



## ASSESSMENT OF LAMBDA-CYHALOTHRIN BIOACCUMULATION IN CYPRINUS CARPIO AND ITS ECOTOXICOLOGICAL SIGNIFICANCE

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### ABSTRACT

Lambda-cyhalothrin is a commonly utilized synthetic pyrethroid insecticide that has known aquatic organism toxicity, but little evidence exists supporting its bioaccumulation with genetic damage in fish especially *Cyprinus carpio*. The ecotoxicological effects of lambda-cyhalothrin on freshwater fish were evaluated based on data retrieved from the U.S. EPA ECOTOX Knowledgebase under the headings of biological effects, tissue-specific responses, genetic effects, exposure duration and bioaccumulation. The fish-result data set comprised 465 fish-result records, most of which were for mortality, biochemical alterations, enzyme-related effects, and genetic responses. Of these, 75 were deemed as genetic effects (DNA damage, micronuclei and nuclear abnormalities, as well as other mitotic changes). Genetic response was reported after several hours up to 192 h (8 days), and liver, erythrocytes, brain, gills, muscle and kidney were the main response sites. There were only two records of direct bioaccumulation, 674.3 and 620.6 L/kg, for *Danio rerio*. The records included a total of ~48 h of exposure and 72 h of observation, which would show measurable short-term bioconcentration. There was no direct ECOTOX record relating the exposure to lambda-cyhalothrin, bioaccumulation and/or DNA damage in the Comet-assay test for *C. carpio*. The results indicate a lack of species-specific knowledge and stress the need to undertake common-carp studies that combine tissue-residue analysis, BCF/BAF estimation, exposure-duration assessment, and standardized endpoints for genotoxicity to facilitate improved ecological risk assessment.

**Keywords:** *Cyprinus carpio*; Lambda cyhalothrin; Bioaccumulation; toxicity

### Introduction

The use of pesticides in agriculture is widespread, and concern has arisen as to the potential for unintended entry into freshwater environments with potential harmful effects on non-target aquatic organisms. Both acute and chronic exposure scenarios can be created for fish, as pesticide residues can enter rivers, ponds,

lakes, and aquaculture systems via leaching, spray drift, and agricultural runoff and drainage. This type of contamination can affect physiological, biochemical, cellular and molecular processes and thus individual health and ecological stability of aquatic systems. Recent assessments on pesticide exposure in aquaculture fish have emphasized that pesticides have the potential to impact fish health and the quality of the environment, underscoring the importance of comprehensive environmental monitoring and ecotoxicological evaluation (Burch et al., 2025). Moreover, pesticide transformation products can be biologically active or toxic which makes environmental risk assessment in aquatic ecosystems more complex (Ghosh & Sarower, 2024). Agrochemical contamination is thus becoming a critical environmental stressor to fish in agricultural and semi-agricultural freshwater ecosystems (Iqbal et al., 2025).

Lambda-cyhalothrin is a synthetic pyrethroid insecticide, which is highly biologically active and may be toxic to aquatic organisms, and so is of ecotoxicological concern among insecticides commonly used. Zebrafish studies revealed high acute toxicological risks of the lambda-cyhalothrin formulations, suggesting that fish may be very susceptible to this insecticide under specific exposure conditions (Huang et al., 2022). Its toxicity is not limited to fish; effects have also been studied in freshwater mussels, highlighting the potential for the adverse effects of lambda-cyhalothrin to extend beyond just fish species (TESSI, 2023). Pesticide exposure can also interfere with critical enzymatic and neurological functions; in vitro studies of the most used pesticides have shown inhibitory effects on enzymes involved in neurotoxicity, which suggests that pesticide exposure causing damage may be multifaceted (Martins-Gomes et al., 2022; AL-Salih et al., 2026).

One of the major issues with hydrophobic pesticides is the potential for them to bioaccumulate in aquatic species. After uptake via the gills, gastrointestinal tract or other routes of exposure, pesticides can be distributed between tissues and stored depending on the pesticide's physical-chemical properties, exposure conditions, and the metabolic capacity of the organism. Studies have shown bioaccumulation of pyrethroid insecticides like deltamethrin in freshwater fish, highlighting the potential for pyrethroids to accumulate in biological tissues, thereby exposing fish to the insecticides over extended periods (Hazarika et al., 2024). Likewise, studies that have integrated pesticide toxicity with the measurement of tissue-bioaccumulation have demonstrated that the accumulation and adverse impacts can happen together and should not be used as an exclusive indicator of environmental exposure – tissue burden should be measured in parallel with external concentrations of pesticides (Jiang et al., 2022). Hence, fish have been emerging as valuable bioindicators of biochemical and tissue toxicity caused by pesticides, as their biological response can give valuable insights into the ecological impact of aquatic contamination (Sohail, 2025; Moghadam et al., 2025).

The common carp, *Cyprinus carpio*, is a species of great value for the assessment of toxicity induced by pesticides, as it can give information of organism-level and molecular responses to the chemical stress in

an organism. One of the most critical is DNA toxicity, as genetic damage caused by pesticides can happen at nonlethal exposures before death or at subtoxic concentrations before any significant morphological damage occurs. The Comet test, also known as single-cell gel electrophoresis assay, is a sensitive tool to measure cell level DNA strand damage, which has been successfully applied to *Cyprinus carpio* in the field of pesticide-genotoxicity assays. The micronucleus test in combination with the Comet assay was previously shown to be effective in quantifying genotoxic responses of common carp to pesticide exposure and was proposed as an aquatic biomonitoring tool (Turan & Ergenler, 2022).

Despite the growing evidence regarding the toxicity of lambda-cyhalothrin in aquatic organisms, information integrating its bioaccumulation, tissue-specific responses, exposure duration, and genetic effects in fish remains limited, particularly for *Cyprinus carpio*. Therefore, the present study aimed to evaluate the available ecotoxicological evidence for lambda-cyhalothrin in freshwater fish using data obtained from the U.S. EPA ECOTOX Knowledgebase. Emphasis was placed on the distribution of toxicological endpoints, biological-effect categories, tissue and response sites, genetic and DNA-related effects, exposure and observation durations, and available bioconcentration data. The assessment also examined whether direct evidence exists linking lambda-cyhalothrin exposure, bioaccumulation, and genetic damage in *C. carpio*, thereby identifying species-specific knowledge gaps relevant to future biomonitoring and ecotoxicological research.

### **Research objectives:**

- To evaluate the temporal characteristics of lambda-cyhalothrin effects in fish by examining reported exposure and observation durations and expressing relevant observation periods in days where appropriate.
- To assess the available evidence for lambda-cyhalothrin bioaccumulation in fish using reported bioconcentration-factor (BCF) records and their associated exposure conditions.
- To determine whether direct evidence exists for lambda-cyhalothrin bioaccumulation and genetic damage in *Cyprinus carpio* and to identify the major data gaps requiring future species-specific investigation.

## **2. Materials and Methods**

### **2.1 Study Design**

A retrospective, database-based ecotoxicological assessment was carried out to compare the effects of lambda-cyhalothrin in freshwater fish, focusing on the genetic effects, the duration of exposure, the tissue-specific responses and the bioaccumulation of lambda-cyhalothrin. The data are from the U.S. Environmental Protection Agency (EPA) ECOTOX Knowledgebase. The study also considered whether

there was direct evidence of bioaccumulation and damage to the genetic material of *Cyprinus carpio* due to lambda cyhalothrin.

## **2.2 Data Source and Database Screening**

The U.S. EPA ECOTOX Knowledgebase was used as the primary source of ecotoxicological data (EPA, 2026). Using the Chemical Abstracts Service (CAS) number 91465-08-6, records for lambda-cyhalothrin were found. The retrieved data were then limited to fish to provide species-specific test and result data pertinent to aquatic ecotoxicology.

## **2.3 Data Selection and Extraction**

Fish records containing lambda-cyhalothrin were scanned for information and the data for fish species, toxicological endpoint, biological-effect category, response site or tissue, exposure concentration, exposure duration, observation duration, and reported effect were extracted. Genotoxicity and bioaccumulation data were investigated in separate record sets to describe the evidence available for both genotoxicity and bioaccumulation.

## **2.4 Classification of Ecotoxicological Endpoints and Effects**

The extracted records were grouped based on the ecotoxicological end point reported, such as LOEC, NOEC, LC50, LOEL, NOEL, EC50, LC10, LC90, and bioconcentration factor (BCF). Biological effects were classified under the following major categories: mortality; biochemical effects; enzymatic effects; genetic effects; physiological effects; histological effects; developmental effects; cellular effects; behavioural effects; morphological effects; hormonal effects; accumulation effects.

## **2.5 Tissue and Response-Site Assessment**

The available information on tissues and biological compartments which were most commonly evaluated after lambda-cyhalothrin exposure was extracted. Responses in liver, erythrocytes, brain, gonads, gills, muscle, kidney, blood and whole organism were major sites of response. Records with no reported/tipped tissue information were kept as “not reported” and “not coded” respectively.

## **2.6 Genetic and DNA-Related Effects**

Records identified as genetic effects were analysed separately to define the extent of available evidence for genetic toxicity of lambda-cyhalothrin in fish. The following responses were extracted: DNA damage, micronuclei, nuclear abnormalities, measurements of DNA relatedness, and other reported abnormalities of the mitoses. The following effects were interpreted in the context of species, exposure site, exposure conditions and observation time.

## **2.7 Exposure and Observation Duration**

Fish data were extracted from the records available to delineate the amount of time that the organism was exposed and the amount of time that it was observed to assess the time periods during which biological and genetic effects were measured. Time durations reported in hours were changed to days (where applicable) (24 h = 1 day), and those reported in days were not changed. Age in developmental terms (e.g., days post-fertilization) were left as per original definition to not mislead the reader. The time period of observation was defined here as the time when an effect was measured or reported and not as the actual time of onset of the biological response.

## **2.8 Bioaccumulation Assessment**

Direct accumulation/direct bioconcentration records were screened separately. Where available, the following were taken from the BCF: available BCF, fish species, exposure concentration, exposure duration, observation period, and steady-state status. Since a limited amount of data for each direct BCF record was available, the bioaccumulation results were not used to develop concentration-response relationships for each species.

## **2.9 Assessment of Evidence for *Cyprinus carpio***

The ECOTOX records were searched to find out if lambda-cyhalothrin studies are available for *Cyprinus carpio*. Records that combined a measurement of bioaccumulation with a genetic/effects endpoint or a Comet assay were given special consideration. This lack of records was deemed not to be evidence that there were no biological effects but rather a species-specific evidence gap.

## **2.10 Data Analysis**

The data obtained were analysed descriptively. The major ecotoxicological endpoints, response sites, genetic-effect records, and biological-effect categories have been calculated as frequencies and percentages. The durations of exposure and observation were expressed in both hours and/or days and the few direct bioaccumulation observations were reported separately. Since the records were from diverse studies using different species of fishes exposed to different conditions, with varying endpoints and experimental designs, no meta-analysis or inferential comparison of the experimental treatment groups was conducted.

## **2.11 Quality Control and Data Interpretation**

Any records that were inconsistent with respect to chemical identity, species classification, endpoint, effect category, response site, exposure duration and observation duration were not interpreted. The information which was missing or coded was kept as is and not estimated. The results were discussed based on the available ECOTOX evidence base, which is limited in both the small number of direct bioaccumulation data and the lack of a direct data set for *C. carpio*–lambda-cyhalothrin.

## **2.12 Ethical Considerations**

The authors did not conduct experiments with live animals to collect data for the present study, only previously reported data from the U.S. EPA ECOTOX Knowledgebase were used. Thus, for the present secondary data analysis, animal ethical approval was not necessary.

### 3.Results

#### 3.1 Ecotoxicological Endpoints of Lambda-Cyhalothrin in Fish

The ECOTOX records were limited to fish and 465 result records were then available for evaluating the ecotoxicological responses associated with lambda-cyhalothrin. There were a variety of typical toxicity and sublethal endpoints available in the records. The largest number of reports were for LOEC (136 [29.25%]), followed by NOEC (131 [28.17%]). The 50 records reporting LC50 values (10.75%) did not have a specifically coded endpoint, compared to 47 records (10.11%). LOEL and NOEL accounted for 24 (5.16%) and 23 (4.95%) records, respectively. Other endpoints reported were NR-ZERO, EC50, NR-LETH, LC10 and LC90. Compared to these traditional toxicity assessments, however, very few records (0.43%) were for direct bioconcentration-factor measurements, and as such quantitative bioaccumulation data for lambda-cyhalothrin are limited for fish. Table 1 gives the distribution of primary ecotoxicological endpoints (fish) for lambda-cyhalothrin. Figure 1 shows the predominance of LOEC and NOEC for the other ecotoxicological endpoints.

**Table 1. Major ecotoxicological endpoints reported for lambda-cyhalothrin in fish**

| Endpoint | Interpretation                         | Records, n | %     |
|----------|----------------------------------------|------------|-------|
| LOEC     | Lowest observable effect concentration | 136        | 29.25 |
| NOEC     | No-observable-effect concentration     | 131        | 28.17 |
| LC50     | 50% lethal concentration               | 50         | 10.75 |
| NR       | Not reported                           | 47         | 10.11 |
| LOEL     | Lowest observable effect level         | 24         | 5.16  |
| NOEL     | No-observable-effect level             | 23         | 4.95  |
| NR-ZERO  | 0% mortality/100% survival             | 12         | 2.58  |
| EC50     | 50% effective concentration            | 9          | 1.94  |
| NR-LETH  | 100% mortality                         | 8          | 1.72  |

|      |                          |   |      |
|------|--------------------------|---|------|
| LC10 | 10% lethal concentration | 7 | 1.51 |
| LC90 | 90% lethal concentration | 5 | 1.08 |
| BCF  | Bioconcentration factor  | 2 | 0.43 |

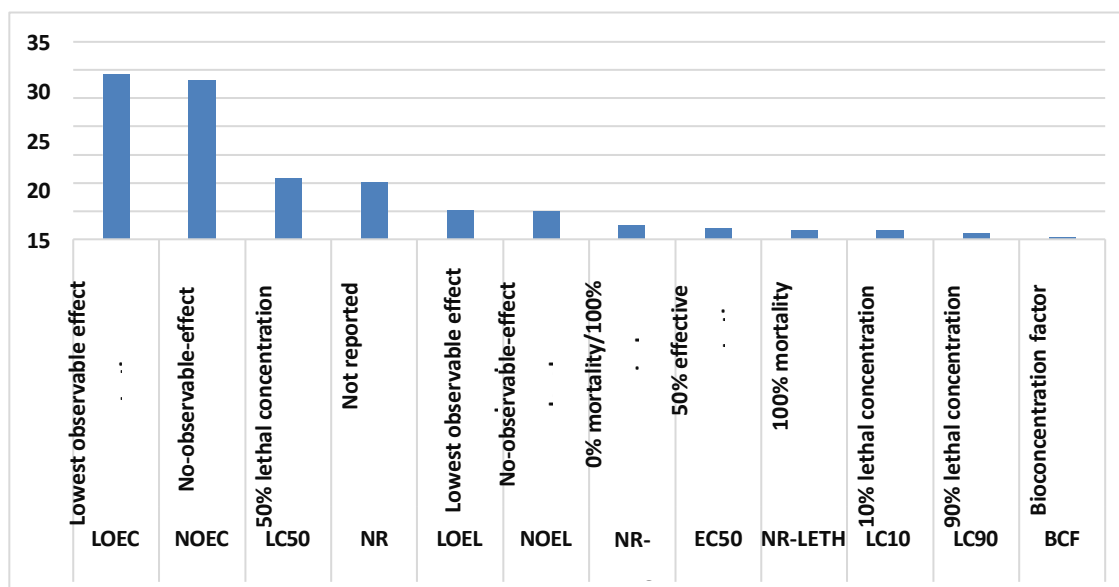


**Figure 1. Distribution of Major Ecotoxicological Endpoints in Lambda-Cyhalothrin Fish Records**

The biological-effect records revealed a fish toxicity that went beyond mortality for lambda-cyhalothrin. The most common effect was mortality, which had 120 records (25.81%). This was followed by the biochemical, enzyme and genetic alteration with 106, 84 and 75 records respectively, representing 22.80%, 18.06% and 16.13% respectively. Physiological effects received 16 records (3.44%) and histological and population level effects received 10 records each (2.15%). Responses to developmental, cellular, behavioural, morphological and hormonal responses were reported less frequently. The direct accumulation effects were only recorded for two cases (0.43%).

The results suggest that there are multiple biological levels affected by exposure to lambda-cyhalothrin in fish. If mortality is the largest category, this is because biochemical, enzymatic and genetic responses are all important sub lethal effects of the biological system, and this is well represented by the data available. The principle biological-effect classes of fish exposed to lambda-cyhalothrin are summarized in Table 2. The distribution of biological responses, including mortality, biochemical, enzymatic and genetic responses, are illustrated in Figure 2

**Table 2. Biological-effect categories associated with lambda-cyhalothrin exposure in fish**

| Effect category    | Records, n | %     |
|--------------------|------------|-------|
| Mortality          | 120        | 25.81 |
| Biochemistry       | 106        | 22.80 |
| Enzyme alterations | 84         | 18.06 |
| Genetics           | 75         | 16.13 |
| Physiology         | 16         | 3.44  |
| Histology          | 10         | 2.15  |
| Population effects | 10         | 2.15  |
| Development        | 8          | 1.72  |
| Cellular effects   | 7          | 1.51  |
| Behavior           | 5          | 1.08  |
| Morphology         | 5          | 1.08  |
| Hormonal effects   | 5          | 1.08  |
| Accumulation       | 2          | 0.43  |

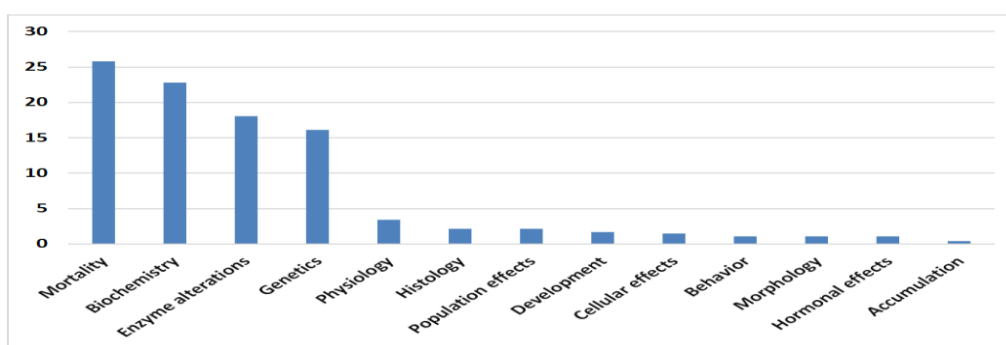


**Figure 2. Major Biological-Effect Categories Associated with Lambda-Cyhalothrin Exposure in Fish**

### 3.3 Tissue and Response-Site Distribution

A good number of the lambda-cyhalothrin fish records were provided by tissue-specific information. Livor, erythrocytes, brain, gonads, gills, muscles and kidneys were the most frequently reported identifiable

responses, with 87 (18.71%), 44 (9.46%), 40 (8.60%), 32 (6.88%), 28 (6.02%), 19 (4.09%) and 18 (3.87%) records respectively. 126 records (27.10%) were not coded for a response site and 25 records (5.38%) were not coded for a specific tissue.

The tissue distribution illustrates the various organs that are affected by chemical uptake, metabolism, neurological activity, and systemic toxicity that have been assessed in the context of lambda-cyhalothrin-associated responses. The primary identified response sites were therefore liver, erythrocytes, brain, gills, muscle and kidney in the fish data set available. Table 3 lists the organs and reactions in fish that are mainly affected by lambda-cyhalothrin. The main response sites such as liver, erythrocytes, brain, gills, muscle and kidney are shown in the distribution Figure 3.

**Table 3. Major response sites recorded for lambda-cyhalothrin effects in fish**

| Response site   | Records, n | %     |
|-----------------|------------|-------|
| Not reported    | 126        | 27.10 |
| Liver           | 87         | 18.71 |
| Erythrocyte     | 44         | 9.46  |
| Brain           | 40         | 8.60  |
| Gonad(s)        | 32         | 6.88  |
| Gill(s)         | 28         | 6.02  |
| Not coded       | 25         | 5.38  |
| Muscle          | 19         | 4.09  |
| Kidney          | 18         | 3.87  |
| Caudal peduncle | 9          | 1.94  |
| Blood           | 8          | 1.72  |
| Whole organism  | 7          | 1.51  |

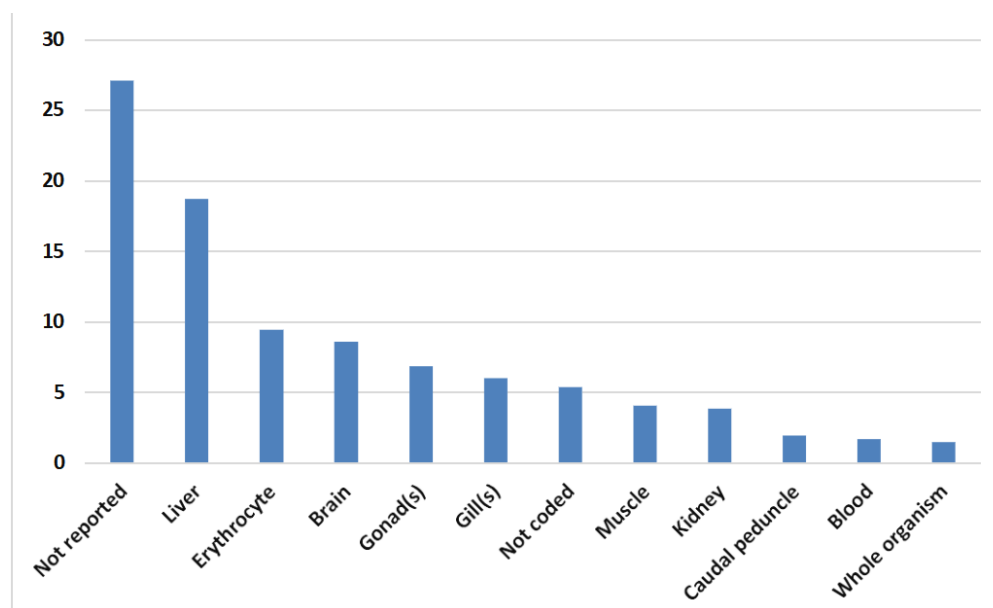


**Figure 3. Distribution of Major Response Sites in Lambda-Cyhalothrin Fish Records**

### 3.4 Genetic and DNA-Related Effects in Fish

The 465 fish-result records included 75 genetic effects (No. 465). These records comprised measurements of DNA damage, DNA concentration, micronuclei, nuclear abnormalities and other mitotic abnormalities. *Prochilodus lineatus* contributed the highest number of genetic-effects records (45.3%), followed by *Gambusia affinis* (18.7%), *Clarias batrachus* (17.3%) and *Channa punctata* (12.0%). Erythrocytes were the most common cell type studied, followed by brain, liver and gills as response sites.

More significantly, the fish records available indicated that genetic effects were assessed using different time periods of observation and not a single fixed time point for exposure. For *Gambusia affinis*, genetic responses were assessed at 6, 12, 24 and 48 h (0.25, 0.5, 1 and 2 days). For *Prochilodus lineatus* genetic responses were assessed at 48, 96, 144 and 192 h (2, 4, 6 and 8 days). Genetic responses in *Clarias batrachus*, *Channa punctata* and *Garra rufa* were frequently seen at about 96 h (4 days), 24 h (1 day) and 36 h (1.5 days), respectively.

Therefore, the evidence of fish indicates that genetic and DNA responses have been detected or evaluated within the first day of exposure to several days. These periods are meant to reflect the time of measurement and/or reporting and are not intended to represent absolute time of DNA damage onset. Table 4 summarizes the observation periods and the number of days for selected lambda-cyhalothrin-induced genetic effects in fish.

**Table 4. Observation periods associated with selected genetic effects of lambda-cyhalothrin in fish**

| <b>Fish species</b>   | <b>Reported observation period</b> | <b>Equivalent in days</b> | <b>Main response</b>          |
|-----------------------|------------------------------------|---------------------------|-------------------------------|
| Gambusia affinis      | 6 h                                | 0.25 day                  | Genetic/DNA-related response  |
| Gambusia affinis      | 12 h                               | 0.5 day                   | Genetic/DNA-related response  |
| Gambusia affinis      | 24 h                               | 1 day                     | Genetic/DNA-related response  |
| Gambusia affinis      | 48 h                               | 2 days                    | Genetic/DNA-related response  |
| Prochilodus lineatus  | 48 h                               | 2 days                    | Genetic/DNA-related response  |
| Prochilodus lineatus  | 96 h                               | 4 days                    | Genetic/DNA-related response  |
| Prochilodus lineatus  | 144 h                              | 6 days                    | Genetic/DNA-related response  |
| Prochilodus lineatus  | 192 h                              | 8 days                    | Genetic/DNA-related response  |
| Channa punctata       | 96 h                               | 4 days                    | Genetic response              |
| Clarias batrachus     | 96 h                               | 4 days                    | Genetic response              |
| Garra rufa            | 36 h                               | 1.5 days                  | Micronucleus/genetic response |
| Cheirodon interruptus | 24 h                               | 1 day                     | Micronucleus/genetic response |

“Genetic effects in fish were observed/evaluated from 6 h (0.25 day) to 192 h (8 days), while the two available bioaccumulation records for Danio rerio involved 48 h (2 days) of exposure and 72 h (3 days) of observation.”

### 3.5 Distribution of Genetic-Effect Records Among Fish Species

The genetic-effect data were not homogeneously distributed among the fish species in the database. The largest number of genetic-effect records was obtained for *Prochilodus lineatus*, *Gambusia affinis*, *Clarias batrachus* and *Channa punctata*. Less genetic-effect observations were found for *Garra rufa*, *Cheirodon interruptus* and *Mystus gulio*. This distribution shows the available evidence for genotoxic effects of lambda-cyhalothrin is largely limited to a few fish species. The results of the lambda-cyhalothrin genetic-effect records for the fish species investigated are presented in Figure 4

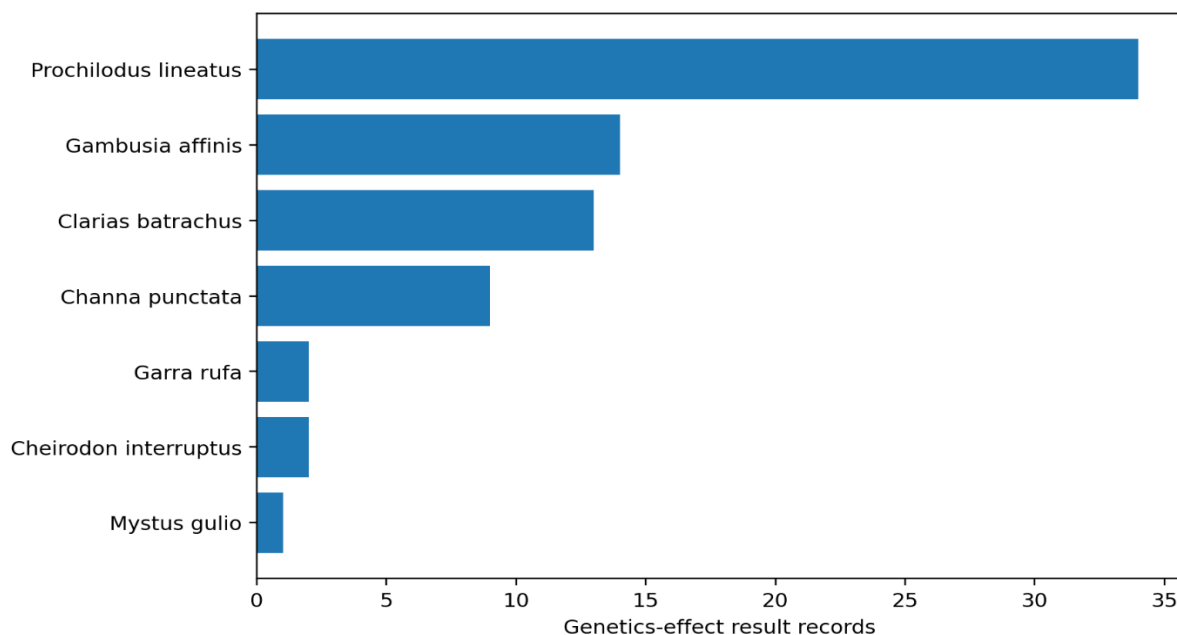


**Figure 4. Distribution of Lambda-Cyhalothrin Genetic-Effect Records by Fish Species**

### 3.6 Bioaccumulation of Lambda-Cyhalothrin in Fish

Direct information on the bioaccumulation of lambda-cyhalothrin in fish was very limited. Two records of bio-concentration factors were found, one for *Danio rerio*. Measurable bioconcentration of lambda-cyhalothrin in fish was confirmed with reported BCF values of 674.3 L/kg and 620.6 L/kg. These two are the values now reported in the manuscript's abstract. The two records were the 0.71 ng/mL and 5.39 ng/mL of lambda-cyhalothrin, respectively. The exposures lasted about 48 h (2 days) and the subsequent observations were made over about 72 h (3 days). The records from the BCF were non-steady state observations. As such, the values are shown as evidence that the concentration of lambda-cyhalothrin in fish can be achieved through transient exposure but should not be viewed as “true” equilibrium BCF values. The bioaccumulation of lambda-cyhalothrin in *Danio rerio* is provided in terms of available BCF values, exposure duration, and observation period, which is shown in Table 5.

**Table 5. Direct bioaccumulation records of lambda-cyhalothrin in fish**

| Species     | Lambda-cyhalothrin concentration | Exposure duration | Observation period | BCF (L/kg) | Interpretation              |
|-------------|----------------------------------|-------------------|--------------------|------------|-----------------------------|
| Danio rerio | 0.71 ng/mL                       | 48 h (2 days)     | 72 h (3 days)      | 674.3      | Measurable bioconcentration |
| Danio rerio | 5.39 ng/mL                       | 48 h (2 days)     | 72 h (3 days)      | 620.6      | Measurable bioconcentration |

The bioaccumulation results should be tested however with a degree of caution. Both were derived for *D. rerio*, and a species-level/CR conclusion is not possible with such a limited number of observations. This restriction is already known about and is mentioned in the manuscript, which says that two observations are not enough for species-level inferences. Above all, these bioaccumulation values should not be reported as the bioaccumulation of *Cyprinus carpio*. They give evidence that lambda-cyhalothrin has bioaccumulation potential for fish (specifically zebrafish) in the dataset.

### 3.7 Fish-Specific Interpretation of Genetic Effects

The updated analysis reveals genetic and DNA-related responses with exposure to lambda-cyhalothrin in several fish species and tissues. The effects observed in fish were in erythrocytes, gills, liver and brain, and the results were tissue and time dependent. The data presented thus indicates a time and tissue specific genetic toxicity in fish. The observation-duration data also showed that in some studies the genetic responses were measured shortly after exposure (e.g., within a few hours) and in other selected genetic-effect records were reported at later observation periods up to about 8 days. It shows the benefit of having several sampling times when measuring genetic effects resulting from exposure to lambda-cyhalothrin in fish.

### 3.8 Specific Evidence Gap for *Cyprinus carpio*

The *Cyprinus carpio* is well characterized in the ECOTOX database with a good amount of toxicity data. About 1,095 chemicals and 17,598 result records, with 1,390 of those records identified as genetic effects, were reported in the manuscript. There were also thirty-four common-carp tests that had references that included the word “Comet.” Therefore, *C. carpio* is a good model organism for the aquatic toxicological and genotoxic evaluation. No ECOTOX record was found which accommodated the exposure to lambda-cyhalothrin and *C. carpio*. Similarly, bioaccumulation data for lambda-cyhalothrin were not available for

this species nor were there any Comet-assay endpoints available. However, even if lambda-cyhalothrin has been shown to have biological, genetic and bioaccumulation effects on other fish species, it is not possible to make quantitative extrapolations to common carp. This is the critical knowledge lacking, as per the present assessment. To evaluate genotoxic responses at various exposure time points, using standardized endpoints from the Comet assay, the residue of lambda-cyhalothrin in *C. carpio* and BCF/BAF values should be measured at other species-specific time points under defined exposure conditions in future studies.

#### 4. Discussion

The present assessment shows that there is a good body of ecotoxicological data available for lambda-cyhalothrin for fish; however, the current ECOTOX records do not directly link exposure, bioaccumulation and DNA-damage for lambda-cyhalothrin in *Cyprinus carpio*. The most frequently reported effects were mortality, biochemical changes, enzyme changes, and genetic effects, which are sublethal and lethal effects of lambda-cyhalothrin toxicity. Sublethal exposure of a common carp to pesticides has been reported to cause similar hemato-biochemical (Arshad et al., 2026) and genotoxic (Banaee et al., 2026) alterations and chemical stress has been linked to oxidative stress and detoxification related pathways in this species.

The high percentage of biochemical and enzymatic endpoints indicates that oxidative imbalance could be a factor in the toxicity of pesticides. Synthetic pyrethroids have the potential to disrupt antioxidant defence, cellular metabolism and membrane stability. Biochemical and oxidative-stress biomarkers have been reported to change in *C. carpio* exposed to deltamethrin (Banaei et al., 2022) and similar oxidative responses have also been reported in freshwater catfish (Barathinivas et al., 2022). Hematological, biochemical, and histopathological changes have also been reported in freshwater fishes exposed to lambda-cyhalothrin (Behera et al., 2026; Pokhrel et al., 2025).

The main response sites found in the data set were liver, erythrocytes, brain, gills, muscle, and kidney. Xenobiotic metabolism is important in the liver whereas the gills are a significant pathway for the uptake of contaminants from the water. Similarly, sublethal exposure to pesticides has been shown to cause behavioral, biochemical, hematological, and histopathological changes in fish in previous studies (El-Bouhy et al., 2023). Other pesticides induced tissue-level and hemato-genotoxic effects in *C. carpio*, which further indicates the usefulness of these biomarkers for ecotoxicological assessment (Korkmaz, 2024; Jindal et al., 2026).

There were also genetic effects, represented by 75 fish records of alterations of the DNA, micronuclei, nuclear abnormalities, and other abnormalities of the passage of the nucleus. Most importantly, these effects were assessed with varying observation times. The genetic response of *Gambusia affinis* was evaluated from 6 to 48 h (0.25 to 2 days), and *Prochilodus lineatus* from 48 to 192 h (2–8 days). So, the genetic effects reported were several hours to several days after exposure, but that is not the actual time when DNA damage

occurs. Variations in species, tissues, concentration and duration of exposure can help explain differences in genetic responses (Kumar et al., 2025; Noreen et al., 2023; Yaseen et al., 2025). Direct evidence of bioaccumulation was reported for only two species (*Danio rerio*, with a BCF of 674.3 and 620.6 L/kg). The records comprise about 48 h exposure and 72 h observation period, thus showcasing measurable short-term bioconcentration of lambda-cyhalothrin in fish. Observations were non-steady state, however, and were not extensive enough to make a species-wide or concentration-response conclusion. Thus, the results of these studies should not be immediately extrapolated to *C. carpio*. Stress due to pesticide exposure can be better understood through integrated biomarker approach e.g., under environmentally relevant conditions such as exposure to pesticide mixtures (Tufail et al., 2025; Sebastião et al., 2025) in common carp.

In summary, there is a general deficiency of knowledge. While widely tested in fish, *C. carpio* is an established biomonitoring species and there is no direct record in ECOTOX that associates bioaccumulation of lambda-cyhalothrin with DNA damage in Comet assay in *C. carpio*. In future research, it is recommended that tissue-residue measurements, estimation of BCF/BAF, the exposure time and selected standardized genotoxicity endpoints should be combined to obtain more species-specific data to support the ecological risk assessment of lambda-cyhalothrin in freshwater.

## 5. Conclusion

The present assessment shows that lambda-cyhalothrin is of high ecotoxicological relevance in freshwater fish not only in terms of mortality, but also biochemical, enzymatic, tissue-specific and genetic effects. The ECOTOX evidence revealed that liver, erythrocytes, brain, gills, muscle and kidney are key response tissues suggesting that several biological systems can be impacted after exposure. Molecular responses were evaluated over both short and long periods of observation: several hours until 192 h (8 days), with genetic effects such as alterations in the DNA, the micronuclei, nuclear abnormalities and other changes in the nuclei reported. Only two records of bioaccumulation were found (L/kg BCF after 48 h and 72 h exposure and observation respectively for *Danio rerio*). The results show measurable short-term bioconcentration but are not extensive enough and are not steady state, making species-level interpretation difficult. Notably, there was no direct ECOTOX evidence of bioaccumulation of lambda-cyhalothrin with Comet-assay induced DNA damage in *Cyprinus carpio*. Thus, the results of studies on other fish species cannot be directly applied to common carp. Future species-specific studies should consider the combination of water and tissue residue measurements, estimation of BCF/BAF, multiple exposure durations, and standardized endpoints for genotoxicity. These studies would provide a better understanding of the relationship between the internal burden of pesticides and genetic damage and enhance the biomonitoring and ecological risk assessment of lambda-cyhalothrin in freshwater ecosystems.

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