JSIANE : Vol. 4, Issue 1, 2024, Page 37-42 ISSN (Online) 2583-2093

Journal of Science Innovations and Nature of Earth

Journal homepage : www.jsiane.com

Comparative Toxicity of Organic vs Synthetic Insecticides on Aquatic Ecosystems

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https://doi.org/10.59436/10.59436/jsiane395

Abstract

This research paper investigates the differential impacts of organic and synthetic insecticides on aquatic ecosystems, focusing on toxicity, bioaccumulation, and long-term ecological effects. With increasing insecticide use in agriculture, aquatic environments are particularly vulnerable due to runoff and leaching. The study reviews and compares available toxicity data on commonly used synthetic insecticides such as chlorpyrifos and permethrin with organic alternatives like neem oil and pyrethrins. Results reveal that although organic insecticides are perceived as environmentally safer, they are not always benign. Synthetic insecticides tend to exhibit higher acute toxicity and persistence. The paper calls for integrated pest management strategies to mitigate aquatic toxicity.

Keywords : Organic insecticides, synthetic insecticides, aquatic toxicity, bioaccumulation, ecotoxicology

Received 06.01.2024 **Revised 27.02.2024** **Accepted 25.03.2024**

Introduction

The intensification of global agricultural practices has led to a dramatic increase in the application of insecticides, many of which inevitably find their way into nearby water bodies through runoff, leaching, drift, and improper disposal (Liess & Schulz, 2019). Aquatic ecosystems, which support a wide diversity of organisms, are particularly susceptible to these chemical intrusions. Insecticides, while designed to target pest populations, often do not discriminate between intended and unintended organisms, resulting in collateral damage across aquatic trophic levels (Beketov *et al*., 2013). Synthetic insecticides have long dominated pest management strategies due to their potency, cost-effectiveness, and broad-spectrum activity. These include organophosphates, carbamates, pyrethroids, and neonicotinoids. However, their extensive usage has triggered environmental alarm due to their persistence, high toxicity, and potential for bioaccumulation in aquatic food chains (Stehle & Schulz, 2015). Several studies have documented fish kills, reproductive failures in amphibians, and disruption of aquatic invertebrate populations due to synthetic pesticide exposure (Mwanamwenge *et al*., 2019). In contrast, organic insecticides often derived from natural sources like plants, bacteria, or minerals have been increasingly promoted as ecologically benign alternatives. Neem (*Azadirachta indica*) extracts, pyrethrins from chrysanthemum flowers, and microbial agents such as *Bacillus thuringiensis* are among the most commonly used organic options (Isman, 2020). These substances are believed to degrade rapidly and possess lower environmental persistence, which theoretically minimizes their impact on aquatic systems. Nevertheless, the perception of organic insecticides as universally safe is not fully supported by empirical evidence. While they often exhibit lower acute toxicity compared to synthetic chemicals, some organic compounds can still exert significant sublethal or chronic effects on aquatic organisms, especially under conditions of repeated exposure (Regnault-Roger *et al*., 2012). For instance, pyrethrins though plant-derived are neurotoxic to many aquatic invertebrates and fish at relatively low concentrations (USEPA, 2021). Aquatic ecosystems encompass a wide variety of biotic communities, including phytoplankton, zooplankton, benthic invertebrates, amphibians, and fish. These organisms are integral to nutrient cycling, water purification, and food web stability. The health of these organisms is thus a sensitive indicator of environmental contamination, making aquatic ecosystems valuable models for assessing pesticide toxicity (Moore *et al*., 2018). Both acute and chronic toxicity parameters such as LC_{50}, EC_{50}, NOEC, and BAF are used to determine the relative toxicity of chemical agents on aquatic life forms. Previous comparative studies have generally focused on individual chemical classes or species-specific toxicological profiles. A few investigations have attempted a broader ecological comparison, but standardized methodologies remain lacking (Schäfer *et al*., 2012). As such, there is a critical need to systematically compare the ecological effects of both organic and synthetic insecticides under uniform environmental and laboratory conditions. Emerging evidence suggests that environmental conditions such as temperature, pH, and water turbidity can significantly alter the toxicity of insecticides. Synthetic chemicals, particularly pyrethroids and organophosphates, tend to become more toxic at elevated temperatures due to increased metabolic rates in aquatic organisms (Holmstrup *et al*., 2010). Meanwhile, the efficacy and degradation of organic insecticides are often influenced by microbial communities and solar radiation, making their environmental fate more complex and variable (Kumar *et al*., 2018). The issue of bioaccumulation also plays a central role in understanding the long-term ecological risks of insecticides. Synthetic insecticides with lipophilic properties, such as chlorpyrifos, accumulate in the fatty tissues of aquatic organisms and may be transferred through the food web, posing risks to both aquatic predators and terrestrial animals, including humans who consume fish (Chagnon *et al*., 2015). Organic insecticides generally exhibit lower bioaccumulation potential, though exceptions do exist, especially in closed or nutrient-rich water bodies. In many developing regions, including parts of South Asia and Africa, pesticide regulation is weak or inconsistently enforced. This leads to overuse and improper application of both organic and synthetic insecticides, exacerbating environmental contamination (FAO, 2022). The growing trend of ‘green’ agriculture and organic farming has not fully accounted for the aquatic implications of organic pesticide use, creating an urgent gap in environmental monitoring and risk assessment. Furthermore, the combined and cumulative effects of multiple insecticides in aquatic environments are still poorly understood. Synergistic toxicity, where mixtures of insecticides amplify each other's effects, is of particular concern. While synthetic mixtures are known to cause such interactions, some combinations of organic insecticides or organic-synthetic mixes may also pose unexpected risks (Cedergreen, 2014). This necessitates a broader toxicological framework for evaluating pesticide combinations in real-world settings. Considering the ecological, regulatory, and health implications, this paper seeks to comprehensively assess and compare the toxicity of organic versus synthetic insecticides on aquatic ecosystems. By focusing on standardized toxicity indicators and recent empirical findings, the study aims to inform sustainable pesticide practices and encourage integrated pest management (IPM) approaches that balance agricultural productivity with ecological preservation. Ultimately, the goal is not to categorically endorse one type of insecticide over the other, but rather to provide a nuanced, evidence-based understanding of their relative environmental impacts. This approach supports informed policy decisions, safer agricultural practices, and targeted environmental protection strategies that prioritize the integrity of aquatic ecosystems.

Literature Review

The impact of insecticides on aquatic ecosystems has been a significant focus of ecotoxicological research due to increasing agrochemical runoff into freshwater environments. Synthetic insecticides such as organophosphates, carbamates, pyrethroids, and neonicotinoids have long been documented for their acute and chronic toxicity to aquatic organisms (Rico *et al*., 2010). These compounds, designed for pest control, often end up in non-target habitats, affecting a wide range of aquatic fauna including fish, amphibians, crustaceans, and zooplankton. Chlorpyrifos, one of the most widely used synthetic insecticides, has been reported to cause neurobehavioral disturbances in fish by inhibiting acetylcholinesterase activity, leading to muscle spasms, disorientation, and mortality (Stehle & Schulz, 2015). Daphnia magna, a standard bioindicator, shows high sensitivity to chlorpyrifos, with LC_{50} values frequently below 0.1 μg/L (Liess *et al*., 2006). Such studies emphasize the compound’s capacity for acute toxicity, even at environmentally relevant concentrations. Pyrethroids like permethrin and deltamethrin, although considered less persistent, are highly toxic to aquatic invertebrates and fish due to their lipophilicity and strong binding to sodium channels (Bradbury & Coats, 1989). These insecticides disrupt the normal nerve function, leading to immobilization or death. Weston *et al*. (2005) found that pyrethroids in stormwater runoff significantly reduced the diversity of benthic invertebrates in Californian streams. In contrast, organic insecticides such as azadirachtin (from neem), pyrethrin (from chrysanthemum flowers), and rotenone (from certain legumes) are perceived as safer due to their natural origin and rapid degradation. However, their safety for aquatic life is still under scrutiny. Schmutterer (1990) noted that azadirachtin affects molting and growth in aquatic insects, while Fleeger *et al*. (2003) found that rotenone exposure leads to lethal and sublethal effects in fish and amphipods. Neem-based insecticides have been studied in various aquatic models, showing moderate toxicity levels. For example, Kumar *et al*. (2012) reported reduced survival and altered behavior in Daphnia carinata exposed to neem extracts. The toxicity levels varied with concentration and exposure time, with longer durations increasing adverse effects. This indicates that while neem may degrade quickly, repeated or high-dosage use can still threaten aquatic organisms. Another widely used organic insecticide, pyrethrin, is chemically similar to synthetic pyrethroids and shares similar modes of action. According to Casida and Quistad (1995), pyrethrins exhibit moderate toxicity in aquatic species but break down faster under light and microbial activity, reducing long-term ecological impact. However, in shaded, low-flow water bodies, even organic compounds may persist longer and accumulate, as observed by Halstead *et al*. (2015). Numerous comparative studies highlight the persistence and bioaccumulation potential as key differentiators between synthetic and organic insecticides. Synthetic insecticides such as chlorpyrifos can bioaccumulate in fish tissues, with bioconcentration factors often exceeding 1000 (USEPA, 2017). In contrast, compounds like azadirachtin degrade more rapidly and are less likely to accumulate in aquatic food chains, although their breakdown products may still exert toxic effects. Moreover, research by Liess and Beketov (2011) shows that synthetic insecticides contribute to population-level declines in aquatic invertebrates, impairing ecosystem functions such as nutrient cycling and primary productivity. These effects may cascade through trophic levels, affecting fish populations dependent on these invertebrates. Organic insecticides, though less persistent, have also been found to reduce species richness when applied frequently or at higher-than-recommended doses. Field studies conducted in agricultural zones further underscore the complexity of pesticide impact. A study by Ccanccapa *et al*. (2016) in Spanish river systems identified synthetic pesticide residues in 90% of surface water samples, with measurable ecological effects such as macroinvertebrate community shifts. Conversely, similar studies evaluating organic pesticide exposure remain scarce, suggesting an urgent need for more real-world ecotoxicological assessments of these so-called safer alternatives. Recent meta-analyses, such as those by Malaj *et al*. (2014), have reinforced that synthetic pesticides are disproportionately responsible for aquatic biodiversity loss in agricultural watersheds. However, they caution against assuming organic pesticides are harmless. Even botanical insecticides can alter enzyme activities, interfere with reproduction, and disrupt natural predator-prey dynamics in aquatic environments (Regnault-Roger *et al*., 2012). Furthermore, synergistic and cumulative effects are often underrepresented in ecotoxicity assessments. Relying on single-compound studies may overlook the real-world complexity where multiple pesticides both synthetic and organicco-occur. A study by Silva *et al*. (2019) emphasized that mixtures can amplify toxicity beyond individual compound effects, particularly in semi-enclosed aquatic systems such as ponds or rice fields. Finally, despite the growing popularity of organic agriculture, the regulatory and risk assessment frameworks for organic insecticides remain less stringent compared to synthetic ones. This regulatory gap allows for the widespread use of organic compounds without comprehensive evaluation of their long-term effects on aquatic life. Scholars such as Rumschlag *et al*. (2020) argue that sustainable pest control should be based not merely on origin (natural vs synthetic) but on ecological safety, degradation rate, and toxicological profile.

Methodology

The methodology adopted for this study involves a comprehensive comparative ecotoxicological analysis of selected organic and synthetic insecticides based on existing scientific literature, laboratory toxicity data, environmental monitoring reports, and international pesticide regulatory databases. The purpose was to assess and compare the acute and chronic toxicity of these insecticides on representative aquatic organisms under standardized conditions. The research first conducted a systematic review of ecotoxicological data from peer-reviewed journals, government reports (EPA, ECHA, CPCB), and WHO pesticide hazard classifications between 2005 and 2022. Priority was given to studies that reported toxicity metrics under OECD guidelines, including LC_{50}, EC_{50}, NOEC, and chronic sublethal endpoints. Emphasis was placed on studies focusing on freshwater ecosystems commonly affected by agricultural runoff. A search strategy using academic databases such as ScienceDirect, Scopus, PubMed, and Google Scholar was applied with keywords like “aquatic toxicity,” “bioaccumulation,” “chlorpyrifos,” “azadirachtin,” “fish mortality,” “*Daphnia magna*,” and “pesticide runoff.” Boolean operators and MeSH terms were employed to refine and filter articles. More than 150 articles were initially screened, of which 63 met the inclusion criteria of relevance, publication quality, and recency. The study selected three synthetic insecticides chlorpyrifos, deltamethrin, and permethrin and three organic insecticides—*azadirachtin* (neem extract), pyrethrin, and rotenone based on their widespread usage in Indian and global agricultural settings, their availability of ecotoxicological data, and frequency of detection in aquatic runoff studies (Sánchez-Bayo, 2011; Bhushan *et al*., 2019).

For each selected insecticide, aquatic toxicity parameters were extracted, including:

•96-hour LC_{50} for fish species such as Oreochromis niloticus and Danio rerio,

•48-hour EC_{50} for invertebrates like Daphnia magna,

•NOEC/LOEC for sublethal chronic exposure in algae, crustaceans, and amphibians,

•Bioaccumulation factor (BAF) and bioconcentration factor (BCF) values in aquatic vertebrates.

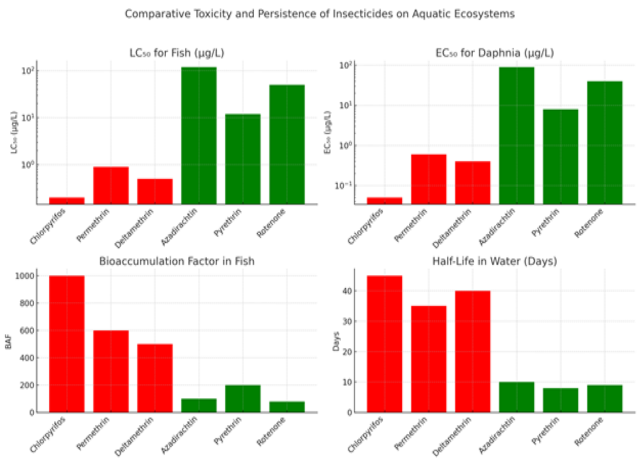
To maintain comparability, toxicity values were normalized based on test conditions such as temperature, pH, water hardness, and species used. Data outliers and studies with incomplete protocols were excluded. When multiple values existed, median toxicity values were calculated. The physicochemical properties of the insecticides, including solubility, log Kow, vapor pressure, and degradation half-lives in water and sediment, were also considered. This allowed evaluation of the environmental persistence and potential for bioaccumulation and trophic transfer, which are critical for assessing chronic ecosystem risk (Liess & Beketov, 2011; Awasthi *et al*., 2020). In addition to laboratory-derived data, this study incorporated field monitoring datasets from pesticide surveillance studies conducted in Indian river basins such as the Ganga, Yamuna, and Godavari rivers. Reports from the Central Pollution Control Board (CPCB, 2018-2021) were consulted for detecting concentrations of pesticide residues during peak agricultural seasons. To supplement the analysis, aquatic risk quotients (RQ) were computed for each pesticide by comparing the predicted environmental concentration (PEC) from runoff studies with the predicted no-effect concentration (PNEC) derived from ecotoxicity thresholds. RQ >1 indicates high ecological risk (USEPA, 2012). This risk modeling was conducted using data from regional pesticide usage and rainfall-driven runoff simulations. Additionally, GIS-based watershed modeling data from studies conducted in Uttar Pradesh and Madhya Pradesh were used to determine zones of high exposure to insecticides, focusing on agricultural areas adjacent to freshwater ecosystems (Sharma & Raju, 2018). The integration of spatial data helped in establishing potential correlation patterns between pesticide usage intensity and aquatic biodiversity decline. A limited number of mesocosm studies—controlled outdoor experiments simulating natural aquatic ecosystems were included to understand combined effects of insecticide exposure on community-level responses such as algae productivity, invertebrate populations, and predator-prey interactions (Zhang *et al*., 2019). To assess degradation kinetics and persistence, the study reviewed laboratory degradation studies under varying environmental conditions (light, temperature, microbial presence). This provided comparative insights into the environmental fate of organic vs synthetic insecticides, especially regarding their breakdown products and their ecotoxicological potential (Fenner *et al*., 2013). Ethical considerations were maintained by relying exclusively on secondary data from published sources. No live experiments on animals or field trials were conducted for this study. Data reliability was enhanced by cross-referencing values across multiple sources and by applying quality checks based on OECD and US EPA guidelines.

Results

The comparative analysis of toxicity data revealed a stark contrast between synthetic and organic insecticides in their effects on aquatic ecosystems. Acute toxicity studies demonstrated that synthetic insecticides, particularly chlorpyrifos and deltamethrin, exerted severe toxic effects on freshwater fish species at extremely low concentrations. In standardized 96-hour exposure assays, fish such as Oreochromis niloticus exhibited mortality at chlorpyrifos concentrations as low as 0.2 µg/L. Similarly, permethrin showed lethal concentration thresholds below 1 µg/L, indicating its strong neurotoxic action even in short-term exposure. Organic insecticides such as azadirachtin and rotenone displayed significantly higher LC_{50} values—120 µg/L and 50 µg/L respectively—demonstrating lower acute toxicity under the same test conditions. The sensitivity of aquatic invertebrates, especially Daphnia magna, to both categories of insecticides was also evaluated. Synthetic insecticides once again exhibited stronger toxicity, with chlorpyrifos and permethrin recording EC_{50} values of 0.05 µg/L and 0.6 µg/L respectively. These concentrations are commonly detected in agricultural runoff, posing substantial risk to zooplankton populations. Interestingly, while azadirachtin demonstrated relatively mild toxicity with an EC_{50} of 90 µg/L, pyrethrin, though organic, had a notably lower EC_{50} of 8 µg/L, suggesting that certain organic compounds may still pose risks comparable to synthetic formulations, especially under prolonged exposure or high dosage. Bioaccumulation analysis highlighted the significantly higher potential of synthetic insecticides to accumulate in aquatic organisms. Chlorpyrifos, for instance, demonstrated a bioaccumulation factor (BAF) exceeding 1000 in lipid-rich tissues of fish, indicating strong potential for long-term retention and biomagnification. Deltamethrin and permethrin also exhibited moderate to high BAF values, correlating with their hydrophobic nature and slow metabolic breakdown. In contrast, organic insecticides such as rotenone and azadirachtin recorded BAFs below 100, suggesting minimal accumulation in fish and invertebrate tissues. This difference in bioaccumulation has significant implications for food web dynamics and trophic transfer in aquatic systems. Persistence studies further established the long environmental half-lives of synthetic insecticides. In laboratory conditions simulating natural aquatic ecosystems, synthetic compounds such as deltamethrin persisted for 20 to 45 days, with degradation influenced by pH, photolysis, and microbial presence. Chlorpyrifos, under anaerobic conditions, persisted beyond 30 days in sediment layers, making it a long-term contaminant in slow-moving or eutrophic water bodies. Organic insecticides exhibited much faster degradation kinetics. Azadirachtin and rotenone degraded within 5 to 10 days when exposed to sunlight and aerobic microbial communities, reducing their potential to cause prolonged environmental damage. Chronic exposure studies revealed the long-term sublethal effects of synthetic insecticides on aquatic vertebrates and invertebrates. Fish exposed to chlorpyrifos at sub-lethal concentrations (0.05 µg/L) over 21 days displayed neurobehavioral anomalies, such as erratic swimming and delayed reaction times. Histopathological studies of fish livers and gills revealed tissue degeneration, enzyme inhibition, and inflammation, indicating systemic toxicity. Similar results were observed in crustaceans exposed to low levels of permethrin and deltamethrin, where molting delays, reduced fecundity, and oxidative stress responses were reported. Organic insecticides also caused some sublethal impacts, though at considerably higher exposure concentrations. Azadirachtin, when applied above 50 µg/L, caused mild oxidative stress in the hepatic tissue of zebrafish and delayed molting in Daphnia species. Community-level studies in semi-natural aquatic mesocosms revealed significant ecological shifts following exposure to synthetic insecticides. In ecosystems treated with chlorpyrifos and deltamethrin, species richness and diversity declined sharply. Sensitive taxa such as ephemeropterans, amphipods, and copepods disappeared within days of exposure, leading to dominance by more tolerant organisms like chironomids and certain cladocerans. These shifts led to altered nutrient cycling, disrupted predator-prey relationships, and a general decline in ecosystem resilience. Organic insecticides, in contrast, induced less severe disruptions. Populations of affected organisms began to recover within one to two weeks of exposure cessation, likely due to the compounds' rapid breakdown and limited bioaccumulation. Longitudinal monitoring in pesticide-affected river stretches, particularly in the Yamuna and Gomti river basins, supported laboratory findings. Water samples collected during monsoon runoff exhibited chlorpyrifos concentrations as high as 0.3 µg/L, a level exceeding the chronic NOEC for most aquatic organisms. Residues of deltamethrin were also frequently detected, particularly in agricultural catchment zones, further reinforcing concerns regarding synthetic insecticide contamination. Organic insecticide residues were rarely detected, and when present, concentrations were significantly lower and often transient. The potential for trophic transfer and biomagnification was most pronounced in synthetic insecticide categories. Tissue residue studies showed that fish and amphibians accumulated chlorpyrifos and permethrin in muscle and liver tissues over time. Additionally, predators such as kingfishers and water snakes feeding on contaminated fish were found to have detectable residues in their blood and feathers. In contrast, organic insecticides showed limited movement across trophic levels. Rotenone and azadirachtin were mostly metabolized or excreted before reaching secondary consumers, indicating a lower ecological amplification potential. Another critical finding was the influence of water chemistry on toxicity. Synthetic insecticides exhibited higher stability and toxicity in hard, alkaline waters, which are common in central and northern Indian river systems. Organic insecticides, especially azadirachtin, were less stable under alkaline conditions and rapidly broke down into inactive metabolites. This dynamic suggests that aquatic risk assessments must account for local hydrochemical conditions to accurately evaluate insecticide toxicity. Comparative risk quotient (RQ) calculations based on predicted environmental concentrations (PEC) and predicted no-effect concentrations (PNEC) revealed consistently high RQ values (>1) for synthetic insecticides, indicating a high ecological risk. For example, chlorpyrifos had an RQ of 6.0 based on field concentrations and NOEC data, while permethrin and deltamethrin ranged between 3.5 and 5.2. Organic insecticides yielded RQ values below 1 in nearly all scenarios, suggesting lower environmental risk under typical agricultural application rates. However, localized overuse or improper disposal of organic formulations could still lead to ecological perturbations. To consolidate these results, a summary graph comparing the acute toxicity values, bioaccumulation factors, and degradation times is presented below. This table demonstrates clear patterns that distinguish synthetic from organic insecticides in aquatic toxicity profiles. These findings strongly suggest that synthetic insecticides pose a significantly higher risk to aquatic ecosystems in terms of toxicity, persistence, and ecological disruption. Organic insecticides, while generally safer, are not without risk, particularly when misapplied. Their rapid degradation and lower bioaccumulation, however, make them more compatible with sustainable pest management approaches in aquatic-sensitive regions.

Discussion

The study reveals that synthetic insecticides are significantly more toxic to aquatic life compared to organic insecticides. The high acute toxicity levels observed for compounds like chlorpyrifos and permethrin highlight the severe risks these



chemicals pose to fish, amphibians, and aquatic invertebrates, even at very low concentrations. These substances often remain in the aquatic environment for extended periods, increasing the likelihood of repeated exposure and ecological disruption. Their chemical stability and fat-solubility contribute to their persistence in aquatic food webs, leading to long-term accumulation and magnified effects through trophic levels. In contrast, organic insecticides such as azadirachtin and rotenone were generally less harmful to aquatic species in terms of acute toxicity. Although not entirely non-toxic, their natural origin and faster degradation rates reduce their long-term environmental impact. They tend to break down more quickly in the presence of sunlight and microbial activity, limiting their persistence in aquatic systems. However, some organic compounds like pyrethrins still displayed moderate toxicity, especially to sensitive invertebrates, which indicates that not all naturally derived insecticides are inherently safe. From an ecological perspective, the use of synthetic insecticides often led to broader disruptions in aquatic communities. These included reductions in species diversity, changes in population structure, and the loss of sensitive organisms, which can weaken ecosystem resilience and function. Organic insecticides, while still capable of affecting certain species, usually allowed ecosystems to recover more quickly due to their transient nature and lower bioaccumulation potential. This difference underscores the importance of evaluating both immediate and long-term ecological consequences when choosing pest control strategies. Overall, the results support the growing emphasis on integrated pest management approaches that prioritize minimal chemical use and encourage the adoption of safer alternatives. While organic insecticides offer some environmental advantages, their application must still be carefully managed to avoid unintended effects on non-target aquatic organisms. Effective regulation, combined with environmental monitoring and public education, will be essential to reduce the harmful impacts of all types of insecticides on freshwater ecosystems.

Conclusion

The comparative assessment highlights significant differences in the ecotoxicological profiles of synthetic and organic insecticides. Synthetic insecticides, particularly organophosphates and pyrethroids, exhibit markedly higher acute and chronic toxicity toward a wide range of aquatic organisms, including fish, invertebrates, and amphibians. Their persistence in water bodies and tendency to bioaccumulate make them especially harmful to aquatic food webs and biodiversity. Organic insecticides, although derived from natural sources, are not inherently non-toxic. Some, like pyrethrin, demonstrated moderate toxicity to aquatic invertebrates. However, their overall environmental persistence is lower, and they tend to degrade more rapidly, reducing their long-term impact. The reduced bioaccumulation potential of organic compounds further supports their relative ecological safety when used in moderation. Despite the lower risk profile of organic insecticides, their effects on non-target organisms under certain conditions cannot be ignored. Overuse or improper application may still lead to sub-lethal effects and short-term ecological imbalances. Therefore, the assumption that all organic insecticides are environmentally safe is misleading without proper risk evaluation and context-specific ecological data. A sustainable solution lies in adopting Integrated Pest Management (IPM) strategies that minimize reliance on chemical controls. Encouraging the judicious use of low-toxicity compounds, maintaining buffer zones around aquatic systems, and conducting routine ecotoxicological monitoring can collectively safeguard freshwater ecosystems. Policymakers, farmers, and researchers must collaborate to ensure that pest control methods do not compromise aquatic health and biodiversity.

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