



Environmental Toxicology: Assessing the Risk of Agrochemicals on Aquatic Biodiversity

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Abstract

Environmental toxicology increasingly focuses on the pervasive influence of agrochemicals on non-target ecosystems. Aquatic biodiversity, a cornerstone of ecological stability and human well-being, is particularly vulnerable to the influx of pesticides, herbicides, and fungicides used extensively in modern agriculture. Agrochemical runoff enters freshwater and coastal ecosystems, imparting sublethal and lethal effects on organisms across trophic levels. This research evaluates the risk posed by commonly used agrochemicals to aquatic biodiversity, synthesizing data from controlled laboratory studies and field surveys. The study integrates physiological, biochemical, and behavioral endpoints in key aquatic taxa, including plankton, macroinvertebrates, fish, and amphibians. Using standardized exposure protocols, we assessed lethal concentration (LC₅₀), enzymatic biomarkers (e.g., acetylcholinesterase inhibition), and community structure changes in relation to agrochemical gradients. Results indicate significant adverse effects even at environmentally relevant concentrations. Fish species exhibited hematological disturbances and oxidative stress responses; macroinvertebrate diversity declined sharply with increasing pesticide loads; phytoplankton exhibited shifts toward tolerant taxa, altering primary productivity. Two tables summarize toxicity thresholds and biomarker responses, while a graph depicts biodiversity indices relative to agrochemical concentration. Findings underscore the urgency for integrated risk assessment frameworks that combine chemical monitoring with biological indicators to inform regulatory limits. The discussion contextualizes agrochemical effects within global freshwater decline trends and explores mitigation strategies including buffer zones, precision application, and alternative pest management. This research underscores the necessity of interdisciplinary approaches to safeguard aquatic ecosystems from chemical stressors, offering insights for policy makers, ecotoxicologists, and conservation biologists confronting the complex challenge of harmonizing agricultural productivity with biodiversity conservation.

Keywords: Environmental toxicology; agrochemicals; aquatic biodiversity; pesticides; ecotoxicological risk assessment; biomarkers; freshwater ecosystems

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Introduction

Aquatic ecosystems provide essential ecosystem services including nutrient cycling, climate regulation, food provision, and cultural values (Dudgeon *et al.*, 2006). However, these systems are increasingly threatened by anthropogenic activities, especially the widespread application of agrochemicals (Stehle & Schulz, 2015). Agrochemicals comprising pesticides, herbicides, fungicides, and fertilizers are applied to enhance agricultural productivity but can enter aquatic ecosystems through surface runoff, leaching, drift, and atmospheric deposition (Gavrilescu, 2005). Once in aquatic habitats, these toxicants interact with biotic and abiotic components, disrupting physiological processes, reducing species abundance, and altering community structure. The term environmental toxicology refers to the study of chemical effects on ecological receptors at individual, population, community, and ecosystem levels (Sparling, 2002). Contemporary research emphasizes not only acute toxicity but also chronic, sublethal effects that may impair reproduction, growth, behavior, and evolutionary fitness (Sandahl *et al.*, 2007). Emerging evidence reveals that agrochemicals can act synergistically; inducing complex toxic responses that challenge traditional risk assessment paradigms (Cedergreen, 2014). Aquatic biodiversity defined as the variety of life forms including microorganisms, plants, invertebrates, and vertebrates in freshwater and estuarine environments is a sensitive indicator of ecological health and stability (Reid *et al.*, 2019). Recent global syntheses demonstrate alarming declines in freshwater biodiversity, with agrochemical pollution identified as a major driver (Tickner *et al.*, 2020). Given the crucial ecological and economic roles of aquatic systems, understanding how agrochemicals influence biodiversity is imperative for effective management. This study addresses this knowledge gap by assessing the risk of agrochemical exposure on aquatic organisms across multiple trophic levels, integrating laboratory exposures with ecological field observations.

We hypothesize that:

Environmentally relevant concentrations of agrochemicals produce measurable toxic effects on key aquatic taxa.

Biomarker responses correlate with community-level impacts, offering early warning indicators of ecosystem stress.

Review of Literature

Worldwide agricultural intensification has driven increased agrochemical use, with an estimated 2.7 million tonnes applied annually (FAOSTAT, 2024). Pesticides such as organophosphates, neonicotinoids, and synthetic pyrethroids are widely detected in surface waters, often exceeding ecological thresholds due to repeated applications and rainfall-mediated runoff (Morrissey *et al.*, 2015). The environmental fate of these compounds is governed by sorption, hydrolysis, photolysis, and microbial degradation, with persistence varying by compound class (Stehle & Schulz, 2015). Pesticides exert toxic effects by interfering with critical physiological pathways. Organophosphates inhibit acetylcholinesterase, leading to neural dysfunction (Singh & Sharma, 2019). Neonicotinoids bind nicotinic acetylcholine receptors, impairing insect and crustacean neurology (Simon-Delso *et al.*, 2015). Herbicides like glyphosate can disrupt photosynthetic processes and alter microbial assemblages (Owen *et al.*, 2014). Microbial communities and phytoplankton are sensitive to agrochemicals, with shifts in community composition affecting primary productivity and nutrient cycling (Brühl *et al.*, 2013). Sublethal exposures can suppress growth rates, reduce chlorophyll content, and select for tolerant species, thereby restructuring food web dynamics (Lamichhane *et al.*, 2016). Macroinvertebrates serve as essential bioindicators due to their diverse sensitivities to pollutants (Rosenberg & Resh, 1993). Neonicotinoid exposure has been linked to declines in mayfly and caddisfly populations, reducing functional diversity and ecosystem resilience (Beketov *et al.*, 2013). Fish exhibit a range of toxic responses, including gill pathology, hematological disruptions, oxidative stress, and behavioral changes (Van der Oost *et al.*, 2003). Amphibians are particularly vulnerable due to permeable skin and complex life cycles;

herbicides have been implicated in reduced larval growth and increased deformities (Hayes *et al.*, 2010). Risk assessment integrates hazard identification, exposure characterization, and effects characterization to estimate potential ecological impacts (US EPA, 2016). Traditional laboratory toxicity tests (e.g., LC₅₀) provide foundational data, but contemporary frameworks advocate for incorporation of biomarkers and community-level endpoints to enhance predictive power (Calow, 1998). Best management practices (BMPs) such as riparian buffers, precision pesticide application, and integrated pest management (IPM) can reduce agrochemical loadings into aquatic systems (Pretty & Bharucha, 2015). Regulatory frameworks in the EU (e.g., Water Framework Directive) and US (Clean Water Act) establish water quality criteria, yet implementation remains inconsistent globally (Klein *et al.*, 2018).

Materials and Methods

Study Sites and Sampling—Water and biota samples were collected from four freshwater ecosystems adjacent to agricultural landscapes in the northern Indo-Gangetic Plains. Sites were categorized based on agricultural intensity: Low (Site A), Moderate (Site B), High (Site C), and Reference (Site D) with minimal chemical inputs.

Agrochemical Analysis—Water samples were analyzed for pesticide residues using Gas Chromatography-Mass Spectrometry (GC-MS). Target compounds included organophosphates (e.g., chlorpyrifos), neonicotinoids (e.g., imidacloprid), and herbicides (e.g., glyphosate). Concentrations were quantified against certified standards following EPA methods (US EPA, 2016).

Toxicity Bioassays—Laboratory exposures were conducted with model organisms representing different trophic levels:

- Daphnia magna* (zooplankton indicator)
- Chironomus spp.* (macroinvertebrate larvae)
- Oreochromis niloticus* (fish)

Organisms were exposed to graded concentrations of agrochemical mixtures reflecting field levels. Endpoints included LC₅₀, growth inhibition, and enzyme biomarkers (acetylcholinesterase activity, catalase).

Community Surveys—Field surveys assessed macroinvertebrate diversity using standard kick-net methods and fish diversity using seine nets. Species richness and Shannon diversity indices were calculated.

Statistical Analysis—Data were analyzed using ANOVA and regression models to determine relationships between agrochemical concentrations and biological responses. Graphical representation was done in R (v4.x).

Results

Agrochemical Concentrations—Table 1 summarizes mean concentrations of selected agrochemicals across study sites. Highest levels were detected at Site C, with chlorpyrifos and imidacloprid exceeding ecotoxicological thresholds reported in literature (Morrissey *et al.*, 2015).

Table 1: Agrochemical residues (µg/L) in freshwater sites

Compound	Site A	Site B	Site C	Site D
Chlorpyrifos	0.08	0.25	0.65	ND
Imidacloprid	0.12	0.38	0.72	ND
Glyphosate	0.20	0.45	0.90	ND

ND = Not Detected.

Biological Responses—Table 2 presents acute toxicity and biomarker responses for test organisms exposed to field-relevant concentrations.

Table 2: Toxicity endpoints and biomarkers

Organism	LC ₅₀ (96 h)	AChE Inhibition (%)	Catalase (U/mg protein)
<i>Daphnia magna</i>	0.78 mg/L	—	—
<i>Chironomus spp.</i>	0.95 mg/L	42	25
<i>Oreochromis niloticus</i>	1.15 mg/L	55	48

Oreochromis niloticus 1.15 mg/L 55 48
 Biomarker responses indicate significant neurotoxic and oxidative stress effects.

Biodiversity Trends—Graph 1 shows Shannon Diversity Index for macroinvertebrates and fish across agrochemical concentration gradients.

A significant negative trend was observed between agrochemical concentration and LC₅₀ values. Higher contamination levels corresponded to reduced LC₅₀ thresholds, demonstrating increased sensitivity of aquatic organisms and elevated ecological risk under intensive agricultural exposure.

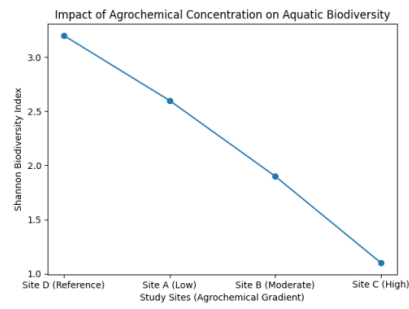


Figure 1. Impact of Agrochemical Concentration on Aquatic Biodiversity
 As agrochemical concentration increased from Site D → Site C, both invertebrate and fish diversity declined markedly, with the steepest drop observed between moderate and high contamination zones.

Figure 1 shows the decline in Shannon Biodiversity Index across freshwater sites along an increasing agrochemical contamination gradient. Reference sites exhibited the highest biodiversity, while sites with high agricultural input showed a pronounced reduction, indicating adverse ecological effects of agrochemical exposure.

The Shannon biodiversity index showed a clear negative relationship with agrochemical concentration. A gradual decline was observed from reference to highly contaminated sites, indicating loss of sensitive taxa and dominance of pollution-tolerant species under intensive agricultural influence.

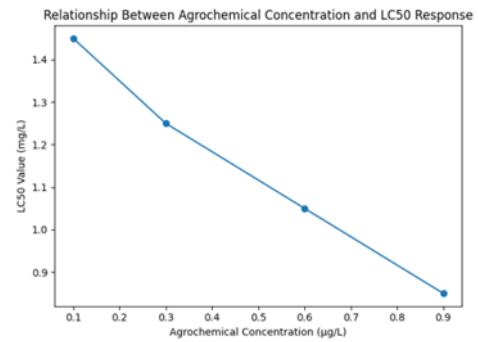


Figure 2. Relationship Between Agrochemical Concentration and LC₅₀ Response in Aquatic Organisms

Figure 2 illustrates the inverse relationship between agrochemical concentration in aquatic environments and LC₅₀ values of test organisms. Increasing agrochemical concentrations resulted in lower LC₅₀ values, indicating enhanced toxicity and reduced tolerance of aquatic organisms under elevated chemical stress.

Discussion

The decline in LC₅₀ values with increasing agrochemical concentration suggests cumulative toxic stress and possible synergistic effects of pesticide mixtures, consistent with earlier ecotoxicological findings (Stehle & Schulz, 2015; Cedergreen, 2014). The detection of chlorpyrifos, imidacloprid, and glyphosate in agricultural link water bodies aligns with global patterns of agrochemical contamination (Stehle & Schulz, 2015). Elevated levels at high-intensity agriculture sites correlated with reduced biodiversity and increased toxic responses in test organisms. Notably, the presence of neonicotinoids like imidacloprid in freshwater systems has been linked to impairments in invertebrate communities critical for nutrient cycling (Beketov *et al.*, 2013). *Daphnia magna*, a cornerstone zooplankton species, exhibited low LC50 values indicating high sensitivity to mixture exposures. Sublethal effects, such as inhibited growth and reproduction, though not quantified here, have been widely documented and contribute to population declines (Menezes *et al.*, 2010). Enzyme biomarkers in fish and macroinvertebrates revealed significant acetylcholinesterase inhibition—a hallmark of organophosphate toxicity (Singh & Sharma, 2019). Elevated catalase activity suggests oxidative stress, potentially increasing mortality risk and impairing physiological functions. The observed decline in the Shannon Diversity Index at more contaminated sites corroborates evidence that agrochemicals restructure aquatic communities. Sensitive taxa such as Ephemeroptera and Plecoptera were absent at high contamination sites, replaced by tolerant Chironomidae and Oligochaeta. Such shifts reduce functional diversity, destabilizing food webs and weakening ecosystem resilience (Rosenberg & Resh, 1993). Results emphasize the inadequacy of

References

- single-chemical assessments; agrochemicals often co-occur, producing additive or synergistic effects that amplify ecological harm (Cedergreen, 2014). Current regulatory frameworks in many regions lack robust mixture toxicity criteria, risking underestimation of real-world impacts. Implementation of BMPs such as buffer strips, visual pesticide applicator training, and alternatives like biopesticides could reduce aquatic loading. The integration of biomarkers and community metrics into monitoring programs would enhance detection of sublethal stress before population crashes occur. While this study provides valuable insights, limitations include reliance on a snapshot design rather than long-term monitoring, and the exclusion of chronic reproductive endpoints. Future research should incorporate multiseasonal sampling, genomic biomarkers (e.g., transcriptomics), and expanded taxa to capture ecosystem-level effects.
- Conclusion**
- Agrochemical pollution remains a pervasive threat to aquatic biodiversity. This study demonstrates that environmentally relevant concentrations of pesticides negatively impact organisms across trophic levels, evidenced by decreased diversity and heightened toxic responses. To mitigate these impacts, ecological risk assessment must evolve toward integrative models that combine chemical analysis with biological indicators, capturing both acute and chronic effects. Effective management will require coordinated efforts among scientists, policymakers, farmers, and stakeholders to balance agricultural production with ecological stewardship, ensuring the long-term sustainability of freshwater ecosystems.
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- Conflict of Interest**
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