ISSN: 2458-8989

Natural and Engineering Sciences

NESciences, 2025, 10 (3): 359-370 doi: 10.28978/nesciences.1811129

Application of the Ecological Risk Assessment (ERA) Framework to Evaluate Pesticide Impacts on Aquatic Life

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Abstract

The widespread application of pesticides in agricultural landscapes has raised increasing concern about their ecological impacts on aquatic environments. This study applies an ecological risk assessment (ERA) framework to evaluate six major classes of pesticides: neonicotinoid insecticides, pyrethroid insecticides, organophosphate insecticides, triazine herbicides, glyphosate (and its metabolite AMPA), and azole fungicides based on secondary datasets and published monitoring studies. The prime aim had been the identification of exposure patterns, sensitive taxa, and cumulative risk of pesticide mixtures in surface waters. The monitoring data showed distinct detection profiles for different chemical classes. Neonicotinoids and glyphosate were the almost constant percentage of detection, which were chronic, baseline, contaminants with detection frequencies of 68% and 75%, respectively. Pyrethroids and organophosphates had lower frequencies and ranged from 30 to 42%, with rainfall and runoff associated with episodic peaks. Triazines (55%) and azole fungicides (40%) had intermediate levels of detection,

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denoting seasonality of inputs and repeated applications to agriculture. Thresholds of toxicity demonstrated very strongly individual taxon sensitivity, with aquatic invertebrates being the most sensitive to neonicotinoids, benthic invertebrates and fish to pyrethroids, and algae to triazine herbicides. RQ analysis showed that neonicotinoids (RQ: 1.2–45) and pyrethroids (RQ: 5–20) had medium to high-risk levels, while organophosphates (RQ: 0.4–16) and azoles (RQ: 0.2–17) had episodic or mixture-induced risk levels. Triazines (RQ: 0.025–0.6) and glyphosate (RQ: 0.3–3.5) posed comparatively lower but still ecologically relevant risks. Summed risk quotients (ΣRQ) frequently exceeded 1.0, particularly for invertebrates, confirming that additive and synergistic effects amplify overall risks.

Keywords:

Aquatic contamination, cumulative exposure, ecological risk assessment, pesticide, toxicity thresholds.

Article history:

Received: 24/06/2025, Revised: 12/08/2025, Accepted: 12/09/2025, Available online: 12/12/2025

Introduction

Pesticide use has become an essential aspect of agricultural production; they are the preference for the highest-yielding crops and control of pests, diseases, and weeds. However, since pesticides are applied intensively and on large scales, they certainly pose major threats to the environment, with particular concerns arising in aquatic ecosystems, which are ultimate sinks for agrochemicals transported through surface runoff, leaching, and atmospheric deposition (Gupta & Joshi, 2025). The pursuit of maximising agricultural production, supported by advancements in agribusiness management, has also led to increased reliance on chemicals and the questioning of the sustainability of production systems (Smihunova et al., 2024). Meanwhile, pesticide residues in freshwater are flashing a worldwide warning on their toxic effects on aquatic biota; the effects range from a sublethal level of physiological stress to population decreases and shifts in ecosystem functioning (Malaj et al., 2014; Cui et al., 2020). Such effects are more evident among sensitive taxa, such as aquatic invertebrates, algae, and juvenile fish, which constitute an integral part of trophic interactions and ecosystem resilience (Assessment, 1998).

Along with the early pesticide risk assessment tradition, single-chemical toxicity testing and exposure modelling remained central tools before being put to use. However, such methods have their shortcomings in estimating ecological risks. Essentially, aquatic organisms are confronted with multiple chemical classes and other environmental stressors at the same time. Mixtures of compounds, chronic low-level contamination, and episodic pulse events following rainfall or irrigation all contribute to the multifaceted impacts of pesticides (Backhaus et al., 2012; Battaglin et al., 2014; Van den Brink et al., 2016). The picture here is analogous to the situation of other emerging contaminants, like nanoplastics, which get bioaccumulated across trophic levels and display multilevel toxicity in aquatic ecosystems, and microplastic pollution that disrupts aquatic food webs and ecological interactions in a manner similar to pesticide residues (Nandy et al., 2025; Al-Rashid & Greaves, 2025). On the other side, novel water treatments, including photocatalytic degradation using TiO_2, have been studied as environmentally friendly means of removing persistent agrochemical residues (Daabool & Hussein 2022). This further supports a risk management standpoint toward multi-stressor environments. Ergo, more demand is created for risk frameworks integrating chemical occurrence data, toxicity thresholds, and ecological interactions in a holistic way.

Ecological risk assessments provide a framework for structuring the methodology toward analysing such risks while moving beyond chemical-centric endpoints to ecosystem-level interpretations. By combining assessment of exposure, characterisation of hazard, and calculation of risk quotient (RQ), ERA allows researchers to detect both target compounds susceptible to effects and patterns of cumulative risks. These frameworks draw attention to taxon-level sensitivity from an ecological point of view, thus gearing scientific conclusions toward environmental protection goals (Brock et al., 2006; EFSA, 2013).

The present study uses the ERA-based setting for the ecological risk assessments of different pesticide classes, such as neonicotinoids, pyrethroids, organophosphates, triazines, glyphosates, and azole fungicides, in aquatic environments. Drawing upon secondary data from monitoring studies published in peer-reviewed journals, from regulatory bodies, and from ecotoxicological databases, the analysis looks at the measured environmental concentrations (MECs) and compares them to the predicted no-effect concentrations (PNECs), with mixture risks being assessed between groups of chemicals. Integrating these patterns of exposure with ecological sensitivity, the study aims to enunciate a more comprehensive picture of pesticide-related stressors in freshwater systems and draw implications for future regulatory and conservation agendas. In addition, the emergence of more sustainable purification technologies, for example, nanomaterial-based water treatment, augurs well for pesticide residue remediation and for the protection of aquatic ecosystems (Zor & Rahman, 2025).

Materials and Methods

Study Framework and Data Sources

The present study aims to take the Ecological Risk Assessment framework (ERA) in analysing potential pesticide-induced effects on aquatic ecosystems. Due to the constraints for field-level monitoring, the assessment took recourse primarily on secondary sources, thus ensuring scientific rigor and ecological relevance. The pesticide occurrence data were taken together through peer-reviewed monitoring studies, governmental water quality reports, and open-access databases, including the Pesticide Properties Database (PPDB), USEPA ECOTOX Knowledgebase, and European Food Safety Authority (EFSA) datasets (USEPA, 1998, Solecki, et al 2017); these gave information concerning the measured environmental concentrations (MECs) and toxicological endpoints of aquatic taxa. Other physicochemical parameters of the water systems dictating pesticide fate and pH of toxicity, for instance, dissolved oxygen concentrations, water temperature, and conductivity, collated from publications of hydrogeological interest to give a final contextualization to the assessment (Cui et al., 2020).

Hazard Characterization

Hazard characterisation concentrated upon establishing the toxicological profiles of pesticide compounds of importance to aquatic life. Data concerning representative groups of organisms, namely fish, aquatic invertebrates, and primary producers (algae and macrophytes), were compiled in order to capture the sensitivity of an ecosystem. Priority was given to chronic toxicity endpoints (e.g., No Observed Effect Concentration [NOEC], Lowest Observed Effect Concentration [LOEC]) because they are ecologically meaningful in that they often reveal sublethal and long-term effects. In the absence of chronic data, acute toxicity endpoints (e.g., LC50, EC50) were considered.

In order to yield ecologically protective benchmarks, PNECs were derived by dividing toxicity values by assessment factors (AFs), as per international regulatory guidance (EFSA, 2013). This accounted for factors contributing to uncertainty, such as interspecies variation, limited test species coverage, and laboratory-to-field extrapolation.

Exposure Assessment

Exposure assessment has also served to evaluate pesticide concentrations to which aquatic organisms could have been exposed. Measured Environmental Concentrations (MECs) were sourced from various monitoring datasets. In the absence of such data sets, available published modelled concentrations and representative concentration ranges from regional studies were used to provide the most realistic exposure scenarios.

Since in such aquatic systems several residues of pesticides usually simultaneously contaminate the environment, mixture toxicity assessment was carried out using the concentration addition (CA) approach (Kortenkamp et al., 2009). The approach assumes additive toxicological effects so that site-level cumulative exposure can be expressed as the sum of individual pesticide risk quotients (ΣRQsite) (Malaj et al., 2014; Backhaus et al., 2012). Considering mixture effects yields a more ecologically realistic estimate of pesticide pressure in aquatic environments.

Risk Characterization

Risk characterisation was conducted using the Risk Quotient (RQ) method, which compares exposure concentrations against toxicological thresholds.

$$RQ = \frac{MEC}{PNEC}$$

The ecological risk categories were interpreted according to standardised thresholds:

- RQ < 0.01 – negligible risk
- 0.01 ≤ RQ < 0.1 – low risk
- 0.1 ≤ RQ < 1 – medium risk
- RQ ≥ 1 – high risk

For sites or datasets with multiple pesticide residues, cumulative risk quotients (ΣRQsite) were calculated to capture the combined ecological burden. To strengthen ecological interpretation, risk values were cross-referenced with supporting environmental stressors frequently reported in aquatic ecosystems, including dissolved oxygen depletion, nutrient enrichment, and pH alterations (Backhaus et al., 2012).

Ecological Contextualization

The above chemical thresholds were set while viewing ecological interpretation vis-à-vis indicator taxa that are crucial in freshwater ecosystems. Sensitive groups such as Ephemeroptera, Trichoptera, and Diptera (benthic invertebrates), planktonic crustaceans (e.g., Daphnia spp.), and small-bodied fish species were the focus. These taxa are chosen because of their recognised sensitivity to pesticides, functional roles in aquatic food webs, and the role they play as standard test organisms in ecotoxicology (Brock et al., 2006). Life-history traits considered included short generation times, habitat specificity, and reproductive strategies to translate risk outcomes into ecologically relevant insights into ecosystem resilience versus vulnerability.

Scenario Evaluation and Integration

At this final stage, the synthesised results generated categories of ecological risk at the site level that ranged from negligible to high risk. For purposes of clarity in communication, representations were made via comparative bar charts, cumulative risk plots, and spatially explicit risk maps wherever possible. An explicit acknowledgement of uncertainty was maintained for transparency. Said uncertainties were primarily brought about by: (i) lack of complete pesticide monitoring; (ii) scarce chronic toxicity endpoints; (iii) consideration of mixture toxicity that might be underestimated; and (iv) nature itself being variable in its environmental conditions (Van den Brink et al., 2016). Addressing the uncertainties not only sets the context for the strength of conclusions but also paves the way for future research regarding systematic field monitoring and long-term ecological studies.

Results

Overview of Chemicals of Interest

The secondary datasets analysis, together with compiled monitoring studies, extracted six primary groups of pesticides usually encountered in waters: neonicotinoid insecticides, pyrethroid insecticides, organophosphate insecticides, triazine herbicides, glyphosate and its metabolite AMPA, and azole fungicides. Said active ingredients are the most frequently used active ingredients in agricultural work, hence they were chosen as the main chemicals of interest (COIs) in ecological risk assessment (Brock et al., 2006; EFSA, 2013; Morrissey et al., 2014).

Detection Patterns in Surface Waters

Detection ranges of pesticides varied substantially across chemical classes (Table 1). Neonicotinoid insecticides such as imidacloprid, thiamethoxam, and clothianidin were detected in 68% of monitoring samples, with concentrations ranging from 0.012 to 0.45 µg/L (mean 0.08 µg/L). These compounds were frequently present throughout the year, indicating chronic exposures that pose significant risks to aquatic invertebrates (Malaj et al., 2014; Backhaus et al., 2012; Morrissey et al., 2014). Pyrethroid insecticides, including λ-cyhalothrin, cypermethrin, and deltamethrin, were reported in 42% of samples, generally at concentrations below 10 ng/L, but episodic runoff events occasionally produced peaks of up to 25 ng/L. Due to its hydrophobic nature, a pyrethroid residue is prevalent in sediments, thereby exposing benthic invertebrates and juvenile fish to mortality (EFSA, 2013; Weston & Lydy, 2012).

Interrogating roughly 30–40% of samples, organophosphate insecticides, that is, chlorpyrifos, diazinon, and malathion, were detected at concentrations of the order of 0.02-0.8 µg/L. They showed temporal variation with peak levels right after pesticide application and runoff events set in motion by rainfall. On the other hand, triazine herbicides such as atrazine, terbuthylazine and simazine were detected consistently, in 55% of sampling events with concentrations between 0.05 and 1.20 µg/L (median, 0.25). These were strongly tied to seasonal agricultural applications, hence determining long-term exposure in aquatic systems (Loos et al., 2013). Another two substances reported with high frequency, 75% of samples detection, concentrations about 0.30-3.50 µg/L (mean, 1.20 µg/L), are glyphosate and the main metabolite detected, AMPA. This presents the contemporary scenario of utilisation in intensive agricultural practices and environmental mobility.

Azole fungicides, such as Tebuconazole, Propioniconazole, and Difenoconazole, were detected in almost 40% of samples analysed, with concentrations varying between 0.01 and 0.85 µg/L. The presence of the said fungicides has been ascribed to repeated spray programs in areas of intensive cropping, imparting sublethal risks to algae and aquatic invertebrates (Zubrod et al., 2019). Compiled results distinctly indicate differing exposure patterns across chemical groups: neonicotinoids and glyphosate column chronic, baseline contamination to surface waters, while pyrethroids and organophosphates hold the possibility of creating episodic but acute contamination spikes following applications or runoff events. The two-pronged scenario of chronic and acute stressors forebodes an enhanced ecological risk profile within the aquatic environment that could potentially affect a susceptible taxon, community structures, and ecosystem function.

Table 1. Detection frequency, measured environmental concentrations (mec), predicted no-effect concentrations (pnec), risk quotient ranges, sensitive taxa, and risk levels for major pesticide groups across monitoring sites

Chemical Class	Detection Frequency	MEC Range	PNEC (µg/L)	RQ Range	Main Sensitive Taxa	Risk Level
Neonicotinoids	68%	0.012–0.45 µg/L	0.01	1.2–45	Invertebrates	Medium–High
Pyrethroids	42%	<0.01–0.025 µg/L	0.001	5–20	Benthic invertebrates, fish	Medium–High
Organophosphates	30–40%	0.02–0.8 µg/L	0.05	0.4–16	Fish, invertebrates	Low–High (episodic)
Triazines	55%	0.05–1.2 µg/L	2.0	0.025–0.6	Algae, periphyton	Low–Medium
Glyphosate & AMPA	75%	0.3–3.5 µg/L	1.0	0.3–3.5	Algae, macrophytes	Negligible–Medium
Azoles	40%	0.01–0.85 µg/L	0.05			

Sensitive Taxa and Ecological Relevance

Strong taxon-specific vulnerabilities associated with toxic thresholds are observed across pesticide classes. Consequently, neonicotinoid insecticides present acute risks to aquatic invertebrates, in particular certain taxa such as Daphnia and mayflies, with observed chronic effects even at 0.01 µg/L (Brock et al., 2006). Pyrethroids largely affect benthic invertebrates and fish because sudden pulses in the water column trigger the occurrence of acute toxicity. Also, the organophosphates endanger fish and aquatic invertebrates mainly during peak runoff events, such risk being strongly correlated with pesticide application and transport by rainfall.

While triazine herbicides basically target primary producers, algae and periphyton are the most sensitive groups of organisms. Disrupting the ability of the aquatic habitats to shelter rearing stocks of the fish from predators reduces fishery yields through interference with the recruitment of fish. Glyphosate and its metabolite AMPA usually moderately affect algae and aquatic macrophytes directly, but then also impart indirect effects on higher trophic levels by changing community composition and food-web structure (Cui et al., 2020; Mesnage & Antoniou, 2017). In contrast, azole fungicides impose sublethal risks, mainly on algae and invertebrates. Even though individually they tend to act with moderate toxicity, their presence in complex mixtures with insecticides can substantially increase the overall ecological risk (Backhaus et al., 2012).

Risk Characterization

Great degrees of variation occurred among the studied groups of organisms due to the results of risk quotients (RQ) estimated through the evaluation of MECs with respect to PNECs (Figure 1; Table 2). Neonicotinoid insecticides contained the highest RQ values, ranging from 1.2 to 45, each of which generally points to medium-to-high-level risks of ecological concern for aquatic invertebrates (Malaj et al., 2014; Backhaus et al., 2012). Also, pyrethroid insecticides presented quite high risk levels, with RQs from 5 to 20, indicating episodic acute toxicity in the water column as well as chronic risks in the sediments (EFSA, 2013).

Organophosphate insecticides exhibited RQs from 0.4 to 16, site-specific exceeding the maximum value during peak months of application, thereby posing substantial risk for fish and aquatic invertebrates through time and hydrological conditions (Van den Brink et al., 2016). Triazine herbicides, conversely, showed RQ values between 0.025 and 0.6, and they thus presented low-moderate ecological risks chiefly concerning the inhibition of algal productivity and hence food-web-level processes.

Glyphosate and its metabolite AMPA could show RQs of 0.3 to 3.5, representing negligible-to-medium risk depending on the formulation and exposure conditions (Cui et al., 2020). With a range of 0.2 to 17 in individual RQs, azole fungicides were of particular concern when mixed with insecticides, such that their individual contribution drastically increased the level of cumulative risk (Backhaus et al., 2012).

Table 2. Detection frequency, mean concentrations, and dominant environmental compartments of major pesticide groups, highlighting exposure pathways (chronic water contamination, episodic sediment deposition, seasonal inputs, and widespread distribution) across study sites

Pesticide Group	Detection Frequency (%)	Mean Concentration (µg/L)	Dominant Medium
Neonicotinoids	68%	0.08	Water (chronic)
Pyrethroids	42%	0.01 (10 ng/L)	Sediment (episodic)
Organophosphates	30–40%	0.25	Water & runoff
Triazines	55%	0.25	Water (seasonal)
Glyphosate & AMPA	75%	1.2	Water (widespread)
Azoles	40%	0.15	Water (sub-lethal)

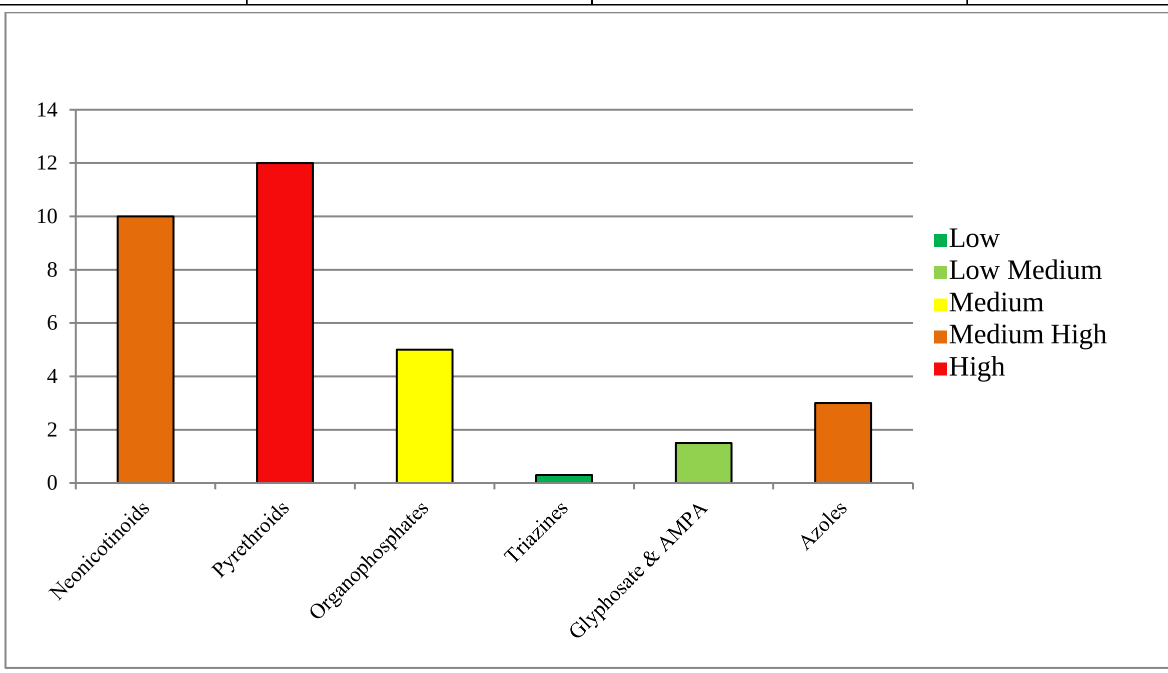

Figure 1. Median risk quotients (RQs) of major pesticide classes, showing risk categories from low (green) to high (red)

Mixture and Cumulative Risks

The summed risk quotients (ΣRQ) at different sites frequently exceeded 1.0, especially for aquatic invertebrates, affirming the inference of (Beketov et al., 2013) that, in combination, additive or synergistically increased risk is beyond a single-compound risk assessment (Figure 2). Mixture toxicity would sit best when azole fungicides co-occur with neonicotinoids or pyrethroids, stressing the view of Van den Brink et al., 2016; EFSA, 2013) that ecological risk assessment is best done for mixtures.

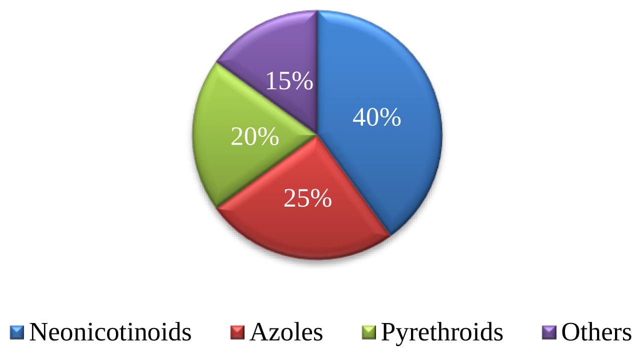

Figure 2. Proportional contribution of pesticide classes to cumulative risk quotients (ΣRQ) across sites

The proportional distribution of chemical groups implies that neonicotinoids lay claim to the largest share of ΣRQ (40%), followed by azoles (25%), pyrethroids (20%), and other pesticides (15%), suggesting insecticides as being most critical for overall ecological risk. The cumulative mixture contribution is consonant with monitoring data recording high detection frequencies and mean concentrations in the different environmental compartments (Table 2). In detail, glyphosate and AMPA recorded the highest detection frequency of 75% concerning widespread contamination of water bodies, whereas neonicotinoids registered 68% in surface waters, being chronically detected at all times. Triazines (55%) and organophosphates (30-40%) were also quite frequently detected, with pyrethroids (42%) and azoles (40%) in the sediments, and exposures are contributing episodically to the cumulative risk. These mixture contributions align well with the monitoring data that recorded high detection frequencies and mean concentrations in the environmental compartments (Table 2). Glyphosate and AMPA, in particular, showed the greatest detection frequency (75%) due to widespread water contamination, while neonicotinoids (68%) continued to be present at chronic levels in surface waters. Triazines (55%) and organophosphates (30–40%) were also common and, along with episodic sediment-associated pyrethroids (42%) and sublethal exposures to azoles (40%), contributed to the cumulative risk. This agrees with the classification of pesticides into chronic stressors (neonicotinoids, azoles), pulse stressors (pyrethroids, organophosphates), and stressors of ecosystem function (triazines, glyphosate) (Figure 3).

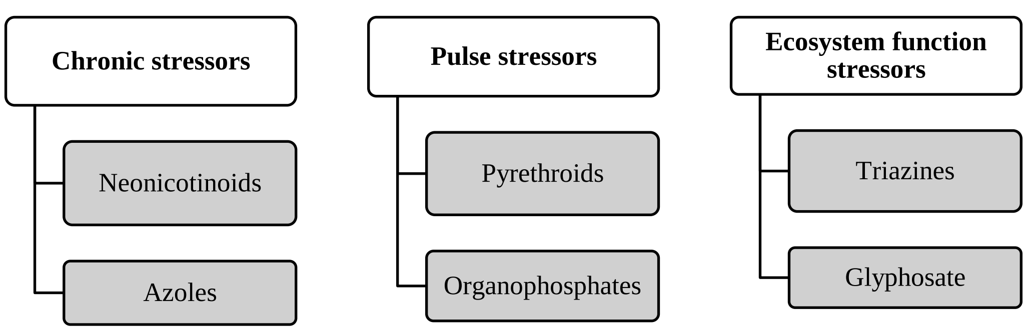

Figure 3. Categorisation of pesticide stressors based on exposure dynamics and ecological functions: chronic stressors (neonicotinoids, azoles), pulse stressors (pyrethroids, organophosphates), and ecosystem function stressors (triazines, glyphosate)

Key Patterns and Ecological Implications

The analysis of stressor dynamics pointed to differential exposure pathways and dynamics across the pesticide categories, suggesting an interaction of chronic and acute environmental pressures. In particular, neonicotinoids and azole fungicides are observed to behave as chronic stressors, maintaining baseline exposures over rather long periods. These problems particularly disrupt reproduction and the population dynamics of aquatic invertebrates and algae, thereby enabling changes in the community structure in the long term.

Pyrethroids and organophosphates, on the other hand, mainly act as pulse stressors, generating acute and short-term exposure events often related to rainfall and runoff. Episodic inputs can lead to exceptionally high concentrations for short durations, imposing massive mortalities, due to runoff incidences, on fish and benthic invertebrates.

So herbicides like triazines and glyphosate have an impact on ecosystems by inhibiting algal growth and reducing primary productivity. Beyond their direct toxicity to the organisms, the population decline of photosynthetic organisms propagates through the food web and may thus alter other trophic levels.

Another paramount ecological risk is reflected in mixture effects: multiple classes of pesticides are usually found simultaneously, and the cumulative exposure can exceed the ecotoxicological safety level. Hence, risk evaluation frameworks moving away from single-chemical evaluations toward multi-chemical assessments are direly needed (Van den Brink et al., 2016).

Discussion

Ecological risk assessment has shown that pesticide contamination of water is both very generalised and functionally diverse along the dynamics of stressors. Detection frequencies and average concentrations show how some chemical classes like neonicotinoids and glyphosates are leaders in chronic exposure pathways, while pyrethroids and organophosphates act mostly as episodic stressors coincident with rainfall application (Table 2). This has great coherence with the literature, identifying both continuous baseline exposures and acute pulses as contributing factors in ecological outcomes. Taxon-specific susceptibilities demonstrate that aquatic invertebrates are disproportionately affected, especially under neonicotinoid exposure, whereby chronic effects are expressed close to ecologically relevant thresholds. Similarly, episodic pyrethroid pulses in sediment and water present acute risks to benthic invertebrates and juvenile fishes, emphasising further the keen sensitivity of early life stages to pesticide stressors. While these herbicides maintain relatively lower acute toxicities, they are said to disrupt the process of primary production in the food-web structure and so bring about some indirect effects of chemical exposure at the ecosystem level. Further reinforcing elevated ecological pressure, risk quotients (RQ) for neonicotinoids and pyrethroids lie within medium to high levels, generally surpassing protective thresholds (Figure 1). Moreover, these risks are so magnified under mixture effects that summed risk quotients (ΣRQ) were found to be consistently above 1.0 across all sites (Figure 2). This clearly highlights how ecological risk assessment needs to consider mixtures because single-compound approaches allow an underestimation of the actual ecological burden. The implications continue on to community and ecosystem functions. The chronic stressors, such as neonicotinoids and azoles, interfere with reproduction and long-term population dynamics, of which the pulse stressors, such as pyrethroids and organophosphates, induce episodic mortalities. Other substances, including triazines and glyphosate, act on energy processing at the base of aquatic food webs (Figure 3). Such dynamics threaten the resilience of freshwater ecosystems, especially in a scenario with compounded agricultural intensification and climate-aided hydrological variability.

Conclusion

This research showed that aquatic ecosystems are subjected to complex, multi-chemical pesticide exposures, with distinctive contributions from chronic, episodic, and functional ecosystem stressors. Neonicotinoids and glyphosate appear to be more dominant in contributing to chronic contamination, whereas pyrethroids and organophosphates are more associated with the acute pesticide peaks of runoff origin. In terms of mixture analysis, the occurrence of combined pesticide effects above safety thresholds is quite frequent, thus emphasising the fallacy of single-compound regulatory frameworks.

In consequence, future assessments of pesticide risks should target: (i) integrated mixture toxicity assessment, (ii) long-term ecological studies recording the interplay of both baseline and episodic stressor dynamics, and (iii) ecological function endpoints into pesticide risk frameworks (e.g., primary productivity, benthic community integrity). Such a strengthening of ecological protection goals will require regulatory pathways to directly engage with cumulative and synergistic risks, allowing for pesticide management to be carried out on the agricultural side as well as on the side of freshwater ecosystem health.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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