Archives of Environmental Contamination and Toxicology
https://doi.org/10.1007/s00244-024-01083-9

Attenuation Effect of *Azolla* spp. on Lambda-Cyhalothrin Toxicity to Aquatic Organisms

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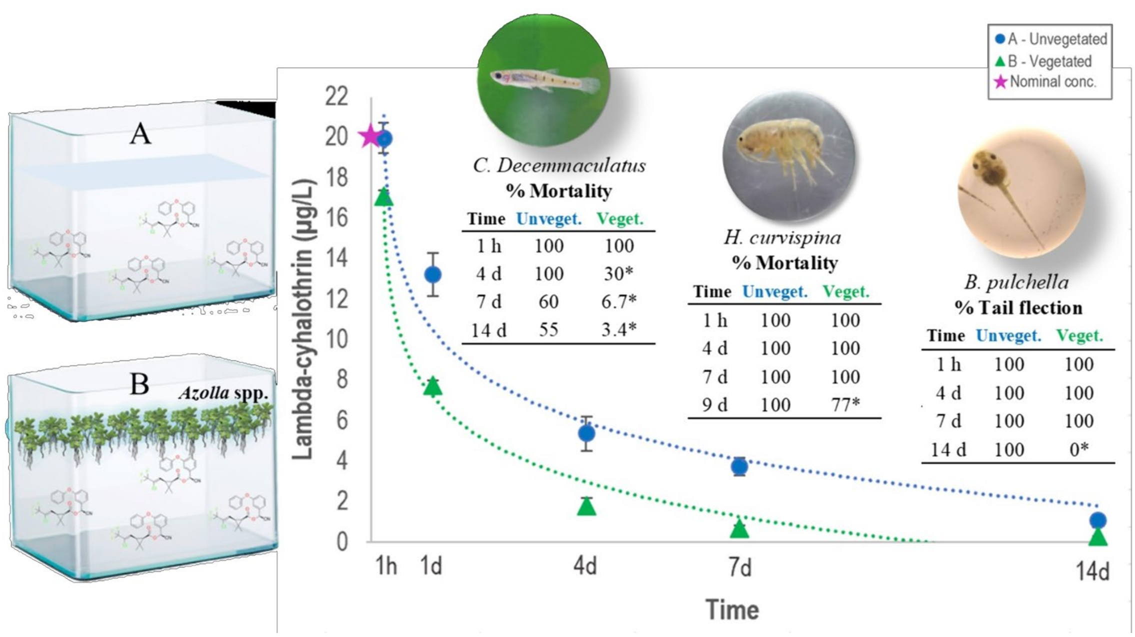
Received: 19 March 2024 / Accepted: 18 July 2024

Abstract

Wetlands play a crucial role in providing valuable ecosystem services, including the removal of various pollutants. In agricultural basins, wetlands are exposed to agrochemical loads. This study aims to assess the attenuation effect of the ubiquitous macrophyte *Azolla* spp. on the toxicity of lambda-cyhalothrin to sensitive aquatic organisms. An indoor mesocosm experiment was conducted to compare the concentration of lambda-cyhalothrin at different time points after pesticide application in vegetated and unvegetated treatments, including a control without pesticide addition. Toxicity tests were performed throughout the experiment on three organisms: a fish (*Cnesterodon decemmaculatus*), a macroinvertebrate (*Hyalella curvispina*), and an amphibian (*Boana pulchella*). The results demonstrated that lambda-cyhalothrin concentration and toxicity in water were significantly lower in the *Azolla* spp. treatment. Furthermore, the half-life of lambda-cyhalothrin decreased from 1.2 days in the unvegetated treatment to 0.4 days in the vegetated treatment. The vegetated treatment also resulted in a significantly lower mortality rate for both *H. curvispina* and *C. decemmaculatus.* However, no mortality was observed in *B. pulchella* for any of the treatments. Sublethal effects were observed in this organism, such as lateral bending of the tail and impairment of the ability to swim, which were attenuated in the vegetated treatment. We conclude that *Azolla* spp. can effectively reduce the concentration and toxicity of lambda-cyhalothrin, suggesting its potential use in farm-scale best management practices to mitigate the effects of pesticide loads from adjacent crops.

Graphical Abstract



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Published online: 01 August 2024

Worldwide, approximately 2 million tons of pesticides are used annually, with China being the major contributing country, followed by the USA and Argentina (Sharma et al. 2019). The use of this wide variety of pesticides in modern agriculture has raised global concerns due to the risk of contaminating nearby aquatic habitats (Khan et al. 2023).

Pesticides can enter water bodies through surface runoff, spray drift, leaching, drainage flows, and atmospheric deposition (Reichenberger et al. 2007). Due to their high persistence and toxicity to the non-target fauna, organochloride, carbamate, and organophosphate insecticides are being replaced by pyrethroids (Weston and Lydy 2010; Moore et al. 2008). Pyrethroids have low toxicity to mammals, but they are highly toxic to invertebrates, fish, and amphibians (Ranatunga et al. 2023). This can have a significant impact on the health of ecosystems and their biodiversity.

Lambda-cyhalothrin is a broad-spectrum pyrethroid insecticide that is increasingly used worldwide. This insecticide is largely hydrophobic (octanol–water partition coefficient Kow = 7), indicating a tendency to adsorb onto organic matter, including vegetation, bottom sediments, and suspended particulate materials in water. These components serve as the primary vectors for its transport through aquatic systems (Hand et al. 2001; He et al. 2008). The combination of extensive use and the close connectivity between land and streams makes the potential risk of lambda-cyhalothrin exposure extremely high for fish, amphibians, and aquatic invertebrates (Lauridsen and Friberg 2005; Gu et al. 2007; Rasmussen et al. 2008; Nørum et al. 2010; Wiberg-Larsen et al. 2021; Marine et al. 2022).

Riparian wetlands play an important role in attenuating agricultural pollution from cropland (Pappalardo et al. 2015; Solis et al. 2021). Wetland macrophytes offer various processes that reduce the mass, toxicity, mobility, volume, or concentration of contaminants, including pesticides (Vianello et al. 2005; Dhir et al. 2009; Otto et al. 2012; Vymazal and Březinová, 2015; Alencar et al. 2020). *Azolla* spp. is a small floating macrophyte commonly found in shallow water environments in tropical, subtropical, and warm temperate regions of Africa, Asia, and America (Sadeghi et al. 2013). *Azolla* spp. is a rapidly growing aquatic plant that can double in size within 2–5 days (Zimmerman 1985), with particularly fast growth in spring and early summer. For several decades, *Azolla* spp. has been utilized as animal feed, as a green manure for rice fertilization due to its ability to fix nitrogen (Salma and Naik 2020), and in phytoremediation processes due to its rapid growth rate, ability to thrive in contaminated waters, and high potential to absorb heavy metals (Sood et al. 2011). In recent years, the ability of *Azolla* spp. to remove pesticides from water has been studied (Saeb and Wani 2022), but information on the removal of pyrethroids, such as lambda-cyhalothrin, is very limited.

The objective of this study was to assess the capacity of *Azolla* spp. to decrease the water concentration of lambda-cyhalothrin and mitigate toxicity to three common aquatic fauna of the Argentine pampas: the fish *Cnesterodon decemmaculatus*, the crustacean *Hyalella curvispina*, and the anuran *Boana pulchella*. It was hypothesized that *Azolla* spp. would decrease the concentration and persistence of lambda-cyhalothrin in water, thereby reducing the pesticide impact on aquatic environments.

Materials and Methods

Lambda-Cyhalothrin Dissipation from Water

The persistence of lambda-cyhalothrin was compared in two treatments, one containing only water, and the other one with the water completely covered by *Azolla* spp. A negative control was conducted with water and vegetation, without the addition of lambda-cyhalothrin (Fig. 1). Both treatments and controls were run in triplicate. The laboratory mesocosms consisted of glass aquariums measuring 60 cm long, 20 cm wide, and 40 cm deep, each containing 30 L of dechlorinated, unfiltered tap water. *Azolla* spp. biomass in the vegetated treatment represented roughly 100 g wet weight in each aquarium. The *Azolla* spp. was obtained from a large wetland about 30 km south of the city of La Plata, surrounded by natural pastures and extensive livestock fields. Previous studies comparing pesticide concentrations in streams with different land uses in the area reported higher concentrations in bottom sediments from horticultural and agricultural basins and traces in extensive livestock and a reserve basin. The sampled wetland represents the best condition in the area (Arias et al. 2020). Sampled *Azolla* spp. was acclimatized in the laboratory for two weeks under controlled conditions, including room temperature, illumination with Indoor Grow Lamps 18W, and a 12-h photoperiod. The water was enriched with six nutrient additions to attain 300 µg/L inorganic nitrogen and 100 µg/L of soluble reactive phosphorus in each addition.

The commercially available formulated product Karate® (lambda-cyhalothrin 25%, SYNGENTA AGRO S.A.) was applied to each treatment at the beginning of the experiment to reach a nominal concentration of 20 µg/L in the aquariums water. A stock solution of lambda-cyhalothrin (250 mg/L) was prepared from the formulated pesticide diluted in

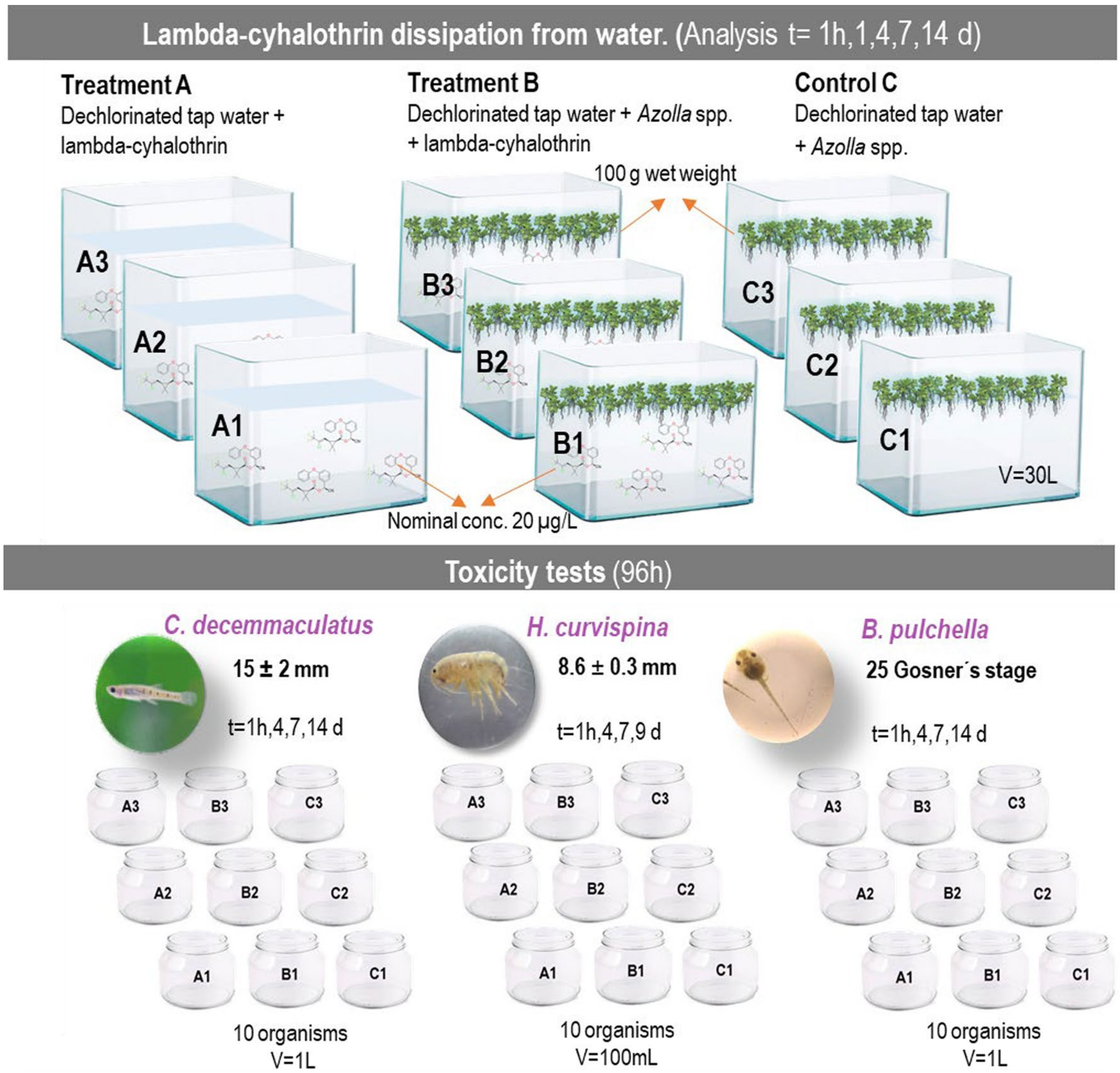

Fig. 1 Experimental design

deionized water. Aliquots (2.4 mL) of this solution were spiked with a pipette into the aquariums in a single dose and the aquariums were gently stirred soon after addition to achieve homogeneous distribution. The pesticide addition and the initial concentration were designed to represent an ephemeral runoff event (Bennett et al. 2005; Mugni et al. 2011; Mahabali and Spanoghe 2013).

Water samples were collected from each aquarium 1 h, and 1, 4, 7, and 14 days after lambda-cyhalothrin addition in amber glass bottles, stored in the dark at 4 °C, and extracted with dichloromethane within 7 days of storage. Lambda-cyhalothrin concentration in *Azolla* spp. biomass was measured at the end of the experiment. The vegetation samples were dried at room temperature, crushed, and 20 g was mixed with sodium sulfate and extracted by sonication with dichloromethane. Cleanup procedures were carried out using Florisil solid phase extraction (USEPA, 2007; Solis et al. 2016). All the evaporated extracts were diluted in hexane and analyzed by gas chromatography (GC HP 6890) with a 30-m HP1 column and a 63Ni electron-capture detector (ECD). Two microliters were injected in splitless mode, with the detector kept at 290 °C. The oven-temperature program started at 190 °C, followed by an increase of 10 °C/min up to 260 °C (maintained for 13 min), then 10 °C/min up to 290 °C (maintained for 7 min). Identification and quantification were performed with a high-purity lambda-cyhalothrin standard pesticide (Accustandard; 4-point calibration curve) and tetrachloro-m-xylene (Ultra Scientific) as an internal standard. The detection limits (3:1 signal-versus-noise value) were 0.002 µg/L and 1.0 ng/g in water and vegetation, respectively. The quantitation limits (10:1 signal-versus-noise value) in water and macrophytes were 0.009 µg/L and 3.5 ng/g, respectively. Ultra-high-purity nitrogen was the carrier and makeup gas, set to a constant flow of 28 cm/s and 40 mL/min, respectively. The procedural and instrumental blanks had concentrations below the detection limits. Mean extraction efficiencies based on fortified samples were > 90% for both, water and vegetation. The analyses were carried out until the concentrations declined below the limit of determination.

Temperature, dissolved oxygen, pH, and conductivity in the aquariums were measured at each sampling. Dissolved oxygen and temperature were measured with a Yellow Spring Instrument (YSI 51B) recorder, pH with an Orion 250A, and conductivity with a Hanna 8733.

Toxicity Tests

Test organisms were collected from a stream not impacted by agricultural activity (35° 07′ 22″ S; 57° 41′ 12″ W) and raised in the laboratory in aquariums containing tap water, at 20 °C and natural photoperiod (light/dark 14/10 h). The locally abundant macrophyte *Lemna* spp. was placed on the water surface. *H. curvispina* fed on the periphytic community associated with its rhizosphere and was supplemented twice a week with a mixture of fresh lettuce leaves and dried algae ad libitum. *C. decemmaculatus* and *B. pulchella* were fed daily ad libitum with Shulet® Carassius commercial fish food.

Toxicity tests were carried out in triplicate with water sampled from each aquarium without vegetation (Fig. 1). The three selected organisms (*C. decemmaculatus, H. curvispina*, and *B. pulchella*) were exposed separately. Toxicity to *C. decemmaculatus* and *B. pulchella* was tested at 1 h, 4, 7 and 14 days and to *H. curvispina* at 1 h, 4, 7 and 9 days since lambda-cyhalothrin application. Standardized protocols were followed for the toxicity tests (USEPA, 2000). Ten organisms were exposed to water samples from both treatments and the control for 96 h. Mortality was the endpoint for *C. decemmaculatus* and *H. curvispina,* and tail flection was the endpoint for *B. pulchella*. *H. curvispina,* 8.6 ± 3 mm, was exposed in 100 mL beakers, *B. pulchella*, in the 25 Gosner´s stage, and *C. decemmaculatus*, 15 ± 2 mm length, 21–35 mg, were exposed in 1000 mL water samples. The tests, performed in the laboratory, were static, without feeding, and with natural photoperiod.

The treatment of the specimens was carried out in accordance with regulations on animal welfare of the National Council of Scientific and Technical Research of Argentina (CONICET), following the guidelines of its Ethics Committee (OCR-RD-20050701–1047.pdf conicet.gov.ar) and its biological sampling guide (https://proyectosinv.conicet.gov.ar/solicitud-colecta-cientifca/).

Statistical Analysis

Analysis of variance (ANOVA) was used to compare both lambda-cyhalothrin concentrations and biological endpoints between treatments (vegetated and unvegetated) and control. Separate ANOVA tests were performed for each time point and organism. After the ANOVA test, Tukey's HSD was used as a post hoc test. Angle transformation was used for data analysis. Normality and homoscedasticity were tested using the Shapiro–Wilk and Bartlett tests. If the assumptions of homoscedasticity or normality were not met, the non-parametric Kruskal–Wallis test was used. The Student's t-test was used to compare the mean measured water quality parameters (conductivity, temperature, pH, and oxygen concentrations) between treatments. A natural logarithmic regression model was used to fit a curve describing lambda-cyhalothrin concentrations along the experiment. The half-life was then estimated from the regression curve. The half-lives were compared between treatments using Student's t-test. A significance level of $\alpha = 0.05$ was used for all tests. Statistical analyses were performed using InfoStat (Di Rienzo et al. 2020) and XLSTAT software.

Results

Table 1 summarizes the environmental variables measured throughout the experiment. The vegetated treatment exhibited lower water pH and dissolved oxygen concentration and higher conductivity than the unvegetated treatment. Pinero-Rodriguez et al. (2021) reported that dense mats of *Azolla filiculoides* decreased pH and oxygen concentration and released nutrients in experimental mesocosms. Water pH and oxygen were attributed to root respiration and impaired water-atmosphere exchange (Pinero-Rodriguez, et al., 2021). Nutrient release by *Azolla* spp. may have contributed to the observed increase in conductivity in our experiment. A detritus layer was formed on the bottom of the vegetated treatment. The source of ions for the increased conductivity observed in this treatment could be either released from the *Azolla* spp. biomass and/or from the decomposition of the bottom detritus layer.

Table 1 Mean ± standard deviation of the measurements carried out in the aquariums

	Temp. (°C)	pH	Cond. (µS/cm)	Dis. Oxygen (mg/L)
Unvegetated	21.8 ± 1.0	7.93 ± 0.27*	865.5 ± 46.9*	7.9 ± 0.4*
Vegetated	22.3 ± 1.0	7.56 ± 0.22	921.0 ± 70.5	6.5 ± 1.5

Significant differences are marked with asterisks

The concentration of lambda-cyhalothrin in water decreased rapidly in both treatments during the experiment, as shown in Fig. 2. Concentrations were significantly lower in the *Azolla* spp. treatment at 1 h ($F = 12.49$, $p = 0.0241$), 1 day ($F = 25.44$, $p = 0.0073$), 4 days, ($F = 14.95$, $p = 0.0181$), 7 days ($F = 43.85$, $p = 0.0027$), and 14 days ($F = 7.25$, $p = 0.0545$). Lambda-cyhalothrin concentration in the *Azolla* spp. treatment decreased to 10% of the initial concentration on the 4th day after pesticide addition, compared to 14 days in the unvegetated treatment.

The estimated half-life of lambda-cyhalothrin was significantly shorter in the *Azolla* spp. treatment (0.4 days) than in the non-vegetated treatment (1.2 days) ($t = 9.51$, $p = 0.0007$).

At the end of the assay, the concentration of lambda-cyhalothrin within the *Azolla* spp. biomass was 2.49 ± 0.44 µg/g (dry weight). The amount of lambda-cyhalothrin retained within the *Azolla* spp. biomass represented approximately 10% of the initial amount added at the beginning of the experiment. Each aquarium contained roughly 25 g dw of *Azolla* spp. biomass.

The mortality of *C. decemmaculatus* was 100% in both treatments after application (1st day) as shown in Fig. 3. From the 4th day until the end of the experiment, mortality was significantly lower in the vegetated treatment compared to the unvegetated treatment (t = 4: $F = 15.05$, $p = 0.0046$; t = 7: $F = 11.58$, $p = 0.0087$; t = 14: $F = 50.23$, $p = 0.0002$). On the 4th day, mortality in the *Azolla* spp. treatment decreased to 30%, while it remained at 100% in the unvegetated treatment. On the 7th day after application, mortality was less than 10% for the *Azolla* spp. treatment, while it remained high (55%) until the end of the experiment (14th day) in the unvegetated treatment.

H. curvispina mortality was 100% up to the 7th day in both treatments (Table 2). On the 9th day, mortality was significantly lower in the *Azolla* spp. treatment (77 ± 9%) than in the non-vegetated treatment (100%) ($F = 50.23$, $p = 0.0002$).

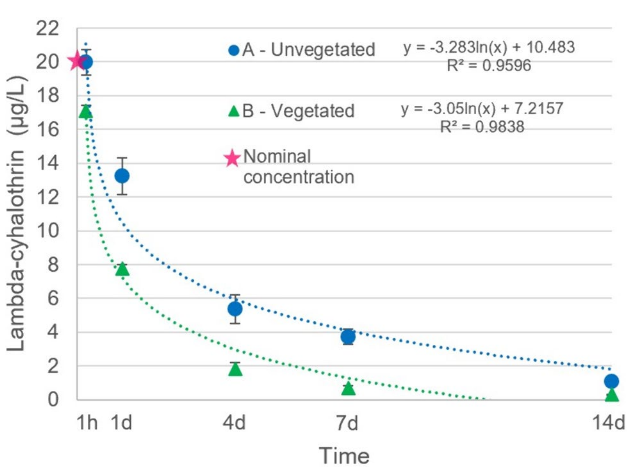

Fig. 2 Lambda-cyhalothrin concentration in the *Azolla* spp. and unvegetated treatments throughout the experiment

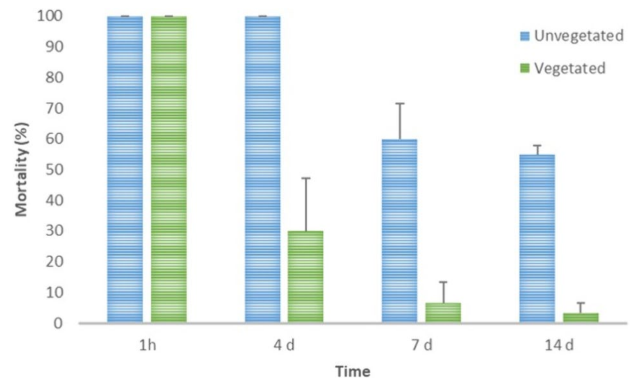

Fig. 3 Mortality of *Cnesterodon decemmaculatus* exposed to aquarium water at diferent times after lambda-cyhalothrin application. Mean of three replicates. Vertical lines represent error bars. Significant differences are indicated by asterisks

The anuran *B. pulchella* did not show mortality in any treatment throughout the experiment. However, sublethal effects were observed, such as lateral flexion of the tail (Fig. 4) and erratic swimming. Lateral tail flexion occurred in 100% of the individuals throughout the experiment in the unvegetated treatment while it completely ceased in the *Azolla* spp. treatment on the 14th day (Table 2).

Discussion

The concentration of lambda-cyhalothrin in the water decreased rapidly, particularly in the vegetated treatment, as expected for a lipophilic compound, indicating significant adsorption to the biomass of *Azolla* spp. The chemical feature of lambda-cyhalothrin determines its environmental

Table 2 Mortality ± standard error of *Hyalella curvispina* and lateral flection of the tail in *Boana pulchella* in the exposure to aquarium water at different times after lambda-cyhalothrin application

	Time (days)	Unvegetated	Vegetated
H. curvispina % Mortality	1 h	100 ± 0	100 ± 0
	4	100 ± 0	100 ± 0
	7	100 ± 0	100 ± 0
	9	100 ± 0	77 ± 9*
B. pulchella % Tail flection	1 h	100 ± 0	100 ± 0
	4	100 ± 0	100 ± 0
	7	100 ± 0	100 ± 0
	14	100 ± 0	0 ± 0*

Significant differences are marked with asterisks

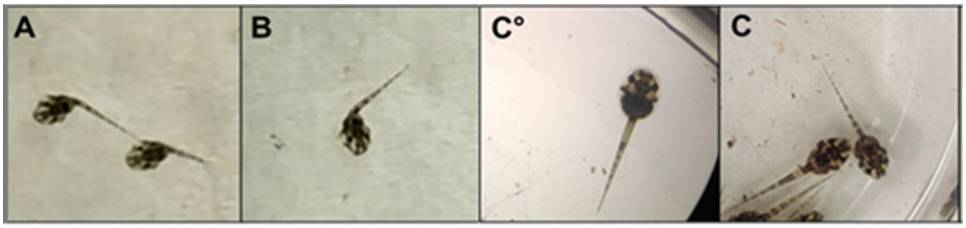

Fig. 4 Sublethal effect of lambda-cyhalothrin on *B. pulchella*. Tail flection caused erratic swimming in the vegetated and unvegetated exposure treatments (**A** and **B**, respectively). No effect was observed in control treatments (**C**)

fate; high Koc and Kow (5,5 and 7, respectively, Bennett et al. 2005), combined with low solubility (0.005 mg/L) favor rapid dissipation from the aqueous phase. Photodegradation takes about 40 days (PPDB database, 2023), much longer than the experimental exposure. Small differences in dissolved oxygen and conductivity between treatments do not appear to have a significant effect on the observed degradation patterns. Adsorption on glass is expected for such a hydrophobic compound. Adsorption of pyrethroids to glass walls in centrifuge tubes and vials is significant (Zhou et al. 1995; Oudou and Hansen 2002). The sorption of lambda-cyhalothrin on organically coated montmorillonite was much greater than on "pure" clay particles (Zhou et al. 1995). Thus, it could be suggested that the glass bond contributes to the rapid decrease in both treatments, while the organic substrate (*Azolla* spp.) contributes to the faster decrease in the *Azolla spp.* treatment. Lambda-cyhalothrin is stable at pH 5–7, but hydrolysis at pH 9 results in a half-life of 8.7 days (Bennett et al. 2005). At the pH ranges recorded in the present experiment, lambda-cyhalothrin may have been partially hydrolyzed, which was greater in the unvegetated treatment (mean pH 7.9) than in the vegetated treatment (mean pH 7.6). However, the overall disappearance was significantly greater in the vegetated treatment. Present evidence suggests that the faster dissipation in the vegetated treatment was mainly caused by rapid and extensive binding to *Azolla* roots. The more rapid dissipation observed in the vegetated treatment, achieved as early as 1 h after application, is consistent with the literature. Hand et al. (2001) reported that the adsorption of lambda-cyhalothrin to *Ceratophyllum demersum* and *Potamogeton crispus* was rapid, extensive, and virtually irreversible for both plant species studied. Degradation occurred by ester cleavage, as evidenced by the rapid increase in the degradation metabolite cyclopropane acid in water, suggesting that cleavage likely occurred at the plant surface. The unicellular green alga *Dunaliella bioculata* was found to excrete esterases capable of extracellular metabolism of deltamethrin (Baeza-Squiban et al. 1990). In an indoor microcosm containing water, sediment, and macrophytes from a pond, Hand et al. (2001) reported that degradation was rapid, with DT50 and DT90 values of less than 3 and 19 h, respectively, lower than estimated in the present study (DT50 = 9 h). Although no specific studies were conducted with *Azolla* spp., previous research has shown that lambda-cyhalothrin binds extensively to aquatic vegetation (Hand et al. 2001; Leistra et al. 2003; Moore et al. 2009). Leistra et al. (2003) studied lambda-cyhalothrin concentrations in enclosures placed in vegetated (*Myriophyllum spicatum, Sagittaria sagittifolia*) and unvegetated ditches. Similarly to our results, they observed that only 24–40% of the dose remained in the water one day after application, the rate of decrease was faster in enclosures with the highest macrophyte biomass (145 g dw). After one day of exposure in the highest biomass enclosure, the lambda-cyhalothrin residue in the plant tissue reached 0.33 µg/g dw, which represented 50% of the dose. This concentration later decreased to 10% after 7 days. At intermediate and low plant densities, the maximum lambda-cyhalothrin concentration was only 3–11% of the dose, after 1–2 days. In our experiment, a higher initial concentration resulted in higher concentrations in plant biomass and similar rates of water disappearance. We measured the biomass concentration at the end of the experiment, whereas Leistra et al. (2003) measured the maximum concentrations in plant biomass in the first days after application, suggesting that, in our experiment, a larger proportion of the lambda-cyhalothrin applied might have been retained earlier in the *Azolla* spp. biomass.

Likewise, Mahabali and Spanoghe (2013) investigated the removal of lambda-cyhalothrin in mesocosms with *Nymphaea amazon* and *Eleocharis mutata*, exposed to low (10 µg/L) and high (30 µg/L) lambda-cyhalothrin concentrations. The half-life of lambda-cyhalothrin was found to be 22–25 h. Between 48 and 72 h, 100% of the lambda-cyhalothrin was removed from the water phase, regardless of the dose applied or the type of plant. Moore et al. (2009) showed that 49% of the lambda-cyhalothrin mass was associated with vegetation in a constructed wetland in the Mississippi Delta, dominated *by Cyprus iria*, *Sorghum halepense*, *Digitaria ischaemum*, *Polygonum lapathifolium*, and *Alternanthera philoxeroides*.

Consistent with the faster decrease in lambda-cyhalothrin concentrations in the vegetated treatment than in the unvegetated treatment, toxicity to the three aquatic organisms tested also decreased faster in the vegetated treatment. Previous studies have shown that macrophytes can reduce toxicity of contaminants in aquatic organisms, but few have evaluated this effect to lambda-cyhalothrin. Bouldin et al. (2005) compared the toxicity of atrazine and lambda-cyhalothrin to the invertebrate *Ceriodaphnia dubia* and the fish *Pimephales promelas* in vegetated and unvegetated mesocosms. The study assessed two different macrophytes: the soft rush *Juncus effuses* and the primrose *Ludwigia peploides*. The temporal patterns of toxicity reduction showed that aquatic vegetation mitigated toxicity. The comparative survival of test organisms suggested the effective mitigation of pesticides from runoff depending on the macrophyte contact and vegetation attributes.

Brogan and Relyea (2017) determined the effect of *Elodea canadensis* on the toxicity to *Daphnia magna* of nine insecticides from three different chemical classes: carbamates (aldicarb, carbaryl, carbofuran); organophosphates (malathion, diazinon, chlorpyrifos); and pyrethroids (permethrin, bifenthrin, lambda-cyhalothrin). The authors reported that *Elodea canadensis* attenuated toxicity, especially for the pesticides of larger octanol–water partition coefficients (Log Kow > 6.0), such as permethrin and lambda-cyhalothrin. The authors suggested that the removal from water by plant sorption represented an important mechanism by which plants attenuate the toxicity of pyrethroid insecticides.

According to Luckeydoo et al. (2002), the contribution of vegetation to the phytoremediation process of water is accomplished through sedimentation, biomass storage, and provision of microhabitats for beneficial microbial organisms. Increased organic matter production enhances the sorption of hydrophobic compounds (Hand et al. 2001).

In the present study, the amphipod *H. curvispina* was found to be the most sensitive, while the fish *C. decemmaculatus* was moderately sensitive and the amphibian *B. pulchella* was largely tolerant. Although no mortality was observed for *B. pulchella* at the tested dose, its swimming ability was reduced, which could lead to competitive impairment in the field. This effect, however, was attenuated by *Azolla* spp.

Azolla spp. is easy to manipulate and could be grown in any sheltered water surface within a farm, even in indoor aquariums, and then transplanted into ponds, ditches, and streams in early spring, when it attains fast growth and may cover the water surface. Intercropped with rice, *Azolla* spp. attained a biomass of 100 g dw/m^2 (Bonetto and Carcaño, 1995). The present study suggests that favoring the development of *Azolla* spp. in small ponds and ditches to achieve a conspicuous cover may be useful to reduce toxicity from nearby crops. Therefore, it can be included in farmers' best management practices (BMPs) to mitigate toxicity from runoff events in crop fields. *Azolla* spp. is a common component of the regional habitats together with other macrophytes. In larger lagoons *Azolla* spp. is swept by the wind and remains at the borders. In small ponds, it may occupy the water surface only temporarily, disappearing after winter freezing and high summer temperatures and irradiances. The regional fauna coexists with abundant aquatic vegetation. Adding *Azolla* spp. to small ponds at a farm scale in spring is not expected to produce any discernible effect on the regional fauna.

Conclusions

Our study demonstrates that *Azolla* spp., a common freshwater wetland macrophyte, reduces the concentration and toxicity of lambda-cyhalothrin to various aquatic organisms in laboratory exposures. We observed a significant reduction in the half-life of lambda-cyhalothrin to less than one day in the presence of *Azolla* spp. These findings suggest that the presence of *Azolla* spp. in small waterbodies adjacent to crop fields will substantially attenuate the impact of lambda-cyhalothrin on aquatic biota.

Given that wetlands are often drained to expand agricultural land, our study highlights the importance of preserving and restoring these ecosystems to safeguard their crucial role in mitigating the effects of pesticide contamination in agricultural basins. *Azolla* spp. can be integrated into farm-scale best management practices, such as constructed wetlands or ditches, to mitigate pesticide contamination. The lambda-cyhalothrin content in the vegetation biomass at the end of the exposure was a small fraction of the initial application, suggesting that there would be no need to harvest and further dispose of the *Azolla* spp. to avoid potential bioaccumulation.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00244-024-01083-9.

Acknowledgements The authors acknowledge the anonymous reviewers for their valuable comments and suggestions.

Author contributions Jezabel PRIMOST, Conceptualization, Methodology, Writing, Formal analysis; Marina SOLIS, Conceptualization, Methodology, Writing; Morena PANTUCCI SARALEGUI, Conceptualization, Methodology, Writing, Formal analysis; Silvia FANELLI, Conceptualization, Methodology, Writing, Formal analysis; Carlos BONETTO, Conceptualization, Methodology, Writing, Funding acquisition, Supervision; Hernán MUGNI. Conceptualization, Methodology, Formal analysis, Investigation, Writing, Funding acquisition, Supervision.

Funding This research was supported by the National Scientific and Technical Research Council (CONICET) (PIP 2021- 2509) and the Argentine National Agency for the Promotion of Science and Technology (ANPCyT) (PICT 2021-0856).

Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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