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Sublethal Effects of Three Insecticides on Development and Reproduction of *Spodoptera frugiperda* (*Lepidoptera*: *Noctuidae*)

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Abstract: *Spodoptera frugiperda* is a serious invasive pest, which has attracted attention globally in recent years. Research on the sublethal effects of common insecticides on *S. frugiperda* is important for its comprehensive management in the field. In this paper, the sublethal effects have been studied for *S. frugiperda* exposed to the LC_{30} concentration of three insecticides, chlorantraniliprole, dinotefuran, and beta-cypermethrin. The results showed that the pupation rates of the treatment groups were significantly lower than that of control group, but there were no significant differences in the eclosion rate. Chlorantraniliprole and beta-cypermethrin significantly inhibited fecundity of the F_0 and F_1 generations, and the number of eggs laid per female decreased by 67.4% and 43.1%, respectively, and that of the F_1 generation decreased by 28.0% and 21.7%, respectively. The intrinsic growth rate (r_m), net growth rate (R_0), and weekly growth rate (λ) of the F_0 generation in the chlorantraniliprole and beta-cypermethrin treatment groups were significantly lower than those in the control group. Additionally, dinotefuran had a certain role in promoting oviposition in the F_0 and F_1 generations, which may stimulate the growth of offspring population and cause the resurgence of pests. The results provide a reference for the effective implementation of the IPM plan in the field to control *S. frugiperda*.

Keywords: fall armyworm; chlorantraniliprole; dinotefuran; beta-cypermethrin; life table

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1. Introduction

The fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), is a pest and casts a great threat over crop production worldwide due to its strong migratory and omnivorous characteristics and its adaptability; it has become a major cross-border and intercontinental agricultural pest [1–5]. The invasion of *S. frugiperda* was first reported in Yunnan Province of China in 2019 [6], and it has rapidly spread to many provinces, causing serious economic losses to local crops, such as corn [7–9]. Currently, the application of chemicals to reduce yield loss remains a practical and important measure.

In addition to directly killing the target pests, the use of insecticides can also cause sublethal effects on the growth and reproduction of pests. The more common indicators for efficacy evaluation of insecticides are the median lethal dose (LD_{50}) or median lethal concentration (LC_{50}) of insecticides, but the sublethal concentration can also be used to evaluate the toxicity of pesticides to pests. Many active components of chemicals left over in the field are diluted by the natural water (rain drop, dew, etc.). The insecticide itself would gradually degrade into low doses or sublethal doses, which are defined as inducing no apparent mortality in the experimental population. Sublethal effects are defined as

biological, physiological, or behavioral effects on individual insects or populations that survive exposure to a toxicant at lethal or sublethal doses [10].

All insecticides can have lethal and sublethal effects on insects in various ways, such as physiology, behavior, fecundity, and development. For example, sublethal concentration treatment with farnesyl acetate, methylthio-diafenthiuron, and chlorantraniliprole significantly delayed the larval or pupal development time of *Plutella xylostella* [11–13]. Treatment with chlorantraniliprole LC_{30} and LC_{50} significantly extended the larval development period and significantly reduced the rate of pupation and egg hatching of *Spodoptera exigua* [14]. In addition, treatment of *Spodoptera exigua* larvae at a sublethal concentration (LC_{20}) in indinavius indoxacarb significantly prolonged the courtship cycle of female adults [15]. In general, exposure to pesticides can affect an insect's mating and reproduction negatively. In the case of *P. xylostella* treated with chlorantraniliprole, the egg numbers per female decreased significantly in the parent generation [16,17], and the hatching of eggs laid per female of the F_1 generation was significantly decreased [16]. However, treated by the sublethal concentration of chlorantraniliprole, the fecundity of *Helicoverpa armigera* is significantly reduced only when both females and males are exposed. It showed a significant impact on the population dynamics of *H. armigera*, such as the net reproductive rate, intrinsic growth rate, and total reproductive rate when the sublethal concentrations are significantly lower than those in the control group [18]. The reproduction of generations F_0 and F_1 of *P. xylostella* was severely disturbed by exposure to sublethal concentrations of chlorantraniliprole [11]. The reproduction of *P. xylostella* was negatively affected when the higher sublethal concentration (LC_{25}) was only treated on male adults or female adults. However, the fecundity of *P. xylostella* was significantly reduced only when both females and males were exposed to low sublethal concentrations (LC_{10}) at the same time [17]. Batuxi et al. showed that the larvae of *S. frugiperda* fed on the leaves grown after the treatment of corn seeds with thiamethoxam seed-coating agent, the duration and generation cycle were prolonged with the increase of the thiamethoxam concentration, and the larval survival rate, pupation rate, and emergence rate decreased with the increase of the thiamethoxam concentration [18]. Spinetoram at sublethal concentrations significantly delayed the developmental time of *S. frugiperda* but significantly reduced the weight of larvae [19]. *H. armigera* larvae that were exposed to an LC_{30} concentration of methoxyfenozide exhibited lower pupal weight and increased larval and pupal developmental times compared with thiodicarb-treated larvae or control larvae [20].

In addition, more studies have shown that the sublethal effect of insecticides might lead target insect pests to evolve resistance and resurgence [21–25]. The reason might be that the use of insecticides directly kills quite a few natural enemies, leading to the rapid increase of the pest population due to the lack of control of natural enemies [10]. On the other hand, sublethal concentrations of insecticides can stimulate pest population dynamics and cause stress responses, such as stimulating reproduction and the population dynamics of pests. The compensation mechanism for the individual life history of insects (e.g., stimulated to increase reproduction) shows favorable changes for insects through physiological and/or behavioral functions [26–29]. For example, the insecticides triazophos and deltamethrin stimulated the reproductive systems of male adults of *Nilaparvata lugens*, leading to increased fertility in female adults after mating [29].

Research on the sublethal effects of insecticides is an important complex subject in sustainable pest management and scientific application of insecticides. At present, there are many reports on the sublethal effects of insecticides on Lepidopteran pests, but there are few reports on the sublethal effects of *S. frugiperda*. In this study, three insecticides with different mechanisms of action that are commonly used in the production of Lepidopteran pests were selected. Dinotefuran (DIN) is the third generation of a new neonicotinoid family insecticide that mainly acts on the acetylcholine receptor and is a nerve agent. Compared with traditional similar insecticides, it has higher efficacy and a wider insecticidal spectrum [30]. Beta-cypermethrin is a pyrethroid insecticide, which mainly acts on calcium channels. Chlorantraniliprole is a new generation of anthranilic

diamide insecticides [31], primarily acting on ryanodine receptors in insects, causing a disorder of muscle contractions in insects that eventually leads to dehydration and the inability to eat [32]. The effects on the developmental time, survival rate, fecundity, and other biological characteristics of the third instar larvae of the F_0 and F_1 generations of *S. frugiperda* were studied by feeding with sublethal concentrations (LC_{30}) of the three insecticides. It is expected to provide a theoretical basis for better understanding the effects of pesticides on *S. frugiperda* for better pest control and rational use of pesticides in the field and for avoiding or reducing the side effects. The study provides a reference for the integrated management of this pest.

2. Materials and Methods

2.1. Spodoptera frugiperda Rearing

The *S. frugiperda* was collected in a corn-growing area of Muqiao Village, Yuhang District, Hangzhou, China (120.27° E, 30.42° N). Colonies were cultured in a rearing chamber at 28 ± 1 °C and 70 ± 5% RH with a photoperiod of L(light)/D(dark) = 16 h/8 h. The 1–3 instar larvae were reared in groups, and the third instar larvae were reared individually by keeping each inside a hole of six-hole plates until the pupal stage. The diet was replaced if necessary. The pupae were collected and placed in boxes in darkness. After emergence, the moths of males and females were paired and placed in 30 cm × 30 cm × 40 cm insect screen cages. Adults were provided 10% fresh honey water.

2.2. Bioassays for LC_{50}

The third instar larvae were selected for bioassay experiments using chlorantraniliprole (95.3% technical, FMC Corporation, Philadelphia, PA, USA), dinotefuran (99.1% technical, Mitsui Chemicals, Inc., Minato City, Tokyo) and beta-cypermethrin technical (95% technical, Nanjing Red Sun Co., Ltd., Nanjing, China). The insecticides were diluted serially into five concentration gradients, and 10 mL of each reagent solution was added into 100 g feed to prepare artificial feed containing five concentrations of mixed toxicity. One gram of artificial feed mixed with the insecticides was added to each petri dish, and then the third instar larvae of *S. frugiperda*, which grew uniformly, strong, and hungry for several hours, were put into dishes and then the lethality was checked after 48 h. Three replicates were set for each concentration of insecticides, and the artificial diet without insecticide was used as the negative one. According to the survey data, the mortality or collected mortality of each treatment, and the regression equation and sublethal concentration were calculated.

2.3. Effects of Sublethal Concentration on Life Table Parameters

The third instar larvae of *S. frugiperda* were fed with artificial diet treated with LC_{30} as the sublethal concentration of the insecticides. Three replicates were set up for each of the three insecticides, with 50 larvae in each replicate; the no-pesticide treatment was the control. The poisonous feed was fed for 48 h, and then the normal feed was replaced for feeding. The treated larvae were kept in the rearing chamber. After that, the number of deaths was recorded every day, and the development duration of each stage was observed and recorded. When the larvae began to pupate, they were taken out day by day, the male pupae and female pupae were weighed, and their pupation periods were recorded. The male and female pupae were put into the respective boxes and covered with black cloth for eclosion. After eclosion on the first day, the male and female were identified again according to the patterns and shapes on the adult bodies and put into different eclosion cages. The eclosion numbers and adult durations were recorded, and 10% honey water was placed in the cage every day for adult supplementary nutrition. The pupation rate was the number of normal pupations divided by the number of viable larvae treated with LC_{30}. The adult eclosion rate was divided by the number of adult eclosion divided by the number of normal pupae. The larval development period started from the third instar insecticide treatment to the first day of pupation until the end of pupation. Each group was treated with 18 pairs, and the number of eggs laid by each female was recorded until the

female died. The eggs in the same day of the control group and the treatment groups were collected, and 100 eggs were randomly selected after mixing, with three replicates for each treatment. The number of survival and death, larval duration, pupation rate, pupation duration, emergence rate, and adult lifespan of the F_0 and F_1 generations were recorded.

2.4. Data Analyzed

The results of the bioassay were analyzed by Excel, and the LC_{30} value, 95% confidence, and toxicity regression equation of each insecticide were calculated by the PROBIT method.

The formula for calculating the health table parameters is as follows:

Net reproduction rate, $R_0 = \sum l_x m_x$;

Average generation period, $T = \sum x l_x m_x / R_0$;

Intrinsic growth rate, $R_m = \ln (R_0 / T)$;

Finite rate of increase, $\lambda = \exp (r_m)$;

Population-doubling time, $D_t = \ln 2 / r_m$.

Where 'l_x' represents the survival probability of female adults at age 'x'; 'm_x' represents the egg numbers per female at age 'x'.

The data was statistically analyzed by BM SPSS Statistics 25.0 Norman H. Nie, C. Hadlai (Tex) Hull and Dale H. Bent, USA. The data among the treatment groups and control group were compared by one-way analysis of variance and Duncan's new complex difference method.

3. Results

3.1. Determination of Sublethal Concentrations

The results of the bioassay of the third instar larvae are shown in Table 1. The LC_{30s} of beta-cypermethrin, chlorantraniliprole, and dinotefuran were 0.433, 0.456, and 0.250 μg/g, respectively. The LC_{30} of chlorantraniliprole was the lowest among the tested insecticides, which is lower than that of the other two agents. In this study, the LC_{30S} of three insecticides were chosen as the sublethal concentrations to observe the sublethal effects on the growth and development of *S. frugiperda*.

Table 1. Results of bioassay of three insecticides on third instar larvae of *Spodoptera frugiperda*.

Treatments	N	Regression Equation	LC_{30} (μg/g)	95% Confidence Interval	χ^2
chlorantraniliprole	270	y = 0.5 + 0.91x	0.456	0.162–0.970	18.95
dinotefuran	270	y = 0.25 + 0.43x	0.250	0.084–0.525	4.67
beta-cypermethrin	270	y = 0.29 + 1.32x	0.433	0.131–0.848	20.12

3.2. Effects of Sublethal Concentrations of Three Insecticides on the Mortality of S. frugiperda

The survival rate is shown in Figure 1. In the larval stage, the larval mortality of the treatment group is significantly lower than that of the control group, and the life cycle of the control group is significantly lower than that of the treatment group. The whole development time of the chlorantraniliprole dinotefuran and beta-cypermethrin treatment groups were 38.97 ± 0.30 d, 38.39 ± 0.35 d, and 37.54 ± 0.37 d, respectively, which were significantly higher than that of the control group 34.87 ± 0.20 d ($F_{3,269} = 43.447$, $p < 0.0001$). The three agents significantly prolonged the growth cycle and reduced the survival rate of *S. frugiperda*.

3.3. Effects of Sublethal Concentrations of Three Insecticides on Population Growth and Development Duration of Male and Female Pupae Weight of S. frugiperda

The results showed that chlorantraniliprole, dinotefuran, and beta-cypermethrin had some effects on the growth and development of *S. frugiperda*. As shown in Table 2, compared with the control group, the larval stage of the treatment group was significantly prolonged ($F_{3,69} = 25.797$, $p < 0.0001$), and the survival rate was significantly reduced ($F_{3,14} = 29.151$,

$p < 0.0001$). The growth days of chlorantraniliprole larvae in the treatment group were the longest, up to 24.38 days. In the pupal duration, the treatment groups showed no significant differences compared with the control group ($F_{3,269} = 43.447$, $p < 0.0001$), but there were significant differences between the treatment groups. In the male pupa development time, the beta-cypermethrin treatment group (10.29 ± 0.52 d) showed significantly prolonged differences compared with the chlorantraniliprole treatment group (9.25 ± 0.16 d); in the female pupa development time, the dinotefuran treatment group (11.00 ± 0.34 d) showed significant differences compared with the beta-cypermethrin group (10.14 ± 0.21 d). Compared with the control group, the adult duration (female: $F_{3,104} = 0.461$, $p = 0.710$; male: $F_{3,58} = 5.505$, $p = 0.244$) and pupal weight (female: $F_{3,41} = 0.602$, $p = 0.618$; male: $F_{3,40} = 0.398$, $p = 0.755$) of the F_0 generation in the three insecticide treatment groups were not significantly affected.

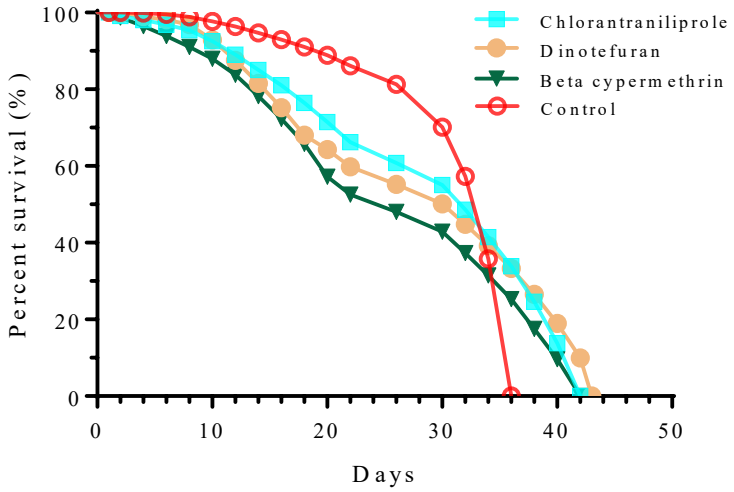

Figure 1. Survival rate of *Spodoptera frugiperda* after treatments with three insecticides (beginning from third instar larva).

Table 2. The mean (±SE) developmental duration and pupa weight of F_0 generation of *Spodoptera frugiperda* exposed to sublethal concentrations of the insecticides.

Treatments	Larval Calendar/d	Pupae Calendar/d		Adults Longevity/d		Pupa Weight (mg)	
		Female	Male	Female	Male	Female	Male
control	19.47 ± 0.45 c	10.00 ± 0.17 ab	10.44 ± 0.18 ab	10.30 ± 0.38 a	9.11 ± 0.43 ab	181.38 ± 7.70 a	197.06 ± 7.41 a
chlorantraniliprole	24.38 ± 0.43 a	10.11 ± 0.35 ab	10.14 ± 0.21 b	10.22 ± 0.39 a	10.71 ± 0.37 a	201.35 ± 11.02 a	205.40 ± 15.91 a
dinotefuran	23.80 ± 0.42 ab	9.25 ± 0.16 b	10.33 ± 0.17 ab	10.22 ± 0.44 a	9.87 ± 0.57 a	192.44 ± 13.49 a	167.25 ± 12.51 a
beta-cypermethrin	21.68 ± 0.31 b	10.29 ± 0.52 a	11.00 ± 0.34 a	9.70 ± 0.40 a	8.13 ± 0.41 b	181.11 ± 16.42 a	185.00 ± 23.20 a

Data following the different letters in the same column are significantly different by Duncan's test (ANOVA, $p < 0.05$).

3.4. Effects of Sublethal Concentrations of Three Insecticides on Population, Survival, and Fecundity of S. frugiperda

It can be seen from Table 3 that chlorantraniliprole, dinotefuran, and beta-cypermethrin have certain effects on the survival rate and fecundity of *S. frugiperda*. The pupation rates of the F_0 generation in the treatment groups were 34.67 ± 2.67%, 28.00 ± 3.06%, and 36.67 ± 2.91%, respectively, which were significantly lower than those of the control group (71.33 ± 5.21%) ($F_{3,8} = 29.151$, $p < 0.0001$). The emergence rates in the treatment groups were slightly lower than that in control group, but there were no significant differences ($F_{3,8} = 1.362$, $p = 0.322$). The female ratios of the F_0 generation in the treatment groups were 56.36 ± 4.68%, 54.85 ± 2.89%, and 60.66 ± 1.29%, respectively, which were not significantly different from those in control group (58.64 ± 0.72%) ($F_{3,8} = 0.777$, $p = 0.539$).

Table 3. Effect of sublethal concentrations of three insecticides on survival rate and fecundity (mean ± SE) of F_0 generation of *Spodoptera frugiperda*.

Treatments	Pupation Rate (%)	Emergence Rate (%)	Female Ratio (%)	No. of Eggs per Female	Hatching Rate (%)
control	71.33 ± 5.21 a	88.67 ± 0.84 a	58.64 ± 0.72 a	506.18 ± 62.55 a	96.33 ± 3.67 a
chlorantraniliprole	34.67 ± 2.67 b	79.58 ± 7.23 a	56.36 ± 4.68 a	165.36 ± 30.41 b	81.33 ± 7.31 b
dinotefuran	28.00 ± 3.06 b	78.09 ± 2.20 a	54.85 ± 2.89 a	579.67 ± 71.72 a	98.67 ± 1.33 a
beta-cypermethrin	36.67 ± 2.91 b	75.46 ± 6.23 a	60.66 ± 1.29 a	288.22 ± 46.55 b	98.00 ± 2.00 a

Data following the different letters in the same column are significantly different by Duncan's test (ANOVA, $p < 0.05$).

The number of eggs per female of treatment groups was significantly different from that of control group ($F_{3,47} = 9.425$, $p < 0.0001$). Chlorantraniliprole and beta-cypermethrin treatments significantly reduced the fecundity of single females in F_0 generation (Chlorantraniliprole: 165.36 ± 30.41 eggs; beta-cypermethrin: 288.22 ± 46.55 eggs). The fecundity of per female in the dinotefuran treatment group (579.67 ± 71.72 eggs) was higher than that in the control group (506.18± 62.55 eggs), but there was no significant difference. Chlorantraniliprole significantly inhibited egg hatchability by 15% ($F_{3,8}$= 3.724, p = 0.061), but there was no significant difference between other treatment groups and control group.

3.5. Effects of Sublethal Concentrations of Three Insecticides on Life Parameters of Adult Population of S. frugiperda

Table 4 showed the effects of the sublethal concentrations of three insecticides on the population life table parameters of F_0 generation of *S. frugiperda*. The sublethal concentration of chlorantraniliprole and beta-cypermethrin treatments had great influence on the population life table parameters of the F_0 generation of *S. frugiperda*. The intrinsic growth rates (r_m) of the chlorantraniliprole and beta-cypermethrin treatment groups were significantly reduced compared with the control group by 48.41% and 31.75% ($F_{3,8}$= 9.684, p = 0.001), respectively. The net growth rate (R_0) of chlorantraniliprole and beta-cypermethrin treatment groups decreased significantly, by 62.88% and 65.02% respectively ($F_{3,8}$ = 16.145, p = 0.001). The weekly growth rate (λ) of the chlorantraniliprole and beta-cypermethrin treatment groups also decreased significantly by 45.35% and 30.99% ($F_{3,8}$ = 0.808, p = 0.025), respectively. The average generation period (T) of adults of the F_0 generation in the chlorantraniliprole treatment group increased by 53.72% compared with the control group ($F_{3,8}$ = 9.89, p = 0.002). There were no significant differences in all parameters between the dinotefuran treatment group and the control group.

Table 4. Effect of sublethal concentrations of three insecticides on the life table population parameters (mean ± SE) of F_0 generation of *Spodoptera frugiperda*.

Treatments	Intrinsic Growth Rate (r_m)	Net Reproductive Rate (R_0)	Average Generation Period (T)	Finite Rate of Increase (λ)	Population Doubling Time (Dt)
control	1.26 ± 0.10 a	209.17 ± 12.55 a	4.30 ± 0.29 b	3.55 ± 0.38 a	0.54 ± 0.04 b
chlorantraniliprole	0.65 ± 0.09 c	77.65 ± 21.94 b	6.61 ± 0.42 a	1.94 ± 0.17 c	1.14 ± 0.15 a
dinotefuran	1.04 ± 0.04 ab	210.48 ± 25.46 a	5.15 ± 0.30 b	2.84 ± 0.13 ab	0.66 ± 0.04 b
beta-cypermethrin	0.89 ± 0.08 bc	73.17 ± 14.36 b	4.82 ± 0.21 b	2.45 ± 0.18 bc	0.82 ± 0.09 b

Data following the different letters in the same column are significantly different by Duncan's test (ANOVA, $p < 0.05$).

3.6. Sublethal Effect on F_1 Generation of S. frugiperda

The results of the effects of sublethal concentrations of three insecticides on the growth and development duration of the F_1 generation of *S. frugiperda* are shown in Table 5. The larvae development times of the F_1 generation of *S. frugiperda* in beta-cypermethrin (18.55 ± 0.98 days), chlorantraniliprole (18.12 ± 1.03 days), and dinotefuran

(17.92 ± 0.88 days) treatment groups were significantly higher than the control group (17.08 ± 0.93 days) ($F_{3,519}$ = 48.746, $p < 0.0001$).

Table 5. The mean (±SE) developmental duration and pupa weight of F_1 generation of *Spodoptera frugiperda* exposed to sublethal concentration of the insecticides.

Treatments	Larval Calendar/d	Pupae Calendar/d		Adults Longevity/d		Pupa Weight (mg)	
		Female	Male	Female	Male	Female	Male
control	17.08 ± 0.08 c	10.14 ± 0.10 b	10.64 ± 0.15 ab	9.53 ± 0.62 a	8.94 ± 0.42 a	195.41 ± 5.59 a	179.60 ± 5.89 b
chlorantraniliprole	18.12 ± 0.092 b	10.60 ± 0.11 ab	10.61 ± 0.15 ab	10.00 ± 0.51 a	8.35 ± 0.52 a	209.18 ± 5.91 a	211.48 ± 8.10 a
dinotefuran	17.92 ± 0.073 b	10.22 ± 0.13 b	10.17 ± 0.17 b	9.29 ± 0.54 a	8.71 ± 0.54 a	179.86 ± 7.97 a	190.32 ± 4.57 ab
beta-cypermethrin	18.55 ± 0.098 a	10.46 ± 0.14 a	10.94 ± 0.16 a	9.41 ± 0.41 a	8.47 ± 0.69 a	130.60 ± 4.58 b	140.00 ± 12.48 c

Data following the different letters in the same column are significantly different by Duncan's test (ANOVA, $p < 0.05$).

There were no significant differences in the development times of male pupae of the F_1 generation in the treatment groups compared with the control group ($F_{3,177}$ = 1.389, p = 0.248). The female pupae duration times of the F_1 generation in the beta-cypermethrin treatment group (10.46 ± 0.14 d) were significantly higher than that in control group (10.14 ± 0.10 d), but there were no significant differences in the other treatment groups. Chlorantraniliprole significantly increased the male pupal weight of the F_1 generation (211.48 ± 8.10 mg, $F_{3,77}$ = 5.653, p = 0.001), and beta-cypermethrin significantly decreased the male pupal weight of the F_1 generation (140.00 ± 12.48 mg; $F_{3,73}$ = 13.974, $p < 0.0001$) and the female pupal weight (130.60 ± 4.58 mg; $F_{3,77}$ = 5.653, $p < 0.0001$). The adult duration time of the F_1 generation in the treatment group had no significant effect compared with the control group (female: $F_{3,64}$ = 0.345, p = 0.793; male: $F_{3,64}$ = 0.223, p = 0.880).

The pupation rate ($F_{3,8}$ = 1.431, p = 0.304), emergence rate ($F_{3,8}$ = 1.615, p = 0.261), female ratio ($F_{3,8}$ = 0.343, p = 0.795), and egg-hatching rate ($F_{3,8}$ = 0.368, p = 0.779) of the F_1 generation of *S. frugiperda* in all treatments were not significantly different, but fecundity of the F_1 generation was significantly different ($F_{3,49}$ = 4.010, p = 0.012) (as shown in Table 6). The sublethal concentration treatment still had an effect on the number of eggs laid by single females in the F_1 generation. The fecundity of the chlorantraniliprole treatment groups (335.08 ± 28.32 eggs per female) was lower than the control group (465.33 ± 59.54 eggs per female). Beta-cypermethrin also reduces the fecundity of the population (364.36 ± 26.47 eggs per female). However, the fecundity of the dinotefuran treatment group (572.43 ± 71.17 eggs per female) was significantly higher than the chlorantraniliprole and beta-cypermethrin treatment groups with high hatching rates (96.00 ± 6.93%), but the differences were not significant compared with the control group. There was no significant difference in the female ratio between the treatment groups and the control group (51.62%) ($F_{3,8}$ = 0.343, p = 0.795).

Table 6. Effect of sublethal concentrations of three insecticides on survival rate and fecundity (mean ± SE) of F_1 generation of *Spodoptera frugiperda*.

Treatments	Pupation Rate (%)	Emergence Rate (%)	Female Ratio (%)	No. of Eggs per Female	Hatching Rate (%)
control	76.7 ± 5.36 a	92.11 ± 1.80 a	51.62 ± 4.07 a	465.33 ± 59.54 ab	97.00 ± 3.00 a
chlorantraniliprole	67.22 ± 6.41 a	93.08 ± 2.91 a	55.73 ± 11.4 a	335.08 ± 28.32 b	79.33 ± 13.12 a
dinotefuran	79.45 ± 4.01 a	89.87 ± 3.57 a	46.67 ± 3.33 a	572.43 ± 71.17 a	96.00 ± 6.93 a
beta-cypermethrin	66.11 ± 6.26 a	85.49 ± 1.94 a	53.58 ± 3.69 a	364.36 ± 26.47 b	97.33 ± 1.45 a

Data following the different letters in the same column are significantly different by Duncan's test (ANOVA, $p < 0.05$).

The effects of the sublethal concentrations of chlorantraniliprole, dinotefuran, and beta-cypermethrin on the life table parameters of the F_1 generation of adults were showed in Table 7. The intrinsic growth rate (r_m), the net growth rate (R_0), the weekly growth rate (λ), and population-doubling time (D_t) of the F_1 generation adults in the treatment group had

no significant effects (r_m: $F_{3,8}$ = 1.640, p = 0.256; R_0: $F_{3,8}$ = 1.019, p = 0.434; λ: $F_{3,8}$ = 1.901, p = 0.208; D_t: $F_{3,8}$ = 1.665, p = 0.251). Treatment with beta-cypermethrin significantly affected the average age period of the F_1 generation, significantly decreased the average generation period by 20.74%, and the other two insecticides had no significant effect.

Table 7. Effect of sublethal concentration of three insecticides on the life table population parameters (mean ± SE) of F_1 generation of *Spodoptera frugiperda*.

Treatments	Intrinsic Growth Rate (r_m)	Net Reproductive Rate (R_0)	Average Generation Period (T)	Finite Rate of Increase (λ)	Population-Doubling Time (Dt)
control	1.01 ± 0.10 a	164.76 ± 13.87 a	5.11 ± 0.44 a	2.79 ± 0.29 a	0.70 ± 0.07 a
chlorantraniliprole	1.06 ± 0.05 a	113.00 ± 15.80 a	4.46 ± 0.15 ab	2.89 ± 0.15 a	0.64 ± 0.05 a
dinotefuran	0.95 ± 0.14 a	158.55 ± 39.78 a	4.59 ± 0.17 ab	2.63 ± 0.33 a	0.77 ± 0.16 a
beta-cypermethrin	1.23 ± 0.05 a	141.73 ± 8.90 a	4.05 ± 0.18 b	3.42 ± 0.17 a	0.49 ± 0.04 a

Data following the different letters in the same column are significantly different by Duncan's test (ANOVA, $p < 0.05$).

4. Discussion

The sublethal concentrations of insecticides will affect the population dynamics of pests and have varying degrees of influence on each stage of insect growth and development. In this study, the survival rate of the F_0 generation of *S. frugiperda* decreased significantly under the exposure of the sublethal concentrations of chlorantraniliprole, dinotefuran, and beta-cypermethrin. Compared with the control group, the survival rates of larvae in the three insecticide treatment groups decreased by 51.4%, 60.7%, and 48.6%, respectively. The lethal effects of the sublethal concentrations of insecticides on target and non-target insects are common [33,34]. The sublethal concentrations of the insecticides not only affected insect survival but also inhibited the growth rate of the insect population by prolonging the developmental period. In this study, the exposure of three insecticides had a significant impact on the development duration of the F_0 generation of *S. frugiperda*, which was prolonged by six to eight days in the treatment groups. Especially in the larval stage, chlorantraniliprole, dinotefuran, and beta-cypermethrin were prolonged by about five days, four days, and two days, respectively, which were significantly different from the control. The exposure of three insecticides had no significant effect on the total development duration of the F_1 generation, and the development duration of the larvae increased by 0.8–1.5 days, which was significantly different from the control. Similar results showed that the development duration of the F_0 and F_1 generations of *S. exigua* and *Spodoptera cosmioides* was prolonged by treating with sublethal concentrations of chlorantraniliprole [14,35]. The sublethal concentration of the cyantraniliprole treatment induced *Agrotis ipsilon* to prolong the development time of larvae and pupae [36]. Studies on the mechanism of the sublethal effect of chlorantraniliprole showed that the chlorantraniliprole could adversely affect larva–pupa transformation in silkworms, and the direct target gene of sublethal effect may be the Ftz-f1 gene [37]. In this study, the exposure of the three insecticides had little effect on the pupal period and adult period of *S. frugiperda*. This could be due to the insecticide killing the weaker larvae while preserving the more resistant larvae.

Generally, pesticide exposure is considered to have a negative impact on insect population reproduction. Chlorantraniliprole and beta-cypermethrin exposure had no significant effect on the sex ratio of the F_0 and F_1 generations but had a significant effect on their reproductive ability. The chlorantraniliprole and beta-cypermethrin treatments had adverse effects on the oviposition of *S. frugiperda*. Compared with the control group, the oviposition of the beta-cypermethrin and chlorantraniliprole treatment groups decreased significantly by about 43.1% and 67.4%, respectively, and the hatching rate of eggs in the chlorantraniliprole treatment group decreased by 15.6%. Insecticides also affected the reproductive ability of the F_1 generation *S. frugiperda*. The fecundity of the F_1 generation decreased significantly. The fecundity of beta-cypermethrin and chlorantraniliprole decreased by about 21.7% and 28.0%, respectively, and the hatching rate of eggs in the chlorantraniliprole

treatment group decreased by 18.2%. The sublethal concentration treatment has adverse effects on the reproduction of insects, such as the rice stem border, *Chilo suppressalis*. The sublethal concentrations of chlorantraniliprole significantly reduced their reproductive capacity by 32.18% (LC_{10}) and 52.94% (LC_{30}) [38]. Under the LC_{15} and LC_{30} treatments of chlorantraniliprole, the oviposition of *S. cosmiodes* was significantly reduced lower by two and eight times, respectively [35]. The sublethal effects of beta-cypermethrin and chlorantraniliprole on the biological and reproductive capacity of *S. frugiperda* will provide some reference for further optimization of integrated pest management.

Some studies have found that sublethal doses of some pesticides can stimulate reproduction of insects. In this study, the fecundity of *S. frugiperda* was enhanced after the sublethal concentration of dinotefuran. Compared with the control, the number of eggs produced per female of dinotefuran treatment group in the F_0 generation and the F_1 generation increased by 20.8% and 14.4% respectively, the hatching was not affected, and the hatching rate was more than 96%. This phenomenon has also been confirmed in other studies, such as the stimulating effect of deltamethrin on the subculture reproduction of the cotton aphid [39]. Sublethal concentrations of dinotefuran at lower doses (LC_{10} and LC_{20}) increased the reproductive capacity of *Rhopalosiphum padi* F_1 generation [40]. However, the study also found that when the sublethal concentration increased to LC_{30}, the reproductive ability of the F_1 generation was inhibited [40], indicating that the lower dose of dinotefuran can stimulate the reproduction of sap-feeding pests, stimulate the growth of the F_1 generation population, and cause the potential problem of pest resurgence. The sublethal doses of pesticides also had different effects on the fecundity of different insects. Bao et al. found that the sublethal concentration LD_{20} of dinotefuran significantly reduced the fecundity of *Nilaparvata lugens* [41]. Lu et al. found that the sublethal concentrations (LC_{10} and LC_{30}) of dinotefuran had no transgenerational effects on *Apolygus lucorum* [42]. In this study, the sublethal concentration of beta-cypermethrin inhibited the oviposition of *S. frugiperda*, but in the study of aphids, it was found that it had different stimulating effects on different populations, which could stimulate the oviposition of *Aphis glycines* but had no significant effect on *Aphis solani* [27]. Another study found that when the females or males treated with beta-cypermethrin LC_{10} mated with the females or males of the normal untreated control group, the number of eggs laid increased significantly [43,44], which may provide a warning for the resurgence of pests.

5. Conclusions

To summarize, at the sublethal concentration (LC_{30}), chlorantraniliprole and beta-cypermethrin significantly inhibited fecundity of the F_0 and F_1 generations. The intrinsic growth rate (r_m), net growth rate (R_0), and weekly growth rate (λ) of the F_0 generation in the chlorantraniliprole and beta-cypermethrin treatment groups were significantly lower than those in the control group, and the population-doubling time (D_t) in the chlorantraniliamide and beta-cypermethrin treatment group was significantly higher than that in the control group. This means that the use of both insecticides on crops can kill *S. frugiperda* directly, while continuing to suppress population growth through low concentrations in the field and may be more effective than other insecticides. However, dinotefuran can reduce the number of F_0 populations and prolong the larval duration of *S. frugiperda*, which had a certain role in promoting oviposition on the F_0 and F_1 generations and which may stimulate the growth of the offspring population and cause the potential resurgence of pests. The potential risk should be considered when using dinotefuran for pest control in the field. Further studies are needed to explore the potential risks of other sublethal concentrations of dinotefuran and the mechanism of action by dinotefuran to stimulate oviposition. The study provides a reference for the rational use of pesticides in the field and provide a theoretical basis for avoiding or reducing the side effects of pesticides.

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