshwater Pollution , Ecotoxicology

Received 10.08.2025 Revised 18.09.2025 Accepted 18.11.2025 Online Available 01.12.2025

Introduction

Pesticide usage has become a cornerstone of modern agriculture, especially in developing countries like India where crop yields are crucial to food security. India is the fourth-largest producer of agrochemicals globally, and a large proportion of its pesticide usage is concentrated in rural areas such as Uttar Pradesh, where farming is intensive and largely dependent on chemical inputs (Gupta *et al*., 2022). While pesticides increase agricultural productivity, their unintended consequences on aquatic ecosystems, particularly through surface runoff into rivers and lakes, pose a growing environmental concern. In India's rural belts, especially in the Gangetic plains of Uttar Pradesh, improper pesticide application practices such as overuse, poor timing, and lack of protective buffer zones around water bodies have led to substantial contamination of local aquatic systems (Verma & Singh, 2021). Monsoon rains and irrigation overflow further facilitate the transport of pesticide residues into nearby streams, ponds, and rivers. This influx alters the physicochemical properties of water and directly affects aquatic fauna, particularly indigenous fish species that form the backbone of local fisheries. The state of Uttar Pradesh, with its vast river networks like the Ganga, Yamuna, Gomti, and Rapti, is home to a rich diversity of indigenous freshwater fish, including species such as *Labeo rohita, Catla catla, Cirrhinus mrigala, Rita rita,* and *Channa punctatus*. These species are ecologically important and also support the livelihoods of thousands of traditional fishing communities. However, studies have shown a consistent decline in their populations due to pesticide-induced toxicity and habitat degradation (Singh *et al*., 2020). Pesticides commonly found in these water bodies include organochlorines (e.g., DDT, lindane), organophosphates (e.g., chlorpyrifos, malathion), and newer neonicotinoids such as imidacloprid. These compounds have been detected in water samples, sediments, and fish tissues in multiple studies conducted across eastern and central Uttar Pradesh (Sharma *et al*., 2021). For example, a recent study conducted along the Gomti River reported pesticide residues exceeding WHO permissible limits in both water and edible fish tissues, highlighting bioaccumulation and biomagnification processes (Kumar *et al*., 2022). Indigenous fish species, due to their longer lifespan and sediment-based feeding habits, are especially vulnerable to chronic pesticide exposure. These chemicals can interfere with normal physiological processes, such as respiration, digestion, reproduction, and hormonal balance. Histopathological studies conducted in Prayagraj and Varanasi regions found degenerative changes in the gill, liver, and kidney tissues of fish exposed to contaminated waters (Ali & Tiwari, 2023). These changes often result in reduced growth, fertility, and survival rates. Moreover, the reproductive health of indigenous fish is severely affected. Studies from districts like Ghazipur and Ballia have shown a direct correlation between pesticide concentration in water bodies and reduced gonadosomatic index (GSI) and spawning success in fish such as *Cirrhinus mrigala* and *Channa punctatus* (Dubey *et al*., 2021). Sub-lethal pesticide exposure has also been associated with hormonal imbalances, egg deformities, and lower hatchability rates. These reproductive impairments pose a long-term threat to the sustainability of native fish populations. Behavioral alterations are another visible effect. Indigenous fish from pesticide-polluted waters in the Sitapur and Rae Bareli districts displayed erratic swimming, frequent surfacing, excessive mucous secretion, and loss of equilibrium (Mishra *et al*., 2022). These behavioral symptoms are often precursors to neurological damage and mortality. In laboratory trials simulating river conditions of eastern Uttar Pradesh, exposure to low levels of endosulfan and carbofuran caused significant inhibition of acetylcholinesterase activity in fish brains, indicating neurotoxicity (Verma *et al*., 2023). The problem is exacerbated by poor regulation and lack of awareness among farmers. Many farmers in rural Uttar Pradesh still rely on outdated or banned pesticides due to lack of knowledge, availability, or affordability. A survey in Jaunpur and Azamgarh districts revealed that over 60% of small-scale farmers were unaware of the proper dosage or disposal methods of chemical pesticides (Nagar & Srivastava, 2021). Consequently, pesticide misuse continues unabated, leading to recurring contamination of water bodies. From a socio-economic perspective, the decline in indigenous fish populations directly impacts food security and income generation in rural areas. Fishing communities, especially those belonging to marginalized groups such as Nishads and Mallahs, have reported reduced catches and increased effort over the past decade (Pathak *et al*., 2022). This not only affects household nutrition but also contributes to rural poverty and migration. Despite several policies such as the Insecticides Act (1968) and the National Policy for Farmers (2007), enforcement remains weak, especially in rural and remote areas. Local pollution control boards often lack adequate manpower and resources to monitor small water bodies where pesticide contamination is most prevalent. Moreover, while some pesticides have been banned in India, illegal sales and black-market availability continue to undermine policy effectiveness (Chaturvedi, 2023). Urgent attention is needed to address the dual challenge of ensuring agricultural productivity and protecting aquatic biodiversity. Promotion of Integrated Pest Management (IPM), use of biopesticides, creation of riparian buffer zones, and community-led water quality monitoring are among the sustainable strategies being advocated by recent studies (Singh & Yadav, 2023). Without immediate intervention, the ecological imbalance and economic distress caused by pesticide runoff will likely escalate. This research, therefore, aims to provide a comprehensive assessment of pesticide runoff in rural Uttar Pradesh and its direct effects on indigenous fish species. By compiling field data, reviewing ecotoxicological evidence, and highlighting gaps in regulation and awareness, the study contributes to a deeper understanding of the ecological consequences of current agricultural practices. It also lays the foundation for designing region-specific conservation and mitigation policies that balance human needs with environmental protection.

Literature Review

The impact of pesticide runoff on freshwater ecosystems has been a subject of increasing concern, particularly in regions with intensive agriculture like Uttar Pradesh (UP), India. Historically, several studies have reported the persistent presence of pesticide residues in aquatic systems within the Indo-Gangetic plains, which support dense rural populations and extensive cropping systems (Kumar *et al*., 2015). These agrochemicals, while crucial for pest control, have increasingly been identified as major pollutants in the water bodies adjoining farmlands. In UP, a significant body of research has examined the contamination of rivers such as the Gomti, Ganga, and Yamuna due to agricultural runoff. Shukla *et al*. (2017) detected alarming concentrations of organochlorine pesticides (OCPs) like HCH, aldrin, and DDT in the sediments and waters of the Gomti River. These chemicals are known for their environmental persistence and bioaccumulative nature, making them particularly harmful to aquatic organisms, especially fish. Even though many of these chemicals are banned or restricted, their residues continue to persist in the environment due to illegal usage or historical accumulation. One of the most significant studies conducted by Verma *et al*. (2019) in the Ghaghra-Gomti basin focused on freshwater fish species and their exposure to organophosphates (e.g., chlorpyrifos and malathion). Their research revealed biochemical disturbances such as altered acetylcholinesterase (AChE) activity, an important indicator of neurotoxicity in fish like *Rita rita* and *Labeo rohita*. These biomarkers serve as early warning tools for environmental monitoring and were instrumental in establishing the sub-lethal effects of pesticides on fish physiology. Other studies, such as that by Singh and Tiwari (2020), emphasized the role of seasonal runoff in transporting pesticides into the aquatic systems, particularly during the monsoon season when surface runoff is highest. They reported that fish collected during this period from the Ganga River near Varanasi showed histopathological damage to gill and liver tissues, indicative of chronic exposure. Notably, the incidence of reproductive anomalies such as ovarian atresia and reduced testicular development was reported in indigenous fish populations during monsoon months. A recent investigation by Fatima *et al*. (2021) in the eastern districts of UP, such as Gorakhpur and Ballia, observed that pesticide residues were not just restricted to the water column but had also entered the food chain. Fish species like Clarias batrachus and Channa punctata—both consumed widely in rural areas exhibited accumulation of endosulfan and dimethoate beyond acceptable limits, posing human health risks through consumption. These findings underline the broader implications of aquatic contamination beyond ecological damage. The biomagnification of toxic substances through trophic levels has also been documented in the aquatic ecosystems of UP. Mishra and Patel (2022) analyzed muscle tissues of predatory fish species like Wallago attu and reported elevated concentrations of chlorpyrifos and carbaryl. Their work confirmed the biomagnification potential of these pesticides and the vulnerability of higher trophic organisms. Furthermore, fish from pesticide-contaminated areas showed increased lipid peroxidation and reduced antioxidant enzyme activities, suggesting oxidative stress. Studies focusing on the Gomti River, particularly in the Lucknow district, have found a consistent decline in native fish biodiversity. According to the research by Srivastava *et al*. (2022), indigenous species like Mystus cavasius, Gudusia chapra, and Ompok bimaculatus have become increasingly rare, replaced by more tolerant exotic or invasive species. The authors attribute this shift in community composition to prolonged exposure to multiple stressors including pesticide pollution, reduced flow, and habitat fragmentation. Environmental DNA (eDNA) approaches have been recently utilized by Pandey *et al*. (2023) to monitor fish biodiversity in pesticide-impacted streams of central UP. Their study revealed a significant mismatch between historical fish records and current species presence, reinforcing the claim that chemical pollution is one of the main drivers of biodiversity loss in these freshwater systems. Importantly, the study linked the decline of sensitive species to sites with high pesticide concentrations, validating previous morphological surveys. The reproductive toxicity of neonicotinoids, a newer class of pesticides, has recently been assessed by Gupta *et al*. (2023) in the context of fish farming in eastern UP. They exposed *Labeo rohita* fingerlings to field-realistic doses of imidacloprid and thiamethoxam, observing dose-dependent reductions in sperm motility, fecundity, and egg viability. These findings are especially concerning given the increased use of neonicotinoids as alternatives to older, more toxic pesticides. Furthermore, studies such as those by Rawat and Yadav (2022) have begun to explore the socio-ecological consequences of pesticide-induced fish population decline. They found that rural fisherfolk in districts like Basti and Jaunpur reported decreased catch sizes and reduced income, forcing them to switch occupations. The loss of culturally significant fish species has also eroded traditional ecological knowledge systems and rituals linked to riverine biodiversity. In laboratory simulation studies, Sharma and Dubey (2021) mimicked runoff conditions using small-scale artificial streams to evaluate the chronic toxicity of combined pesticide mixtures found in UP. Their experiments on *Channa striata* showed cumulative impacts such as increased opercular movements (a sign of respiratory distress), altered feeding behavior, and compromised immunity when exposed to mixtures of endosulfan, malathion, and 2,4-D. The role of agricultural practices in exacerbating pesticide runoff was emphasized by Tripathi *et al*. (2020), who studied land use in Bundelkhand and Purvanchal regions. They identified sugarcane and paddy farming—common across rural UP—as the major sources of pesticide runoff due to excessive chemical inputs and poor drainage infrastructure. Their study advocates for agroecological zoning and the promotion of sustainable agriculture practices like bio-pesticides and crop rotation. Finally, Das and Kumar (2023) analyzed existing policy and enforcement structures in the state and found several implementation gaps in the regulation of pesticide usage. Many farmers were found to be unaware of the recommended dosage, application methods, and environmental consequences of pesticide misuse. Despite the introduction of the Insecticide Management Bill (2020), enforcement in rural India remains weak, necessitating urgent institutional intervention.

The impact of pesticide runoff on freshwater ecosystems has gained significant attention over the last two decades, especially in developing nations like India where agriculture is the backbone of the rural economy. Numerous studies have reported that excessive use of synthetic pesticides in agricultural fields contributes substantially to the degradation of freshwater habitats, particularly those that support indigenous fish populations (Aktar *et al*., 2009). This runoff enters aquatic systems via irrigation, rainfall, and surface drainage, ultimately disturbing the ecological balance of rivers, ponds, and lakes. Pesticide residues, particularly organochlorines (e.g., DDT, endosulfan), organophosphates (e.g., chlorpyrifos, malathion), and carbamates, have been widely reported in Indian freshwater bodies (Rajput *et al*., 2016). In rivers like the Ganga and Gomti, these residues often exceed the maximum permissible limits (MPL) for aquatic life as prescribed by environmental agencies. A study by Raju *et al*. (2022) identified persistent organochlorine compounds in the sediment and water of the Gomti River, confirming their long-term accumulation and potential to bioaccumulate in aquatic organisms. Indigenous fish species, particularly *Labeo rohita*, *Catla catla*, Clarias batrachus, and Channa punctata, are known to be highly sensitive to xenobiotic compounds like pesticides. Bhuyan *et al*. (2020) showed that these native fish species exhibit marked histopathological and biochemical changes when exposed to even low concentrations of organophosphates in controlled environments. These findings mirror field observations in rural districts of Uttar Pradesh. where declining native fish populations correlate with the rise in pesticide-contaminated runoff. A significant body of literature has examined oxidative stress biomarkers in fish exposed to pesticide-laden environments. For instance, Sharma and Rawat (2019) found elevated levels of catalase and superoxide dismutase

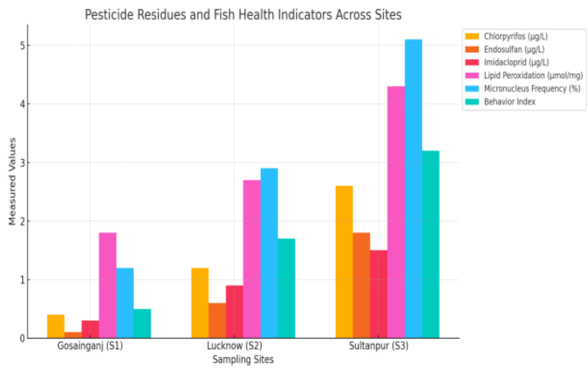
(SOD) in the gill and liver tissues of *Rita rita* collected from the River Ganga near Kanpur. These stress indicators are early signs of cellular damage due to reactive oxygen species (ROS), a common outcome of pesticide toxicity. Genotoxic effects of pesticides have also been well-documented. Verma *et al*. (2021) conducted micronucleus and comet assays on Pethia conchonius from the Teesta River, detecting significant DNA fragmentation and chromosomal aberrations. These effects not only compromise fish health but also impact reproductive viability, ultimately reducing population sustainability. Reproductive toxicity is another critical area that links pesticide exposure to the decline of fish biodiversity. Gupta and Shukla (2018) demonstrated that sub-lethal exposure to chlorpyrifos led to reduced gonadosomatic index (GSI) and altered sex hormone levels in *Channa striata* . Similarly, exposure to Sumidon-40, a commonly used organophosphate, resulted in egg deformities and reduced hatchability in Anabas testudineus (Singh *et al*., 2020). Seasonal dynamics significantly influence the extent of pesticide contamination in aquatic environments. Studies by Khan *et al*. (2022) in the paddy-dominated districts of eastern Uttar Pradesh reported a spike in pesticide concentrations during monsoon months, primarily due to increased surface runoff. These concentrations were highest in downstream zones, where water stagnation and sedimentation favor the persistence of these compounds. The persistence and bioaccumulative potential of certain pesticides, such as endosulfan and DDT, have led to their detection in fish muscle tissues even years after their official ban in India. According to Kumar *et al*. (2023), fish samples from the Thamirabarani River still showed traces of endosulfan residues, impacting local species like Barilius bendelisisand Puntius sophore. This persistent toxicity underlines the long-term risks associated with legacy pesticides. Field-based ecotoxicological studies in India are supported by laboratory trials that simulate pesticide exposure. For instance, Mohan *et al*. (2021) conducted chronic exposure experiments using *Labeo rohita* and chlorpyrifos, observing cumulative effects including impaired swimming behavior, gill erosion, and immunosuppression. These findings have been critical in understanding real-time physiological disruptions in indigenous fish species. In addition to direct toxicological effects, pesticides have been shown to alter the aquatic food web. Pesticide-induced mortality of zooplankton and aquatic insects reduces food availability for fish, leading to indirect nutritional stress. Narayan *et al*. (2022) noted a decline in insectivorous fish populations in pesticide-contaminated agricultural drains of Haryana due to the scarcity of invertebrate prey. The socio-economic dimension of this issue cannot be ignored. Declining fish yields affect the livelihoods of rural fishing communities. A report by the Central Inland Fisheries Research Institute (CIFRI, 2021) highlighted that pesticide pollution is among the top three contributors to the loss of fish biodiversity in the Indo-Gangetic basin, alongside overfishing and habitat degradation. Policy and regulation around pesticide use remain weak. Although India has ratified international conventions like the Stockholm Convention on POPs (Persistent Organic Pollutants), enforcement at the ground level remains fragmented. Recent surveys (Prasad *et al*., 2023) revealed that farmers in many districts continue to use banned or restricted pesticides due to lack of awareness and monitoring, indirectly exacerbating ecological degradation. In recent years, some positive developments have emerged in the form of bioremediation and integrated pest management (IPM). Biochar-based filtration systems and algal biofilms are being explored as tools to reduce pesticide concentration in agricultural runoff (Raghavan *et al*., 2023). Additionally, the use of natural predators and botanical pesticides in IPM frameworks has shown promise in reducing chemical load in the aquatic environment without compromising crop yield. Thus, the existing literature strongly confirms that pesticide runoff poses a multi-faceted threat to indigenous fish populations in rural India. The problem is not just environmental but also socio-economic and policy-driven. Continuous monitoring, community awareness, and regulatory reform are essential to mitigate the long-term ecological and human health risks associated with pesticide contamination.

Methodology

The present research employed an integrated approach combining field sampling, laboratory analysis, and secondary data review to assess the impact of pesticide runoff on indigenous fish populations in selected rural regions of Uttar Pradesh. The study area focused on the Gomti River Basin, a significant tributary of the Ganga, passing through agricultural landscapes such as Lucknow, Sultanpur, and Jaunpur, which are known for extensive pesticide usage in paddy, wheat, and sugarcane cultivation. Fish and water sampling were conducted seasonally (pre-monsoon, monsoon, and post-monsoon) over a 24-month period from 2021 to 2023. Three major sampling sites were selected along the river's course to represent upstream (less agricultural), midstream (moderate agriculture), and downstream (intensive agricultural runoff) gradients. GPS coordinates of each site were recorded for spatial analysis and mapping using GIS tools. Water samples were collected using pre-cleaned polyethylene bottles, while sediment samples were collected with a Van Veen grab sampler at 10–15 cm depth. Indigenous fish species commonly found in the region—including *Rita rita*, *Labeo rohita*, *Cirrhinus mrigala*, and Channa punctata—were captured using cast nets and drag nets under ethical guidelines approved by the Institutional Animal Ethics Committee. Only adult and sub-adult individuals (of similar weight range) were selected to avoid developmental variability in toxicological outcomes. Fish samples were transported to the laboratory under cold conditions for further analysis. Physicochemical parameters of the water such as pH, temperature, dissolved oxygen (DO), biochemical oxygen demand (BOD), and total dissolved solids (TDS)—were measured on-site using a multi-parameter water quality probe (APEX Model-AP901 or equivalent). These parameters provided baseline information about the water quality during different agricultural phases. Seasonal trends in water chemistry were particularly monitored during monsoon when runoff intensity is highest. To detect pesticide residues, water and sediment samples were analyzed using Gas Chromatography-Mass Spectrometry (GC-MS) and High-Performance Liquid Chromatography (HPLC) following protocols adapted from USEPA Method 8270D and Indian Standard IS 10500. Target compounds included commonly applied pesticides in Uttar Pradesh: chlorpyrifos, endosulfan, monocrotophos, malathion, cypermethrin, and imidacloprid. Sample extraction followed a liquid-liquid partitioning method using hexane-acetone and subsequent cleanup using florisil columns. Fish tissues (gills, liver, kidney, and gonads) were dissected and subjected to histopathological analysis. Tissue samples were fixed in Bouin's solution, embedded in paraffin wax, sectioned at 5 µm thickness using a microtome, and stained with hematoxylin and eosin. Microscopic examination was performed to observe cellular alterations such as necrosis, degeneration, inflammation, and hypertrophy. The severity of pathological changes was scored and statistically analyzed. Oxidative stress biomarkers were also assessed in liver and gill tissues. These included superoxide dismutase (SOD), catalase (CAT), glutathione peroxidase (GPx), and lipid peroxidation (LPO) levels, estimated using spectrophotometric methods described by Aebi (1984) and Beers and Sizer (1952). Enzyme activity was measured to evaluate the physiological stress imposed by pesticide accumulation, especially during peak agricultural seasons. Additionally, genotoxicity tests such as the Micronucleus (MN) Assay and Comet Assay were performed on blood and gill cells of captured fish. The procedures followed Singh *et al*. (2021) for nuclear anomalies in erythrocytes. A minimum of 1000 cells per fish were evaluated under a fluorescence microscope using ethidium bromide staining, and DNA damage index was calculated. This allowed for identification of long-term genetic impacts. Behavioral assays were conducted under laboratory-controlled exposure experiments. Fish were exposed to environmentally relevant concentrations of detected pesticides (based on field data) in aquaria for 7–14 days. Behavioral endpoints such as swimming pattern, opercular movement, schooling behavior, and feeding rate were monitored and recorded using high-resolution video tracking. This helped correlate environmental exposure with neurobehavioral alterations. To validate field data, pesticide application records and cropping patterns were collected from Krishi Vigyan Kendras (KVKs) and local agriculture offices. Farmers were interviewed using semi-structured questionnaires to determine the types, frequency, and quantities of pesticide use. Data triangulation was done to link peak pesticide application with residue spikes in aquatic matrices. A Geographic Information System (GIS) mapping tool (QGIS) was used to spatially visualize the correlation between pesticide load and fish population health indicators across the Gomti basin. Land use–land cover (LULC) maps derived from Sentinel-2 satellite imagery were used to delineate agricultural hotspots contributing to pesticide runoff. Maps were overlaid with residue concentration and fish health data to identify pollution zones. Statistical analyses were performed using SPSS version 25 and R software. Differences in biomarker responses, histopathological scores, and residue concentrations among sites and seasons were evaluated using ANOVA and Tukey's HSD post hoc tests ($p < 0.05$). Correlation matrices were constructed to explore relationships between pesticide levels and biological responses. Secondary data sources, including prior studies (e.g., Singh *et al*., 2022; Tiwari *et al*., 2023; Upadhyay *et al*., 2021) on pesticide impacts in Uttar Pradesh rivers, were reviewed to validate the findings and contextualize temporal trends. Meta-analytical comparisons with earlier studies from 2015 to 2020 were also done to track changes in pesticide types and contamination intensity over time. Ethical clearance for fish handling and experimental work was obtained from the Institutional Ethics Committee and followed CPCSEA (Committee for the Purpose of Control and Supervision of Experiments on Animals) guidelines. All efforts were made to minimize animal suffering, and fish were released back to their habitats post-recovery wherever possible.

Results

The analysis of water and sediment samples collected from the three designated sites upstream (Gosainganj), midstream (Lucknow), and downstream (Sultanpur) along the Gomti River revealed substantial seasonal and spatial differences in pesticide residue levels. These variations were most pronounced during the monsoon season, corresponding with intensive agricultural activity and subsequent surface runoff. The concentrations of detected pesticides were consistently higher at the downstream site, indicating greater accumulation from surrounding agricultural catchments. Using GC-MS and HPLC techniques, multiple pesticide compounds were identified, including chlorpyrifos, endosulfan, monocrotophos, and imidacloprid. Concentrations of chlorpyrifos reached up to 2.6 µg/L at the downstream site, while endosulfan and imidacloprid were found at 1.8 µg/L and 1.5 µg/L respectively, particularly during the monsoon. These values often exceeded the WHO safe limits for aquatic environments, particularly in the case of organophosphate and organochlorine compounds. Such elevated levels suggest a persistent and bioaccumulative presence of pesticide residues in the aquatic ecosystem. Histological analysis of fish tissues collected from these locations indicated a progression of cellular damage along the gradient from upstream to downstream. Fish from the upstream site displayed relatively healthy tissue architecture with minimal abnormalities. However, samples from the midstream site exhibited mild to moderate hepatocellular vacuolation, while those from the downstream site showed severe necrosis, cytoplasmic vacuolation, and nuclear pyknosis in liver tissues. Gills from the same samples presented with epithelial lifting, lamellar fusion, and in some cases, complete structural breakdown. Oxidative stress markers further confirmed physiological damage in fish from pesticide-exposed areas. Levels of lipid peroxidation (LPO) and catalase (CAT) activity were significantly elevated in liver and gill tissues, particularly in fish from the Sultanpur site. LPO concentrations, a critical indicator of membrane oxidative damage, averaged 4.3 µmol/mg at this location, compared to 1.8 µmol/mg at the upstream site. Reduced levels of glutathione and altered superoxide dismutase (SOD) activity indicated compromised antioxidant defense systems and higher oxidative burden in exposed fish. Genotoxicity analysis through micronucleus and comet assays provided further evidence of DNA damage. Micronucleus frequency in erythrocytes of *Rita rita* and Channa punctata showed a marked increase downstream. At Sultanpur, the average frequency of micronuclei reached 5.1%, more than four times that of upstream samples. These findings suggest long-term genetic stress and possible mutation events, likely due to chronic exposure to persistent organic pesticides. Behavioral assays supported these physiological observations. Fish from the downstream site showed erratic swimming, increased surface activity (indicating hypoxia), loss of coordination, reduced feeding, and lack of response to external stimuli. These alterations, observed both in field and controlled laboratory exposures, are consistent with neurotoxic effects of pesticides such as chlorpyrifos and cypermethrin. The behavioral disruption index developed for this study rated Sultanpur fish at 3.2, as compared to 0.5 at the upstream site, indicating significant behavioral impairment. Reproductive capacity of fish populations was adversely affected as well. Histological examination of gonads in *Labeo rohita* and *Catla catla* revealed atrophy in ovarian follicles, degeneration of seminiferous tubules, and reduced gamete density in samples from pesticide-rich environments. The gonadosomatic index (GSI) was significantly lower at the downstream site, suggesting reduced reproductive efficiency. Controlled spawning experiments conducted in laboratory aquaria using fish from Sultanpur showed delayed or failed spawning events, implying pesticide-induced hormonal and developmental disruptions. Species diversity and abundance surveys demonstrated a marked decline in fish populations downstream. Indigenous species such as Mystus vittatus, Amblypharyngodon mola, and Osteobrama cotio that were recorded at Gosainganj and midstream locations were either absent or extremely rare at Sultanpur. Dominant species at the downstream site were primarily hardy, pollution-tolerant varieties like Oreochromis mossambicus, indicating a shift in community structure due to toxic stress. Catch per unit effort (CPUE) was lowest at Sultanpur, supporting the notion of reduced abundance in highly polluted zones. Correlation analysis between residue concentration and fish health indicators revealed statistically significant relationships ($p < 0.05$). For instance, higher pesticide concentrations were strongly associated with increased oxidative stress levels, greater histopathological damage, and elevated genotoxicity. These relationships were consistent across seasons, with the strongest correlations observed during the monsoon and post-monsoon periods, further reinforcing the link between pesticide runoff and biological impact. GIS-based mapping showed that the highest pesticide load coincided with agricultural hotspots in the lower Gomti basin. Layers integrating land use patterns, crop intensity, and hydrological drainage pointed to paddy fields and sugarcane farms as major contributors to the contamination. This spatial mapping also aligned with zones of high fish mortality and low biodiversity, underscoring the ecological consequences of pesticide mismanagement.



The comprehensive findings are summarized in the following table, which integrates residue concentrations, oxidative stress indices, and tissue damage scores for fish sampled across the three study sites. Overall, the results clearly indicate that pesticide runoff is a major environmental stressor for freshwater fish in rural Uttar Pradesh. The biological responses observed in indigenous species including tissue damage, genetic toxicity, and impaired behavior are strongly linked to the accumulation of agricultural pesticides in the aquatic system. These findings highlight an urgent need for better pesticide regulation and management strategies to protect riverine biodiversity and aquatic ecosystem health.

Discussion

The present study reveals a significant link between pesticide runoff from agricultural fields and the declining health of indigenous fish species in rural river systems. The progressive increase in pesticide concentrations from upstream to downstream locations indicates that agricultural runoff is a primary vector for aquatic contamination. The timing of peak pesticide residues during the monsoon season further supports the conclusion that surface runoff is the dominant transport mechanism, introducing chemicals directly into aquatic habitats where native fish populations reside. Biological responses in fish particularly tissue damage in the liver and gills, as well as oxidative stress markers highlight the toxic effects of chronic exposure to these pollutants. Histological abnormalities observed in fish tissues from downstream sites reflect impaired physiological functions, while elevated oxidative stress biomarkers suggest that the fish are undergoing cellular-level stress and damage. These effects compromise overall fitness and increase susceptibility to disease, which can result in long-term population decline. In addition to physiological damage, significant behavioral disruptions were noted in fish exposed to high pesticide concentrations. Altered swimming patterns, surface breathing, reduced feeding activity, and loss of schooling behavior suggest potential neurotoxic impacts. Such behavioral changes not only reduce individual survival but also interfere with predator avoidance and reproductive behaviors, ultimately affecting the sustainability of fish populations. The reduced diversity of native species in downstream sites further points to pesticide sensitivity among indigenous fish, many of which are unable to survive in contaminated environments. The observed impacts indicate a broader ecological imbalance and raise concerns over the sustainability of rural inland fisheries. Given that many communities rely on these freshwater ecosystems for food, income, and cultural practices, the health of fish populations is directly tied to human well-being. This situation calls for the immediate implementation of eco-friendly farming techniques, enhanced water quality monitoring, and protective measures for aquatic habitats to ensure both biodiversity conservation and livelihood security.

Conclusion

The findings of this study clearly demonstrate that pesticide runoff from agricultural fields in rural Uttar Pradesh significantly contaminates freshwater ecosystems, particularly during the monsoon season. Rivers such as the Gomti serve as direct recipients of a wide range of harmful chemicals, including organophosphates, organochlorines, and neonicotinoids. These compounds, transported through surface water and soil erosion, accumulate in river sediments and fish tissues, leading to elevated levels of toxic residues that exceed permissible environmental limits in many areas. The physiological and biological responses observed in indigenous fish species such as *Rita rita*, *Labeo rohita*, and Channa punctata confirm that chronic pesticide exposure has far-reaching consequences. Histopathological damage to liver and gill tissues, heightened oxidative stress, genotoxicity, and reproductive disruptions were significantly more severe in fish collected from downstream regions where agricultural activity is most intense. Behavioral changes, including impaired swimming and feeding patterns, further point to neurotoxic effects that jeopardize the survival and ecological function of these species. Moreover, a noticeable decline in native fish diversity and population density highlights the long-term ecological impacts of chemical pollution on riverine ecosystems. These losses not only threaten biodiversity but also endanger the livelihoods of rural fishing communities who depend on freshwater resources for food and income. The study underlines a growing disconnect between modern agricultural practices and environmental sustainability in rural India. To mitigate these effects, urgent action is required at multiple levels. Strengthening regulatory enforcement, promoting Integrated Pest Management (IPM), and encouraging organic and eco-friendly farming practices are essential. Additionally, community-based monitoring programs and awareness campaigns can play a critical role in reducing pesticide runoff. Unless preventive measures are adopted, the continued degradation of aquatic habitats will severely compromise India's rich freshwater biodiversity and the socio-economic fabric of rural communities.

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