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Effects of LC_{50} chlorantraniliprole using different application methods on adult *Spodoptera exigua* and across generations

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Introduction: The beet armyworm Spodoptera exigua (Hübner, 1808) (Lepidoptera: Noctuidae) represents a cosmopolitan polyphagous lepidopteran pest of paramount agricultural significance, necessitating strategic intervention during the reproductive-competent imaginal stage to mitigate population amplification and geographic dissemination. Chlorantraniliprole is an anthranilic diamide insecticide with high selectivity for arthropod ryanodine receptors (RyR).
Methods: This investigation systematically evaluated median lethal (LC_{50}) ramifications of chlorantraniliprole upon adult *S. exigua* demographic performance and transgenerational fitness consequences utilizing three distinct administration modalities: oral consumption via chlorantraniliprole-fortified sucrose solution, pronotal microdroplet deposition, and pedal contact exposure.
Results: Pronounced inter-treatment variability was documented across multiple life-history parameters. Oral ingestion of the toxic nutrient matrix dramatically curtailed adult longevity by 6.067 days and median lethally diminished reproductive output by 309.3 eggs, while concurrently suppressing parental egg viability by 52.01% relative to untreated controls. Pronotal topical application demonstrated negligible effects on parental demographic metrics but significantly compromised F_1 egg hatchability by 42.93%. Tarsal contact exposure exerted the most profound transgenerational perturbations, prolonging F_1 larval developmental duration by 2.969 days, augmenting pupal biomass by 0.008 g, and extending pupal metamorphic chronometry by 17.6 hours. Additionally, this treatment modality reduced F_1 egg viability by 42.83%, decreased F_1 fecundity by 411.9 eggs, suppressed imaginal emergence rates by 30.8%, and elevated developmental malformation incidence by 5.28%.
Discussion: These findings demonstrate that delivery methodology fundamentally modulates chlorantraniliprole's demographic impact trajectory, with oral administration optimizing parental suppression while pedal contact maximizing transgenerational attenuation of *S. exigua* population dynamics. Future research should explore developing chlorantraniliprole-laced food attractants and advancing pest control timing to enhance efficacy.

KEYWORDS

***Spodoptera exigua*, chlorantraniliprole, median lethal effects, adult control, application methods**

1 Introduction

The beet armyworm, *S. exigua*, a ubiquitous and voracious lepidopteran pest, has emerged as an increasingly phytophagous pest, inducing severe foliar abscission in *Gossypium* spp., diverse horticultural cultivars, and ornamental flora. This highly adaptable phytophagous noctuid, renowned for its polyphagous nature, wreaks havoc on an extensive spectrum of agricultural commodities, including but not limited to potatoes, tomatoes, beans, peas, asparagus, tobacco, cotton, cereals and chickpea cultivations (Rajesh Chowdary et al., 2024). Particularly in tropical and subtropical regions, early-instar larvae feed on leaf mesophyll, leaving translucent "window-like" epidermis, while older larvae create notches in leaves and may completely defoliate plants, leaving only the midrib. Severe infestations disrupt crop growth and development; besides damaging leaves, larvae also bore into fruits and flower buds (Idris and Emelia, 2001). With its remarkable ability to exploit diverse host plants across varied agroecosystems, *S. exigua* has established itself as a pervasive menace in global agriculture. The pest's capacity to thrive during seasonal transitions allows it to perpetuate its destructive cycle, sowing the seeds of impending agricultural calamities. As it traverses from one crop to another, the beet armyworm engenders a cascade of latent threats that ultimately manifest as severe and widespread crop damage (Richardson et al., 2020; Hafeez et al., 2022a).

Arthropod herbivores represent a significant biotic stressor to global agricultural productivity and zoonotic health. Phytophagous insects inflict annual reductions in crop biomass estimated at 18-20% of total primary production, equivalent to a monetary deficit exceeding 470 billion USD (Hafeez et al., 2022a). Chemical pest management, particularly the application of synthetic insecticides, remains a crucial component of modern agronomic practices, facilitating crop protection through the suppression of pestiferous arthropod populations, including *S. exigua* (Xu et al., 2016). The primary xenobiotic intervention for *S. exigua* population suppression currently relies on chemical control methodologies. However, this lepidopteran taxon exhibits remarkable genomic plasticity and elevated fecundity. Under intense anthropogenic selection pressure, *S. exigua* has evolved resistance mechanisms against diverse insecticidal compounds (Che et al., 2013), including macrocyclic lactones such as diacyl hydrazine ecdysone agonists like tebufenozide (Moulton et al., 2002), spinosyns (Osorio et al., 2008), anthranilic diamides (Zuo et al., 2020), and *Bacillus thuringiensis*-derived crystalline endotoxins (Moar et al., 1995).

Diamide insecticides, demonstrating particular efficacy against lepidopteran pests, comprise four commercialized variants: the anthranilic diamides chlorantraniliprole (Cordova et al., 2006), and the phthalic diamide flubendiamide (Tohnishi et al., 2005), cyantraniliprole (Jeanguenat, 2013), and cyclaniliprole (Sparks and Nauen, 2015). Chlorantraniliprole, the inaugural commercialized ryanodine receptor modulator from the anthranilic diamide class, exhibits exceptional insecticidal potency against a spectrum of lepidopteran taxa (Lahm et al., 2009). The molecular mechanisms underpinning chlorantraniliprole's efficacy involve perturbation of calcium homeostasis in insect muscle tissue, leading to feeding cessation, paralysis, and ultimately, mortality. Chlorantraniliprole, a novel diamide insecticide targeting insect ryanodine receptors (RyR), induces calcium ion release by activating RyR, leading to neuromuscular paralysis (Chen et al., 2019). While effective against lepidopteran pests, its widespread field use has accelerated resistance development in target species (Sial and Brunner, 2010). Recent studies indicate that *S. exigua* populations exhibit varying resistance risks to chlorantraniliprole, with some reaching high resistance levels (Lai et al., 2011).

Current control strategies for *S. exigua* rely heavily on chemical insecticides, primarily targeting the larval stage. However, adult *S. exigua* exhibit strong reproductive capacity, seasonal host-switching behavior, and long-distance migration, which drive rapid population surges and regional outbreaks (Zhang et al., 2020). Therefore, enhancing adult-stage control is critical to reducing the population base, limiting dispersal, and achieving regional suppression.

Chemical-based food attractants constitute a potential for resistance management strategies. These formulations selectively attract both male and female adults across multiple lepidopteran taxa (Utrio and Eriksson, 1977; Del Socorro et al., 2010). Commercially deployed systems have demonstrated significant suppression of economically critical Lepidopteran pests. Current *S. exigua* management, including *Spodoptera frugiperda* (J.E. Smith, 1797) (Lepidoptera: Noctuidae) and *Helicoverpa armigera* (Hübner, 1808) (Lepidoptera: Noctuidae)in key cropping systems (cotton, maize) throughout Australia, the United States, and South Africa (Mensah et al., 2013; Gregg et al., 2016; Justiniano et al., 2021).

Within China, the field efficacy of the biological food attractant exhibits crop-specific variability (Xiu et al., 2018; Wang et al., 2023). Preliminary studies document its trapping efficiency against *H. armigera*, *S. exigua*, *Spodoptera litura* (Fabricius, 1775) (Lepidoptera: Noctuidae), and *Agrotis ipsilon* (Hufnagel, 1766) (Lepidoptera: Noctuidae) adults in localized peanut agroecosystems (Shandong Province) (Wang et al., 2024). This study investigates median lethal effects of chlorantraniliprole on adult *S. exigua* and their offspring using three application methods. The findings aim to advance eco-friendly pest management strategies.

2 Materials and methods

The experiment was conducted in 2024 at the Insect Ecology Laboratory, College of Plant Protection, Yangzhou University.

2.1 Insect source

S. exigua larvae were collected in July 2024 from an asparagus field in Jiangyan District, Taizhou City, Jiangsu Province, China (120.2532541°N, 32.50480302°E).

2.1.2 Insect rearing

Larvae were maintained in artificial climate chambers at coordinates 120.2532541°N, 32.50480302°E, under controlled

conditions (27 ± 1°C, 16L:8D photoperiod, 65–75% relative humidity). Larvae were fed an artificial diet until they pupated. Newly emerged adults were paired (1♀:1♂) in plastic containers (diameter 8.5 cm, height 5.6 cm) and provided with 10% honey water for nutrition (Hafeez et al., 2022b). Used subsequently for treatment, three groups were established, each comprising 10 pairs of healthy adults, and a control group. Egg masses laid on the surfaces of the plastic cups were harvested by cutting out the relevant sections of the cup, which were then placed directly into paper boxes (diameter 4.3 cm, height 1 cm) for incubation for larval hatching, allowing the study to continue across generations.

2.1.3 Diet preparation

The artificial diet for *S. exigua* was prepared using a mixture of 100g of soybean meal, 100g of cornmeal, 50g of wheat bran, 80g of yeast powder, and 5g of casein. Bake at 120°C for 2 hours. Then use 25g agar, 10g sugar, and 1000 mL of water. After boiling, add the dried mixture along with 5g of sorbic acid, 3g of citric acid, 5g of ascorbic acid, 2g of multivitamins, 1g of cholesterol, and 1g of choline chloride. Stir thoroughly and cook until done, then wait for it to cool before using it for feeding. This formulation was adapted and modified based on previously established protocols (Cohen, 2003), as well as incorporating insights from Singh and Moore (1985). The diet was designed to ensure optimal growth and development of the larvae under controlled laboratory conditions.

2.2 Test chemicals

- 96% chlorantraniliprole technical material (Shanxi Qixing Pesticide Co., Ltd.).
- Methanol and Triton X-100 (Sinopharm Chemical Reagent Co., Ltd.).

2.3 Experimental methods

2.3.1 Bioassay

The leaf immersion method Following Chinese standards NY/T 1154.14-2008 (Guidelines for Laboratory Bioassay of Insecticides – Part 14: Leaf Dip Method) and NY/T 2361-2013 (Technical Code for Monitoring Resistance in Vegetable Noctuidae Pests), fresh amaranth leaves were dipped in chlorantraniliprole solutions (25, 50, 100, 200, 400 mg/L) diluted from a 1 g/L stock using 0.1% Triton X-100. After air-drying, 3rd-instar larvae were placed on treated leaves in Petri dishes. Mortality was assessed after 48 hours; larvae unresponsive to gentle brush probing were considered dead.

2.3.2 Toxic honey water feeding

A 1 g/L chlorantraniliprole stock solution was prepared by dissolving 0.01 g technical material in 10 mL of methanol. For the working solution (113.5 mg/L), 4.54 mL stock was mixed with 10% honey water to a final volume of 40 mL. Adult pairs (30 per group with three replicates having 10 adults each) were housed in plastic boxes with cotton balls soaked in the toxic solution. Controls received 10% honey water alone. Mortality was recorded after 24 hours (non-flying, unresponsive adults counted as dead).

2.3.3 Dorsal thoracic plate micro application method

The pesticide solution was prepared by diluting 4.54 mL of a stock solution (1 g/L chlorantraniliprole) with 0.1% Triton X-100 "which acts as a surfactant to enhance wetting and permeability, thereby facilitating better penetration of the insecticide through the insect cuticle" to a final volume of 40 mL, achieving a LC50 concentration of 113.5 mg/L for the experimental group. For the control group, 4.54 mL of methanol was similarly diluted to 40 mL with 0.1% Triton X-100. Following the method (Huang et al., 2016) with minor modifications, newly emerged adults were paired (one male and one female), and 0.5 µL of either the experimental or control solution was applied to the dorsal thoracic plate of each adult using a micro applicator (Yu et al., 1984). Each replicate comprised 10 pairs of adults, with a total of 30 adults per group were housed in plastic boxes. Both groups were reared under identical conditions, and mortality was assessed after 24 hours. Adults that exhibited an inability to fly normally and showed no response to tactile stimulation were recorded as dead.

2.3.4 Tarsal contact exposure

Per NY/T 1154.14-2008 (*Insecticide Laboratory Bioassay Guidelines – Part 8: Filter Paper Residue Method*), The pesticide solution was prepared by diluting 4.54 mL of a stock solution (1 g/L chlorantraniliprole) with 0.1% Triton X-100" to a final volume of 40 mL, achieving a LC50 concentration of 113.5 mg/L for the experimental group solution was evenly applied to filter paper lining insect-rearing boxes. After solvent evaporation, adult pairs were introduced for 15 minutes of tarsal contact. Each replicate comprised 10 pairs of adults, with a total of 30 adults per group were housed in plastic boxes. Controls used untreated solutions; 4.54 mL of methanol was similarly diluted to 40 mL with 0.1% Triton X-100. Mortality was assessed after 24 hours.

$$\text{Mortality rate}\,(\%) = \frac{\textit{Number of dead insects}}{\text{Total number of treated insects}} \times 100\,\%$$

$$\textit{Corrected mortality}\,(\%) = \frac{\textit{Treatment mortality} - \textit{Control mortality}}{\text{Control mortality} - 1} \times 100\,\%$$

2.3.5 Assessment of transgenerational biological traits

Following the exposure of parental (P) generation adults to the median lethal concentration (LC_{50}) of chlorantraniliprole via the three application methods, the resulting biological impacts on both the surviving P adults and their F_1 offspring were systematically evaluated.

For the Parental (P) Generation, the biological impacts on surviving adults were assessed by recording adult longevity, calculated in days until death. Daily fecundity was evaluated by collecting all egg masses and counting the total number of eggs per female under a stereomicroscope (Motic, Model SMZ-171). Fertility, expressed as the egg hatch rate, was determined by maintaining the collected eggs under standard rearing conditions (27 ± 1°C, 16L:8D photoperiod, 65–75% relative humidity) and calculating the percentage of eggs that successfully hatched into larvae.

For the F_1 Offspring Generation, individuals were monitored throughout their development without further insecticide exposure via the two application methods (since the F_1 generation was not produced from the toxin-honey water feeding treatment in the parental generation due to complete adult mortality). New eggs that successfully hatched into larvae (larval F_1 n=30 per replicate) were individually reared to track larval duration (from hatching to pupation) and pupal duration calculated in hours (from pupation to adult). Pupae were weighed 24 hours after formation using a precision electronic balance (Sartorius, Model BSA124S). Pupation rate was calculated as the percentage of larvae that successfully pupated, and eclosion rate was determined as the percentage of pupae that developed into adults. The deformity rate was recorded as the percentage of F_1 individuals exhibiting morphological abnormalities in the pupal or adult stage.

Bioassay results were analyzed using Abbott's formula (Abbott, 1925) to calculate corrected mortality. The toxicological regression equation and median lethal concentration (LC50) were computed using IBM SPSS Statistics 26. Differences in parental adult lifespan, fecundity, egg hatch rate, and offspring larval duration, pupal weight, pupal period, adult emergence rate, deformity rate, adult lifespan, and sex ratio were analyzed with IBM SPSS Statistics 26 and visualized using GraphPad Prism 9. Normality and homogeneity of variance were tested, followed by one-way ANOVA, independent-sample t-tests, and Mann-Whitney U tests.

3 Results and analysis

3.1 Median lethal concentration (LC_{50}) of chlorantraniliprole on 3rd-instar *S. exigua* larvae

The LC_{50} of chlorantraniliprole for 3rd-instar *S. exigua* larvae was 113.518 mg/L (Table 1). This concentration was used to evaluate its effects on adult *S. exigua* and offspring development.

3.2 Effects of different median lethal chlorantraniliprole treatments on adult *Spodoptera exigua* and F1 egg hatchability

The ingestion of a toxic nutrient solution by *S. exigua* adults resulted in a marked suppression of parental egg hatchability (P< 0.001), with treated cohorts exhibiting a 52.01% reduction relative to controls (Figure 1). The other two treatment methods didn't significantly affect egg hatchability (P > 0.05). Additionally, there were no significant differences in the impact of these three treatment methods on egg hatchability (P > 0.05). Treating *S. exigua* by topical application to the pronotum had no significant effect on the hatchability of F1 adult eggs (P > 0.05). In contrast, the tarsal contact treatment significantly reduced the hatchability of F1 adult eggs (P< 0.01). Compared to the control group, these two treatments decreased F1 egg hatchability by 42.93% and 42.83%, respectively (Figure 1). However, there was no significant difference in their effects on F1 egg hatchability (P > 0.05).

3.2 Effects of different median lethal chlorantraniliprole treatments on larval development duration of *Spodoptera exigua* F1 generation

Exposure to median lethal chlorantraniliprole through tarsal contact markedly extended the larval stage duration in the F1 generation of *S. exigua* (P< 0.0001), with an increase of 2.969 days compared to untreated controls (Figure 2). In contrast, pronotal topical application didn't produce a statistically significant alteration in larval development time (P > 0.05). Furthermore, no significant difference was observed between the two treatment methods in their impact on larval duration (P > 0.05)."

3.4 Effects of different median lethal chlorantraniliprole treatments on F1 pupal development in *Spodoptera exigua*

The F1 generation exhibited significant changes in pupal weight and duration following tarsal contact treatment. Pupal weight rose by 0.008 g (P< 0.001), while pupal duration lengthened by 17.6 hours (P< 0.01) compared to the control (Figure 3). In contrast, pronotal topical application showed no significant influence on either pupal weight or duration (P > 0.05). While the two treatments did not differ significantly in their impact on pupal weight (P > 0.05), their effects on pupal duration were markedly distinct (P< 0.01).

TABLE 1 Median lethal concentration (LC_{50}) of chlorantraniliprole on 3rd-instar *S. exigua* larvae.

Test subject	Number of larvae	LC50 (mg/L)	Slope ± SE	Chi-Square	R^2
3rd-instar larvae	200	113.518 mg/L (99.677–129.668)	0.215 ± 0.047	3.945	0.834

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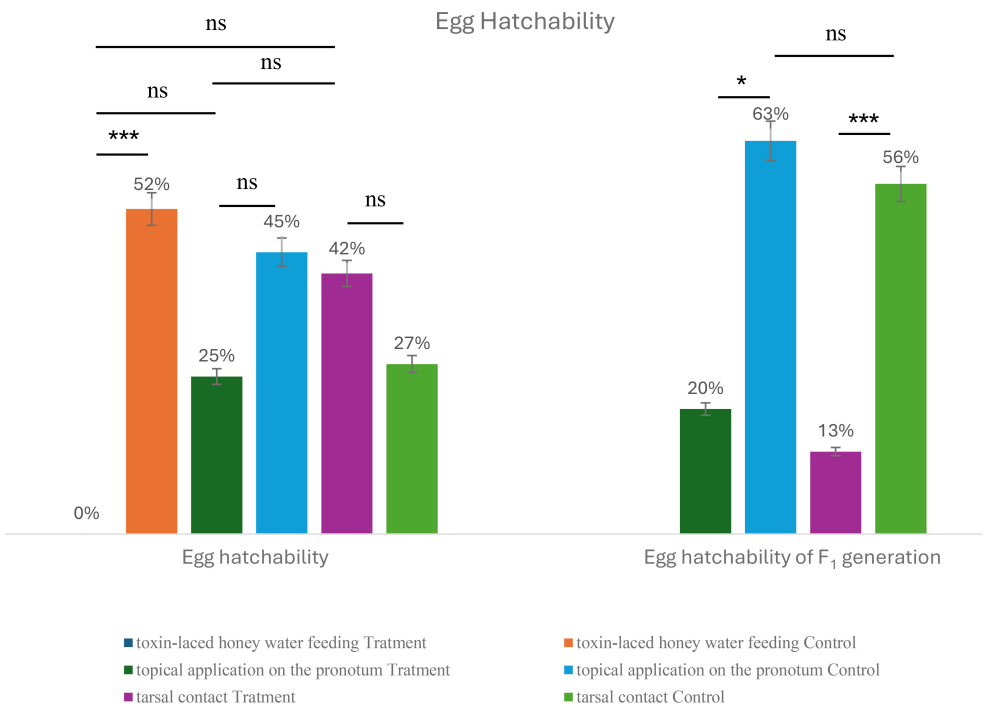

FIGURE 1
Impact of median lethal chlorantraniliprole treatments on adults and F1 egg hatchability in Spodoptera exigua (Except for the intragroup differences in the parental tarsal contact group, which were analyzed using the Mann-Whitney U test, other intragroup differences were analyzed using independent sample t-tests. Intergroup differences were assessed using one-way ANOVA. Asterisks (*) on the bars indicate significant differences (*P< 0.05, ***P<0.001). The adult eggs in the toxic nutrient solution feeding treatment group did not hatch, resulting in no offspring. All subsequent F1 data analyses were based on this condition.). ns, not significant.

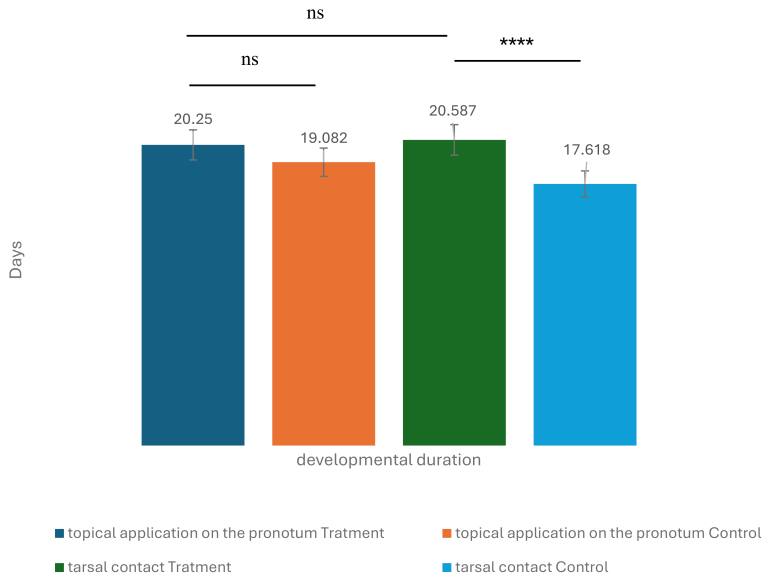

FIGURE 2
Impact of median lethal chlorantraniliprole exposure on larval development duration of beet armyworm F1 generation (Data were analyzed using independent sample t-tests. Asterisks (*) on the bars indicate significant differences (****P<0.0001). ns, not significant.

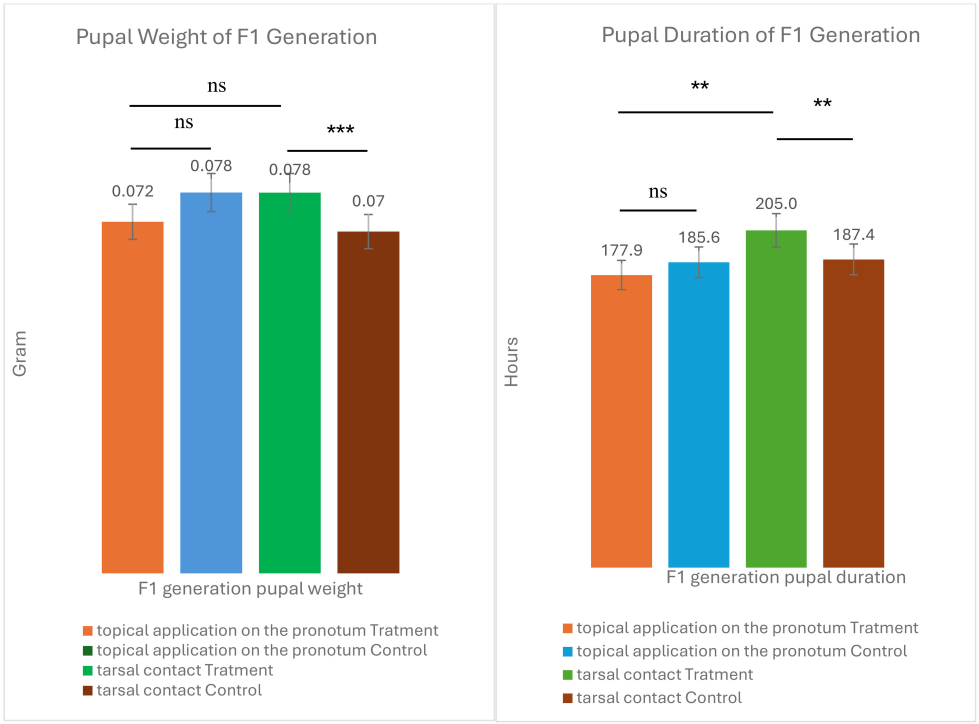

FIGURE 3
Effects of median lethal chlorantraniliprole treatments on F1 pupal weight in Spodoptera exigua and on pupal duration of F1 generation in Spodoptera exigua (Pupal weight data in Figure 3 were analyzed using independent sample t-tests, while pupal duration data were analyzed using the Mann-Whitney U test. Asterisks (*) indicate significant differences (**P<0.01, ***P<0.001). ns, not significant.

3.5 Effects of different median lethal chlorantraniliprole treatments on adult lifespan across generations in *Spodoptera exigua*

Median lethal chlorantraniliprole exposure differentially influenced adult longevity. When adults consumed a toxic nutrient solution, their lifespan was drastically reduced by 6.067 days (Figure 4) relative to controls (P< 0.0001). In contrast, the remaining two treatments showed no significant lifespan alteration (P > 0.05). The toxic nutrient solution had a median lethal greater negative effect compared to pronotum topical application and tarsal contact, shortening lifespan by 9.167 days (P< 0.0001) and 11.2 days (P< 0.0001), respectively (Figure 4).

While pronotum application slightly extended F1 adult lifespan (2.1 days) and tarsal contact marginally reduced it (1.433 days) (Figure 4), neither effect was statistically significant (P > 0.05). Additionally, no significant difference was observed between these two treatments (P > 0.05).

3.6 Effects of different median lethal chlorantraniliprole treatments on fecundity in *Spodoptera exigua* across generations

Feeding adults a toxic nutrient solution significantly reduced fecundity (P< 0.001), decreasing egg production by 309.3 eggs compared to the control group (Figure 5). The other two treatments had no significant effect (P > 0.05). The toxic nutrient solution's impact on fecundity differed significantly from the effects of topical pronotum application and tarsal contact, reducing egg production by 249.9 eggs (P< 0.0001) and 368.6 eggs (P< 0.0001), respectively (Figure 5).

Tarsal contact treatment significantly reduced F1 adult fecundity (P< 0.001), decreasing egg production by 411.9 eggs compared to the control group (Figure 5). Topical pronotum application had no significant effect (P > 0.05). There was no significant difference between the two treatments (P > 0.05).

3.7 Effects of different median lethal chlorantraniliprole treatments on F1 adult emergence rate, malformation rate, and sex ratio in *Spodoptera exigua*

The adult emergence rate of the F1 generation remained unaffected by topical pronotum application (P > 0.05). In contrast, tarsal contact exposure caused a significant 30.8% (Figure 6) decline in emergence rate relative to controls (P< 0.05), with a statistically distinguishable impact between the two application methods (P< 0.05). Regarding adult malformations, tarsal contact induced a marked 5.28% (Figure 6) increase in deformity incidence (P< 0.05), whereas pronotum treatment

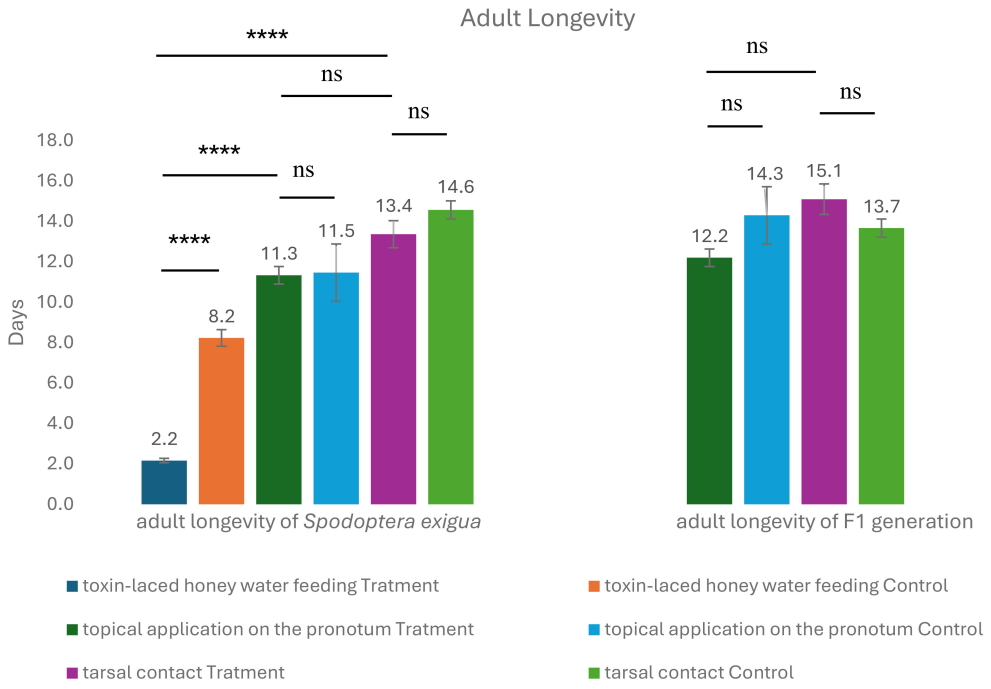

FIGURE 4
Impact of median lethal chlorantraniliprole treatments on adult lifespan across generations in Spodoptera exigua(Intragroup differences in parental adults fed toxic nutrient solution, topical pronotum application, and F1 tarsal contact were analyzed using the Mann-Whitney U test. Intragroup differences in parental tarsal contact and F1 topical pronotum application were analyzed using independent sample t-tests. Intergroup differences in F1 treatments were assessed using the Kruskal-Wallis test. Asterisks (*) indicate significant differences (***P<0.001, ****P<0.0001). ns, not significant.

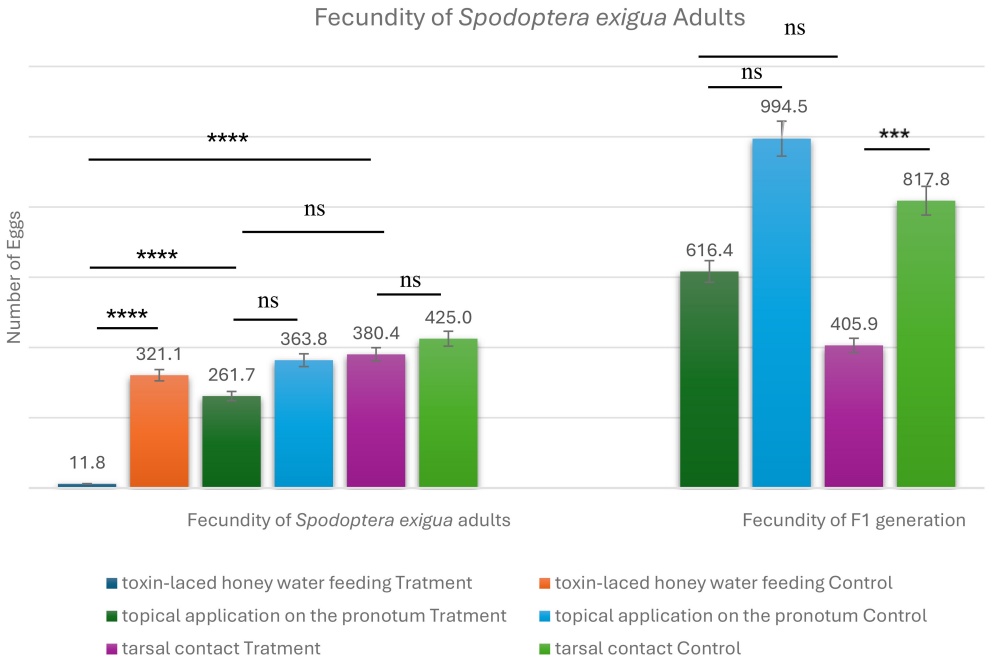

FIGURE 5
Effects of median lethal chlorantraniliprole treatments on fecundity in Spodoptera exigua across generations(Intragroup differences in parental adults fed toxic nutrient solution, topical pronotum application, and F1 tarsal contact were analyzed using the Mann-Whitney U test. Intragroup differences in parental topical pronotum application, F1 tarsal contact, and intergroup differences were analyzed using independent sample t-tests. Intergroup differences in parental treatments were assessed using the Kruskal-Wallis test. Asterisks (*) indicate significant differences (***P<0.001, ****P<0.0001). ns, not significant.

showed no significant influence ($P > 0.05$). The two application methods did not differ significantly in their effects on malformation rates ($P > 0.05$). Both treatments produced modest elevations in the F1 sex ratio (pronotum: +0.1612; tarsal: +0.1432) (Figure 6), though these changes lacked statistical significance ($P > 0.05$). Furthermore, no significant differential effect was detected between the treatment modalities ($P > 0.05$).

4 Discussion

The invasive lepidopteran pest S. exigua poses a significant phytophagous threat to economically important crops in the world, with potential for complete crop devastation if left unmanaged. The mode of action of chlorantraniliprole operates within the framework of muscular physiology, whereas the binding to these receptors prompts uncontrolled calcium release, leading to impaired muscle function and persistent contractions (Akhtar et al., 2022). These data concord with our experimental outcomes, likely because chlorantraniliprole absorbed via the digestive system acts on ryanodine receptors in adults, causing muscle paralysis and neurological dysfunction.

Regarding effects on adults, this study revealed that treating beet armyworm adults with median lethal concentrations of chlorantraniliprole through distinct methods differentially impacted their own and their offspring's growth, development, and reproduction. The physiological impact on lepidopterans following the administration of a median lethal concentration of chlorantraniliprole is significant. This directly impairs mobility, foraging, and reproductive capacity, ultimately shortening lifespan, reducing egg production, and lowering hatch rates. Corroborating evidence from (Hasnain et al., 2023) revealed that median lethal chlorantraniliprole exposure significantly compromised female longevity and fecundity in *S. frugiperda*. Similarly (Zeng et al., 2006), reported that median lethal imidacloprid doses induced reproductive suppression and abbreviated adult lifespan in *Myzus persicae*. Furthermore, corroborating this mechanism, exposure through nutrient sources in the present study elicited median lethal physiological perturbations in adults, manifesting as reduced longevity, diminished oviposition capacity, and impaired embryonic viability, which was in agreement (Teixeira et al., 2009; Han et al., 2012). Notably, toxic nutrient feeding differed significantly from dorsal thoracic plate microapplication and tarsal contact in its effects on adult lifespan and fecundity (Zhou Chao et al., 2011). found that chlorantraniliprole's toxicity via toxic nutrient feeding was 2.17 times higher than via adult contact film assays, confirming its stronger stomach toxicity over contact efficacy, consistent with our findings. Median lethal

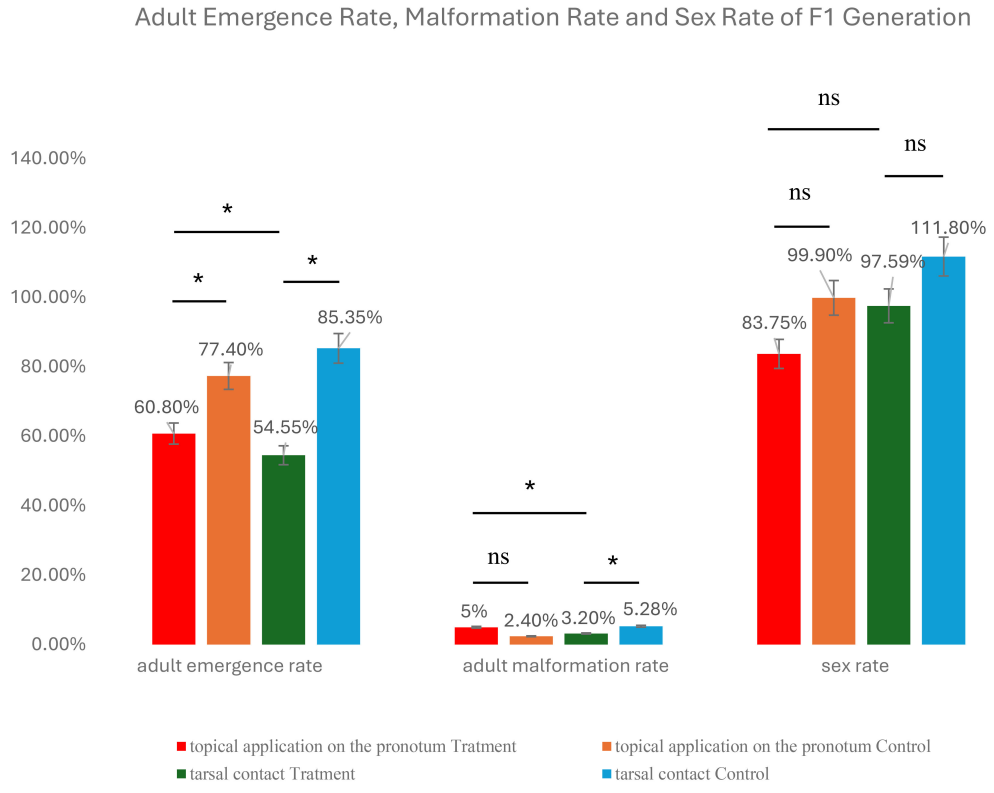

FIGURE 6
Effects of median lethal chlorantraniliprole treatments on emergence rate, malformation rate, and sex ratio of F1 adults in Spodoptera exigua (Data on emergence rate and malformation rate (topical pronotum application intragroup and intergroup differences) were analyzed using the Mann-Whitney U test. Data on sex ratio and malformation rate (tarsal contact intragroup differences) were analyzed using independent sample t-tests. Asterisks (*) indicate significant differences (*P< 0.05). ns, not significant.

concentrations of cyantraniliprole induce significant transgenerational effects in *S. frugiperda*, manifesting as prolonged development and reduced fecundity across both the directly exposed (F_0) and subsequent (F_1) generations (Abbas et al., 2025) This decline in relative fitness and population growth inhibition underscores the potential of cyantraniliprole to exert sustained suppressive pressure on this pest. Concerning effects on eggs, the ovicidal efficacy profile differed, with thiodicarb showing greater potency than chlorantraniliprole against egg stages (Mao et al., 2023). Tarsal contact and dorsal thoracic plate microapplication with LC50 chlorantraniliprole significantly reduced F1 egg hatch rates, with tarsal contact also suppressing F1 egg production. Studies by (Ou et al., 2012; Batool et al., 2024) corroborated these findings. Residual toxins transferred via eggs may impair ovarian development in offspring, reducing egg quality and quantity.

For larvae and pupae, this anthranilic diamide insecticide, which targets ryanodine receptors, surpassing emamectin benzoate, flubendiamide, spinetoram, spinosad, and azadirachtin in larvicidal potency (Mahesh et al., 2020; Moustafa et al., 2024). Notably, chlorantraniliprole targeting ryanodine receptors demonstrated superior larvicidal efficacy against *S. frugiperda* at 72 hours post-application (Guruprasad et al., 2024). Our investigation revealed that tarsal exposure to LC50 chlorantraniliprole induced pronounced transgenerational developmental inhibition in *S. exigua*, manifested through protracted larval and pupal stadia, elevated imaginal morphogenetic aberrations, augmented pupal biomass accumulation, and diminished eclosion success. Dorsal thoracic plate microapplication similarly disrupted F1 progeny viability through reduced emergence rates. Also, our findings on the transgenerational impact are similarly in accordance (Ali et al., 2021), who found that the developmental stages of the larval and pupal stages were severely altered in comparison to the control. This phenotypic disruption aligns with documented arthrological cross-generational effects across (Akhtar et al., 2022) observed significant alterations in biological parameters across multiple generations of S. *frugiperda* exposed to median lethal concentrations of chlorantraniliprole, including prolonged larval and adult durations and reduced fecundity in later generations, while (Guo et al., 2013) reported congruent developmental arrest in chlorantraniliprole-exposed *Plutella xylostella* (Linnaeus, 1758) (Zeng et al., 2006). identified parallel suppression of eclosion dynamics in imidacloprid-challenged *Myzus persicae* (Sulzer, 1776), and (Yu et al., 2015) documented hypertrophic pupal phenotypes in cyantraniliprole-treated *S. exigua* cohorts, mirroring our biomass anomalies. Furthermore (Sun et al., 2019), demonstrated reduced pupal malformation and emergence rates in metaflumizone-treated *S. exigua*, reinforcing the broader neuroendocrine and morphogenetic perturbations induced by sodium channel blocker insecticides across insect lineages. The extended larval and pupal stages may result from toxin transfer via eggs, impairing embryonic development and causing larvae to exhibit reduced activity, limited foraging, and slower growth. Extended larval feeding phases could also lead to greater nutrient accumulation, increasing pupal weight. Contrastingly (Zhang et al., 2023), observed reduced pupal weights in F1 fall armyworms (*S. frugiperda*) treated with LC25 emamectin benzoate and chlorantraniliprole, possibly due to differences in concentration or developmental stage. Prolonged toxin exposure likely disrupts neural regulation and muscle development during pupation, leading to malformed adults and reduced emergence rates.

Overall, tarsal contact outperformed dorsal thoracic plate micro application in suppressing beet armyworm growth and reproduction. These stage-specific and dose-dependent variations in insecticidal efficacy underscore the importance of targeted application strategies. Given its history of insecticide resistance development and rapid global dissemination, further elucidation of chlorantraniliprole's mode of action and potential synergistic effects with other compounds may enhance its role in integrated pest management programs for *S. frugiperda* (Kumar et al., 2022). However, different application methods yield varying control efficiencies (Zhou Chao et al., 2011). This study evaluated three methods for applying median lethal chlorantraniliprole to beet armyworm adults, offering insights for eco-friendly pest control (Yao et al., 2018). emphasized targeting adult stages during peak oviposition, exposure of 3rd instar larvae to median lethal concentrations of chlorantraniliprole resulted in decreased fecundity in adult *Chilo suppressalis* (Walker, 1863) (Lepidoptera: Crambidae) females. Chlorantraniliprole resulted in greater than 90% mortality on new leaves at all evaluation intervals (Adams et al., 2016). Our findings suggest that spraying chlorantraniliprole formulations during adult stages could suppress population expansion by reducing egg production and quality. Toxic nutrient feeding with median lethal chlorantraniliprole significantly lowered adult fecundity and population growth potential. Field applications could integrate chlorantraniliprole-laced honey baits with traps or direct sprays to attract and kill adults during outbreaks, reducing migration and subsequent generations. 75.81% and 67.01% female mortality in *H. armigera* was found using attractants mixed with low-dose chlorantraniliprole (Zhang et al., 2020). Another study demonstrated significant efficacy of chlorantraniliprole against migratory moths *A. ipsilon* and *A. segetum* was demonstrated when combined with attractants. Low doses of chlorantraniliprole (LC20 and LC50) resulted in median lethal adult mortality. The study also reported significant reductions in fecundity, effective oviposition rate, and egg hatching rate in both species (Zhang et al., 2022). These collective findings underscored the multifaceted impacts of median lethal insecticide exposure on insect population dynamics, emphasizing the importance of comprehensive toxicological assessments across various life stages and physiological parameters for effective integrated pest management strategies. These findings highlight the potential of low-dose chlorantraniliprole with attractants as an effective strategy for managing migratory moth populations, while emphasizing the need to consider long-term effects on pest dynamics and flight performance. And also, these findings collectively underscore the complex and multifaceted effects of chlorantraniliprole and related

compounds on lepidopteran pests, highlighting the need for a comprehensive assessment of both lethal and median lethal effects in developing effective and sustainable pest management strategies.

5 Conclusion

This study demonstrates that a median lethal concentration of chlorantraniliprole (LC_{50} = 113.518 mg/L) significantly impacts the survival, reproduction, and development of *S. exigua* adults and their offspring, with method-dependent efficacy. Toxic honey water feeding caused the highest adult mortality, while tarsal contact exposure induced the strongest transgenerational effects, including prolonged larval and pupal durations, increased pupal weight and deformity rates, and reduced emergence and egg hatch rates. These results underscore the potential of chlorantraniliprole in adult-stage integrated pest management (IPM) and highlight the need for context-appropriate application techniques, such as bait formulations for population suppression or spray timing to coincide with adult activity, to proactively mitigate resistance and reduce reliance on larval-targeted insecticides.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

LW: Writing – review & editing, Conceptualization, Software, Methodology. ZZ: Writing – original draft, Investigation, Data curation, Software, Methodology, Writing – review & editing, Formal Analysis. MA: Writing – original draft, Investigation, Writing – review & editing. YL: Software, Writing – review & editing, Investigation, Methodology. CY: Writing – review & editing, Methodology, Formal Analysis, Software, Data curation. QG: Writing – review & editing, Methodology, Data curation, Formal Analysis. HS: Visualization, Conceptualization, Resources, Writing – review & editing, Supervision, Validation, Project administration, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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