Lethal, Sub-Lethal and Trans-Generational Effects of Chlorantraniliprole on Biological Parameters, Demographic Traits, and Fitness Costs of *Spodoptera frugiperda* (Lepidoptera: Noctuidae)

Zunnu Raen Akhtar 1, Ayesha Afzal 2,3,*, Aatif Idrees 3,*,†, Khuram Zia 1,*, Ziyad Abdul Qadir 5,6,*, Shahbaz Ali 7, Inzamam Ul Haq 1,*, Hamed A. Ghramh 8, Yasir Niaz 7, Muhammad Bilal Tahir 9, Muhammad Arshad 1 and Jun Li 3,*

1 Department of Entomology, University of Agriculture Faisalabad, Faisalabad 38000, Pakistan
2 Institute of Molecular Biology and Biotechnology, The University of Lahore, 1-Km Defense Road, Lahore 54000, Pakistan
3 Guangdong Key Laboratory of Animal Conservation and Resource Utilization, Guangdong Public Laboratory of Wild Animal Conservation and Utilization, Institute of Zoology, Guangdong Academy of Sciences, Guangzhou 510260, China
4 Office of Research, Innovation & Commercialization (ORIC), University of Agriculture Faisalabad, Faisalabad 38000, Pakistan
5 Honeybee Research Institute, National Agricultural Research Centre, Park Road, Islamabad 45500, Pakistan
6 Department of Entomology and Wildlife Ecology, University of Delaware, Newark, DE 19716, USA
7 Department of Agricultural Engineering, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan 64200, Pakistan
8 Research Center for Advanced Materials Science (RCAMS), King Khalid University, P.O. Box 9004, Abha 61413, Saudi Arabia
9 Department of Physics, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan 64200, Pakistan

* These authors contributed equally to this work.
† These authors contributed equally to this work.

**Abstract:** This is the first study providing important time-specific, age-specific, and reproduction-specific data for managing *Spodoptera frugiperda* infestations in maize crops using chlorantraniliprole. The application of chlorantraniliprole insecticide suppressed the population of *S. frugiperda*. The results revealed that fecundity was affected by chlorantraniliprole in the second filial generation, which suggests that the insecticide application during spring will prevent *S. frugiperda* infestation in maize crops during the autumn season.

**Simple Summary:** This is the first study providing important time-specific, age-specific, and reproduction-specific data for managing *Spodoptera frugiperda* infestations in maize crops using chlorantraniliprole. Chlorantraniliprole is a selective insecticide with a novel mode of action and is used against Lepidopteran, Coleopteran, Isopteron, and Dipteran pests. This study determined chlorantraniliprole’s lethal, sub-lethal, and trans-generational effects on two consecutive generations (*F₀*, *F₁*, and *F₂*) of the fall armyworm. Bioassays revealed that chlorantraniliprole exhibited higher toxicity against fall armyworms with a LC₅₀ of 2.781 mg/L after 48 h of exposure. Significant differences were noted in the biological parameters of fall armyworms in all generations. Sub-lethal concentrations of chlorantraniliprole showed prolonged larval and adult durations. The parameters related to the fitness cost in *F₀* and *F₁* generations showed non-significant differences. In contrast, the *F₂* generation showed lower fecundity at lethal (71 eggs/female) and sub-lethal (94 eggs/female) doses of chlorantraniliprole compared to the control (127.5–129.3 eggs/female). Age-stage specific survival rate (*Sₓj*), life expectancy (*Eₓj*) and reproductive rate (*Vₓj*) significantly differed among insecticide-treated groups in all generations compared to the control. A comparison of treated and untreated insects over generations indicated substantial differences in demographic parameters such
as net reproduction rate ($R_0$), intrinsic rate of increase ($r$), and mean generation time ($T$). Several biological and demographic parameters were shown to be negatively impacted by chlorantraniliprole. We conclude that chlorantraniliprole may be utilized to manage fall armyworms with lesser risks.

**Keywords:** *Spodoptera frugiperda*; chlorantraniliprole; demographic parameters; fitness costs; two-sex life table

1. Introduction

The fall armyworm [*Spodoptera frugiperda* (*S. frugiperda* hereafter)] is a devastating pest in most of the tropical and subtropical Americas [1,2]. In Africa, it has become a noxious agricultural pest [3,4]. Commonly affected crops by *S. frugiperda* include corn, rice, sugarcane, sorghum etc. [5,6]. It may have several broods yearly and covers great distances in a single night’s flight. The larvae of the pest eat the leaves, stalks, and flowers of cultivated plants [1,7]. The *S. frugiperda* populations are often controlled using chemical pesticides [8,9]. Different types of insecticides work in different ways to kill the target organisms [10]. Most pesticides are neurotoxic due to their effects on acetylcholine receptors (e.g., neonicotinoids), acetylcholine esterases (e.g., carbamates), or ion channel activity in nerve cell membranes (pyrethroïds) [11]. Few insecticides act on chitin biosynthesis (benzoylurea, buprofezin), juvenile hormone (phenoxypyenoxy ether), or ecysdose to affect insect growth and molting (triazine). Other insecticides damage the midgut membrane or act on the mitochondrial respiratory electron transport chain (e.g., carbamates) (toxin of *Bacillus thuringiensis*) [11]. Different insecticides, such as emmamectin benzoate [12] and neem extracts [13], have been used to control *S. frugiperda*.

The baseline susceptibilities of deltamethrin, chlorantraniliprole, flubendiamide, thiodicarb, and chlorpyrifos have been determined against *S. frugiperda* [14]. Similarly, the baseline susceptibilities of different insecticides with control failure estimation for *S. frugiperda* were determined in Burkina Faso [15]. Entomopathogenic nematodes were used to control *S. frugiperda* in Thailand [16]. Insecticide ‘ampligo’ was used against *S. frugiperda* in the coastal Savannah agroecological zone of Ghana [17]. Different insecticides having field efficacy against *S. frugiperda* have been tested [18–20]. However, the lethal, sub-lethal and trans-generational effects of chlorantraniliprole on biological parameters, demographic traits, and fitness costs of *S. frugiperda* have been less explored in Pakistan.

Anthranilic diamides have a unique mode of action that activates the unregulated release of internal calcium storage channels, resulting in the depletion of calcium from an insect body, ultimately leading to paralysis and insect death [21]. Chlorantraniliprole belongs to anthranilic insecticides and is registered against Lepidopteran, Coleopteran, Dipteran, and Hemipteran insects [22,23]. Insecticides exert sub-lethal impacts on insects depending upon exposure time and dose [5,24,25]. Due to these sub-lethal impacts, insects experience minor effects on fecundity, reproduction, and development [26]. In addition to the lethal effects (direct killing), insecticides can also result in the degradation and chemical distribution in the field, negatively impacting insect physiology, behavior, reproduction, longevity and biology [23,27–29]. Chlorantraniliprole showed toxicity and field efficacy against *S. frugiperda* [30]. It also showed effective control against *S. frugiperda* when used through drip irrigation in China [31]. Chlorantraniliprole also provided effective control over the pest when used in combination with other pesticides/plant extracts [32]. Similarly, chlorantraniliprole showed toxicity in combination with carbaryl against *S. frugiperda* [33]. In the same way, chlorantraniliprole showed toxicity against *S. frugiperda* when combined with neem extract [34]. Different insecticides, including chlorantraniliprole showed sub-lethal effects on the development and reproduction of *S. frugiperda* [12].

Insect mortality, fertility, and lifespan may all be affected by environmental variables, including heat, pesticides, and secondary plant metabolites. Demographic toxicology, or the life table, is useful for assessing these impacts [35–38]. The conventional life table
focused only on the female population and overlooked the male population. Furthermore, it does not consider data about individual variations and developmental phases [39]. Age-stage two-sex life tables eliminated the inherent inaccuracies present in life tables based on females by adding data from both sexes of a community into their calculations [40,41].

Understanding these population dynamics, which may assist explain distinct sub-lethal consequences on target insects, can be aided using the age-stage two-sex life table [42,43]. Knowing the population dynamics of certain insect species is important for the timely implementation of integrated pest control, two-sex tables with sub-lethal doses may serve this purpose [44,45].

Numerous studies implemented the two-sex life table for this purpose. For example, the development and reproduction of *S. frugiperda* were studied by Xie et al. [46] using an age-stage, two-sex life table to see how the effects of various hosts (maize and kidney bean) affected the organism. Guo et al. determined the larval performance and oviposition of *S. frugiperda* using two sex tables on three host plants [47]. The fitness and population life tables of *S. frugiperda* on solanaceous and oilseed crops have been determined in earlier studies [48,49]. Using a two-sex life table, sub-lethal effects of spinetroid against *S. frugiperda* growth and fecundity were determined [50]. Similarly, Iqbal et al. [51] used an age-stage, two-sex life table to investigate the impact that zinc oxide generated in the culture supernatant of *B. thuringiensis* had on the demographic characteristics of *Musca domestica*.

Likewise, an age-stage, two-sex life table analysis was used to assess the predatory functional response and fitness characteristics of *Orius strigicollis* Poppius-fed *Bemisia tabaci* and *Trialeurodes vaporariorum* [52]. In the same way, ecotoxicological experiments were used to examine the sub-lethal effects of propargite on *Amblyseius swirskii* (Acari: Phytoseiidae) utilizing an age-stage, two-sex life table [53]. Various control measures for the management of arthropod pests are now being developed by researchers. These tactics are aimed to be less harmful to humans, the environment, and predators [54–58]. However, synthetic insecticides are still among the best options available.

The current study aimed to identify the lethal, sublethal, and transgenerational effects of chlorantraniliprole on *S. frugiperda* in Pakistan. Determining the lethal concentration and its impact on all larval instars of *S. frugiperda* survival will be helpful in understanding its chemical control in a better way. The impacts of sub-lethal concentrations on development, reproduction, and fecundity till two generations will help to overcome future resistance development in the maize cropping systems. A two-sex life table will help understand the control of *S. frugiperda* during its all larval, pupal, and adult exposure involving both the male and female sexes, which will further help control it under field conditions.

2. Materials and Methods

2.1. Field Insect Collection

For laboratory studies, the insects were collected from the research fields of the University of Agriculture in Faisalabad, Pakistan (31° 26' 15.2" N 73° 04' 37.9" E) and were kept in cages. Insecticide-free maize leaves were given for colony preparation, and the adults were fed with a 10% honey solution. The studied species is an agricultural pest; therefore, no ethical permissions were required for the study.

2.2. Bioassay for Larvae

A bioassay study was conducted on newly hatched larvae using the leaf dip method. Maize leaves were cut into 6 cm discs and dipped in insecticide for 20 s. Chlorantraniliprole was added to distilled water according to the chosen concentrations. A preliminary test to find the dilution was conducted, and concentration was chosen accordingly. Leaves were dried after soaking and placed individually in Petri dishes. Each treatment was repeated three times, and mortality was observed after 48 h.
2.3. Lethal and Sub-Lethal Effects of Chlorantraniliprole on F₀, F₁ and F₂ Generations

Lethal and sub-lethal concentrations were used in this experiment to observe mortality, survival, development duration (larva, pupa, and adult), fecundity, and reproductive parameters of *S. frugiperda*. Leaves were dipped in lethal concentration solutions (Table 1) of insecticide for 20 s. An untreated control was also included in the study for comparison. One larva was released in each Petri dish, and observations were taken after 48 h. Mortality was recorded, and surviving larvae were fed with fresh leaves of maize. For pairing the insects, pupae were taken to other dishes, differentiated during the pupal stage, and released pairwise in Petri dishes. Cotton soaked in a honey solution was placed inside the vial. The pairs were observed daily for their fecundity.

| Table 1. Toxicity of chlorantraniliprole on six larval instars of the F₀, F₁ and F₂ generations of *Spodoptera frugiperda*. |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Generation | LC₁₀ (mg/L) | LC₂₅ (mg/L) | LC₅₀ (mg/L) | LC₉₀ (mg/L) | Slope ± SE | X² | p-Value | df |
|-------------|-------------|-------------|-------------|-------------|-------------|---|-------|-----|
| First instar |
| F₀ | 1.04 (0.86–1.16) | 1.21 (1.06–1.31) | 1.43 (1.32–1.51) | 1.96 (1.84–2.17) | 9.27 ± 1.05 | 33.16 | 2.07 | 16 |
| F₁ | 0.33 (0.26–0.42) | 0.51 (0.41–0.61) | 0.81 (0.69–0.92) | 1.90 (1.68–2.19) | 3.44 ± 0.16 | 53.50 | 3.34 | 16 |
| F₂ | 0.34 (0.26–0.41) | 0.52 (0.43–0.60) | 0.82 (0.72–0.93) | 1.99 (1.76–2.30) | 3.36 ± 0.14 | 58.60 | 3.66 | 16 |
| Second instar |
| F₀ | 1.10 (0.89–1.22) | 1.25 (1.08–1.34) | 1.44 (1.33–1.51) | 1.88 (1.76–2.15) | 11.02 ± 1.57 | 36.36 | 2.27 | 16 |
| F₁ | 0.37 (0.27–0.46) | 0.54 (0.43–0.65) | 0.84 (0.71–0.96) | 1.92 (1.69–2.22) | 3.58 ± 0.17 | 59.27 | 3.70 | 16 |
| F₂ | 0.36 (0.26–0.45) | 0.54 (0.42–0.64) | 0.83 (0.70–0.96) | 1.92 (1.69–2.23) | 3.54 ± 0.17 | 61.57 | 3.84 | 16 |
| Third instar |
| F₀ | 1.08 (0.85–1.30) | 1.55 (1.30–1.76) | 2.29 (2.06–2.50) | 4.83 (4.41–5.43) | 3.95 ± 0.25 | 40.88 | 2.55 | 16 |
| F₁ | 0.99 (0.76–1.19) | 1.42 (1.18–1.63) | 2.13 (1.90–2.33) | 4.58 (4.20–5.12) | 3.86 ± 0.26 | 36.34 | 2.27 | 16 |
| F₂ | 0.65 (0.51–0.78) | 1.06 (0.90–1.21) | 1.85 (1.66–2.03) | 5.23 (4.60–6.13) | 2.83 ± 0.12 | 54.21 | 3.38 | 16 |
| Fourth instar |
| F₀ | 0.88 (0.69–1.06) | 1.44 (1.22–1.63) | 2.47 (2.23–2.73) | 6.95 (5.94–8.83) | 2.86 ± 0.13 | 65.39 | 4.08 | 16 |
| F₁ | 0.80 (0.62–0.96) | 1.33 (1.12–1.51) | 2.32 (2.08–2.56) | 6.73 (5.76–8.25) | 2.77 ± 0.12 | 63.76 | 3.98 | 16 |
| F₂ | 0.81 (0.63–0.97) | 1.34 (1.14–1.52) | 2.35 (2.12–2.59) | 6.83 (5.85–8.85) | 2.76 ± 0.13 | 61.22 | 3.82 | 16 |
| Fifth instar |
| F₀ | 1.39 (1.23–1.53) | 1.97 (1.81–2.11) | 2.89 (2.75–3.03) | 6.02 (5.66–6.48) | 4.03 ± 0.25 | 14.38 | 0.89 | 16 |
| F₁ | 1.49 (1.31–1.65) | 2.05 (1.88–2.21) | 2.93 (2.77–3.07) | 5.74 (5.40–6.18) | 4.38 ± 0.30 | 16.86 | 1.05 | 16 |
| F₂ | 1.48 (1.27–1.66) | 2.05 (1.85–2.23) | 2.96 (2.79–3.12) | 5.94 (5.53–6.48) | 4.24 ± 0.30 | 20.33 | 1.27 | 16 |
| Sixth instar |
| F₀ | 1.41 (1.07–1.69) | 2.34 (2.02–2.60) | 4.11 (3.97–4.54) | 12.01 (9.49–17.26) | 2.75 ± 0.22 | 38.21 | 2.38 | 16 |
| F₁ | 1.05 (0.82–1.27) | 2.00 (1.73–2.25) | 4.08 (3.65–4.64) | 15.77 (12.09–22.86) | 2.18 ± 0.12 | 47.73 | 2.98 | 16 |
| F₂ | 1.31 (0.93–1.62) | 2.25 (1.885–2.54) | 4.10 (3.73–4.62) | 12.82 (9.75–20.07) | 2.59 ± 0.21 | 48.36 | 3.02 | 16 |

The values in parentheses present the range of the respective means; values are means ± SE (standard errors of the means).
2.4. Transgenerational Effects of Chlorantraniliprole on F₁ and F₂ Generations

Ninety (90) eggs were placed in an insect breeding chamber at 27 ± 1 °C and 75% relative humidity for each treatment to observe the transgenerational effects of chlorantraniliprole on the F₁ and F₂ generations of S. frugiperda. Upon hatching, one larva was placed in each Petri dish for observation and fed with insecticide-dipped leaves. The leaves were dipped in insecticide for 20 s, dried and provided to the larvae for feeding. Later, fresh leaves were changed every 24 h. The developmental period and survival rate of males and females were recorded.

2.5. Statistical Analysis

Concentrations (LC₁₀, LC₂₅, LC₅₀, and LC₉₀) that caused 10%, 25%, 50%, and 90% mortality were calculated using POLO-Plus [59]. The data on mortality were examined using a one-way analysis of variance, and the mean differences were determined using Tukey’s HSD test in SAS software [60] at 95% probability. Using a two-sex table [42], and TWO-SEX MS CHART Program [61], we were able to assess many biological and fitness characteristics, as well as survival rate, adult lifespan, and age-specific fertility. Bootstrap analysis with a sample size of 10,000 was used to assess the means and standard errors of various life and biological parameters [62]. A confidence interval of difference was used to calculate the results of the bootstrap and paired bootstrap tests [63]. Age-stage specific survival rate (sₓj), age-stage specific net reproductive value (vₓj), and age-stage specific survival rate (eₓj) were determined according to Chi [42]. To create the graphs for the demographic factors, SigmaPlot version 12.0 was used.

The following equations were used to construct the age-stage component of the two-sex life table lₓ:

\[ l_k = \sum_{j=1}^{k} s_{xj} \]

where k is the last stage of the study cohort.

Similarly, age-specific fecundity (mₓ) was calculated as follows:

\[ m_x = \frac{\sum_{j=1}^{k} s_{xj} f_{xj}}{\sum_{j=1}^{k} s_{xj}} \]

According to Goodman’s recommendation, the Euler–Lotka equation was used to determine the intrinsic rate of rise [64].

\[ \sum_{x=0}^{\infty} e^{-r(x+1)} l_x m_x = 1 \]

The R₀ (net reproductive rate), which is the total number of offspring that an individual can produce during the lifetime, was calculated as:

\[ R_0 = \sum_{x=0}^{\infty} l_x m_x \]

The relationship between R₀ and mean female fecundity (F) was calculated as:

\[ R_0 = F \frac{Nf}{N} \]

The N in the above equation represents the total number of individuals, while f presents the number of female adults in the study [65].

The finite rate (λ) was recorded as:

\[ \lambda = e^r \]
The mean generation time (T) presents the time span that the population needs to increase \( R_0 \) folds of its size. The value of T was calculated as follows:

\[
T = \frac{\ln R_0}{r}
\]

Age-stage life expectancy (\( e_{xj} \)) was calculated as follows:

\[
e_{xj} = \beta \sum_{i=x}^{\infty} \sum_{y=j}^{\infty} s'_{iy}
\]

where \( s'_{iy} \) is considered as probability, an individual of \( x \) and \( j \) will survive to age \( i \) and stage and calculated by the equation below:

\[
s'_{iy} = 1
\]

Age-stage reproductive value is (\( V_{xj} \)) defined as the contribution of individuals of age \( x \) and stage \( j \) for the future population of insects. For age stage-specific, two-sex tables, the following equation is used [66] and calculated as follows:

\[
V_{xj} = \frac{e^{r(x+1)}}{s_{xj}} \sum_{i=x}^{\infty} e^{-r(x+1)} \sum_{y=j}^{\infty} s'_{iy} f_{iy}
\]

3. Results

3.1. Toxicity of Chlorantraniliprole to \( F_0, F_1, \) and \( F_2 \) Generations

The lowest (1.432 mg/L) and the highest \( LC_{50} \) (4.119 mg/L) value in \( F_0 \) generation was recorded for the first and sixth instar larvae, respectively. Similarly, the lowest (0.810 mg/L) and the highest (4.080 mg/L) \( LC_{50} \) values of the \( F_1 \) generation were noted for the first and sixth instar larvae, respectively. A similar trend for the \( LC_{50} \) value was noted for the \( F_2 \) generation. The lowest (0.829 mg/L) and the highest (4.10 mg/L) \( LC_{50} \) value of the \( F_2 \) generation was observed for the first and sixth instar larvae, respectively (Table 1).

The \( LC_{10} \) and \( LC_{25} \) values were determined from mortality concentration-response lines. The lowest (1.042 mg/L) and the highest (1.413 mg/L) \( LC_{10} \) value of the \( F_0 \) generation was noted for the first and sixth instar larvae, respectively. Similarly, the first and sixth instar larvae of the \( F_1 \) generation recorded the lowest (0.334 mg/L) and the highest (1.055 mg/L) \( LC_{10} \) values, respectively. Moreover, a similar trend in the \( LC_{10} \) value was observed of the \( F_2 \) generation, where the first and sixth instar larvae had the lowest (0.345 mg/L) and the highest (1.315 mg/L) \( LC_{10} \) values, respectively (Table 1).

The lowest (1.212 mg/L) and the highest (2.345 mg/L) \( LC_{25} \) values of the \( F_0 \) generation were noted in the first and sixth larval instars, respectively. Similarly, the first and sixth instar larvae of the \( F_1 \) generation recorded the lowest (0.516 mg/L) and the highest (2.002 mg/L) \( LC_{25} \) values, respectively. A similar trend of \( LC_{25} \) values was noted for the \( F_2 \) generation, where the lowest (0.52 mg/L) and the highest (2.25 mg/L) \( LC_{25} \) values were recorded for the first and sixth larval instars, respectively (Table 1).

The lowest (1.969 mg/L) and the highest (12.012 mg/L) \( LC_{90} \) values of the \( F_0 \) generation were recorded for the first and sixth larval instars, respectively. Similarly, the first and sixth instar larvae of the \( F_1 \) generation recorded the lowest (1.908 mg/L) and the highest (15.776 mg/L) \( LC_{90} \) values, respectively. A similar trend of \( LC_{90} \) values was noted for the \( F_2 \) generation, where the lowest (1.99 mg/L) and the highest (12.82 mg/L) \( LC_{90} \) values were recorded for the first and sixth larval instars, respectively (Table 1).
3.2. Sub-Lethal and Transgenerational Effects of Chlorantraniliprole on Biological and Reproductive Parameters and of F₀, F₁ and F₂ Generations

The LC₁₀ and LC₂₅ concentrations of chlorantraniliprole were used to observe biological and reproductive parameters on all instars and pupae in F₀, F₁, and F₂ generations (Tables 2 and 3).

**Table 2.** Sub-lethal (LC₁₀, LC₂₅) effects of chlorantraniliprole on biological traits of *Spodoptera frugiperda* for three generations.

| Conc. | Duration (Egg-Larva) (Days) | 1st Instar | 2nd Instar | 3rd Instar | 4th Instar | 5th Instar | 6th Instar | Pupa |
|-------|-----------------------------|------------|------------|------------|------------|------------|------------|------|
| F₀    |                             |            |            |            |            |            |            |      |
| Control | 2.80 ± 0.04               | 3.18 ± 0.04 | 1.26 ± 0.04 | 1.32 ± 0.04 | 1.26 ± 0.04 | 2.19 ± 0.04 | 3.12 ± 0.03 | 8.68 ± 0.06 |
| LC₁₀  | 3.28 ± 0.04               | 3.42 ± 0.05 | 1.40 ± 0.05 | 1.51 ± 0.05 | 1.56 ± 0.05 | 2.53 ± 0.05 | 3.69 ± 0.04 | 9.57 ± 0.07 |
| LC₂₅  | 3.65 ± 0.04               | 3.93 ± 0.02 | 1.92 ± 0.02 | 1.80 ± 0.04 | 1.82 ± 0.03 | 2.81 ± 0.04 | 3.93 ± 0.02 | 10.17 ± 0.07 |
| p-value | 0.21                      | 0.000124   | 0.0152     | 0.088      | 0.037      | 0.013      | 0.0009     | 0.243 |
| F     | 6.40                       | 8.92       | 4.43       | 9.75       | 2.78       | 1.85       | 4.42       | 1.39  |
| df    | 89                         | 89         | 89         | 89         | 89         | 89         | 89         | 89    |
| F₁    |                             |            |            |            |            |            |            |      |
| Control | 2.68 ± 0.05               | 3.12 ± 0.03 | 1.23 ± 0.04 | 1.31 ± 0.04 | 1.28 ± 0.04 | 2.27 ± 0.04 | 3.10 ± 0.03 | 8.65 ± 0.07 |
| LC₁₀  | 3.45 ± 0.05               | 3.48 ± 0.05 | 1.38 ± 0.05 | 1.52 ± 0.05 | 1.40 ± 0.05 | 2.62 ± 0.05 | 3.70 ± 0.04 | 9.77 ± 0.08 |
| LC₂₅  | 3.87 ± 0.03               | 3.95 ± 0.02 | 1.89 ± 0.03 | 1.96 ± 0.03 | 1.93 ± 0.02 | 2.86 ± 0.03 | 3.95 ± 0.02 | 9.94 ± 0.09 |
| p-value | 0.205                     | 0.066      | 0.010      | 0.024      | 0.384      | 0.011      | 0.26       | 0.646 |
| F     | 5.45                       | 2.79       | 4.21       | 9.56       | 3.83       | 1.89       | 1.23       | 0.51  |
| df    | 89                         | 89         | 89         | 89         | 89         | 89         | 89         | 89    |
| F₂    |                             |            |            |            |            |            |            |      |
| Control | 2.54 ± 0.05               | 3.07 ± 0.02 | 1.07 ± 0.02 | 1.36 ± 0.05 | 1.25 ± 0.04 | 2.19 ± 0.04 | 3.07 ± 0.02 | 8.79 ± 0.06 |
| LC₁₀  | 3.39 ± 0.05               | 3.22 ± 0.04 | 1.45 ± 0.05 | 1.50 ± 0.50 | 1.54 ± 0.05 | 2.62 ± 0.05 | 3.55 ± 0.05 | 9.65 ± 0.07 |
| LC₂₅  | 3.76 ± 0.04               | 3.92 ± 0.02 | 1.93 ± 0.02 | 1.88 ± 0.03 | 1.90 ± 0.03 | 2.87 ± 0.03 | 3.93 ± 0.02 | 9.88 ± 0.08 |
| p-value | 0.65                      | 0.123      | 0.989      | 0.94       | 0.007      | 0.068      | 0.20       | 0.130 |
| F     | 0.63                       | 0.28       | 4.25       | 10.70      | 2.48       | 3.14       | 1.93       | 0.36  |
| df    | 89                         | 89         | 89         | 89         | 89         | 89         | 89         | 89    |

Values are means ± SE (standard errors of the means).

**Table 3.** Sub-lethal (LC₁₀, LC₂₅) effects of chlorantraniliprole on reproductive parameters of *Spodoptera frugiperda* for 3 generations.

| Concentration | Pre-Oviposition Period (Days) | Fecundity | Female Adult Longevity (Days) |
|---------------|--------------------------------|-----------|-------------------------------|
|               | F₀                             |           |                               |
| Control       | 3.36 ± 0.065                   | 394.53 ± 5.74 | 4.519 ± 0.067 |
| LC₁₀          | 3.53 ± 0.068                   | 341.73 ± 6.17 | 4.538 ± 0.068 |
| LC₂₅          | 3.65 ± 0.065                   | 337.15 ± 6.19 | 4.576 ± 0.067 |
| p-value       | 0.523                          | 0.991      | 0.368                         |
| F             | 0.955                          | 1.738      | 0.412                         |
|               | F₁                             |           |                               |
| Control       | 3.30 ± 0.063                   | 368.71 ± 6.16 | 4.480 ± 0.067 |
| LC₁₀          | 3.42 ± 0.067                   | 343.38 ± 5.013 | 4.384 ± 0.066 |
| LC₂₅          | 3.59 ± 0.067                   | 346.76 ± 5.92 | 4.461 ± 0.068 |
| p-value       | 0.0032                         | 0.172      | 0.468                         |
| F             | 3.27                           | 1.390      | 0.095                         |
|               | F₂                             |           |                               |
| Control       | 3.28 ± 0.062                   | 368.38 ± 5.535 | 4.384 ± 0.066 |
| LC₁₀          | 3.44 ± 0.068                   | 361.80 ± 5.799 | 4.423 ± 0.067 |
| LC₂₅          | 3.69 ± 0.063                   | 329.07 ± 5.177 | 4.403 ± 0.067 |
| p-value       | 0.00040                        | 0.284      | 0.943                         |
| F             | 3.61                           | 0.295      | 1.894                         |

Values are means ± SE (standard errors of the means).

Significant differences were noted among LC₁₀ and LC₂₅ concentrations and control treatment of the study. There was no significant difference in hatching duration of F₀
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(F = 6.40; df = 89; p = 0.214), F1 (F = 5.45; df = 89; p = 0.205) and F2 (F = 0.63; df = 89; p = 0.65) generations (Table 2). Significant difference was recorded for the first instar larval duration of F0 (F = 8.92; df = 89; p = 0.000124) generation, but not for the F1 (F = 2.79; df = 89; p = 0.066) generation. Similarly, F2 generation (F = 0.28; df = 89; p = 0.123) remained non-significant in this regard (Table 2). Significant differences were noted in 2nd instar larval duration of F0 (F = 4.43; df = 89; p = 0.0152) and F1 (F = 4.21; df = 89; p = 0.010) generations, whereas non-significant differences were noted for the F2 generation (F = 0.25; df = 89; p = 0.089) (Table 2). For 3rd instar larvae, non-significant differences were observed in larval duration of F0 (F = 9.75; df = 89; p = 0.088); however, in F1 (F = 9.56; df = 89; p = 0.024) generation significant difference was observed, while non-significant differences were noted for the F2 generation (F = 10.70; df = 89; p = 0.94) (Table 2).

The fourth instar larvae noted significant differences for larval duration in F0 (F = 2.78; df = 89; p = 0.0037), but non-significant for F1 (F = 3.83; df = 89; p = 0.384) and significant differences for the F2 generation (F = 2.48; df = 89; p = 0.007) (Table 2). Significant differences were observed in the larval duration of fifth instars belonging to the F0 (F = 1.85; df = 89; p = 0.013), F1 (F = 1.89; df = 89; p = 0.011) generations; however, non-significant differences were recorded for the F2 (F = 3.14; df = 89; p = 0.068) generation (Table 2). Similarly, significant differences were observed in the larval duration of sixth instars belonging to F0 (F = 4.42; df = 89; p = 0.0009), whereas those belonging to F1 (F = 1.23; df = 89; p = 0.26) and F2 (F = 1.93; df = 89; p = 0.20) generations remained non-significant (Table 2). For pupa duration, non-significant differences were noted in F0 (F = 1.39; df = 89; p = 0.243), F1 (F = 0.51; df = 89; p = 0.646) and F2 (F = 1.30; df = 89; p = 0.36) generations (Table 2).

Reproductive parameters of the F0, F1 and F2 generations are given in Table 3. Preoviposition for F0 had non-significant differences (F = 0.955; p = 0.523), while significant differences were noted for F1 (F = 3.27; p = 0.0032) and F2 (F = 3.61; p = 0.00040) generations. Fecundity for F0 (F = 1.738; p = 0.991), F1 (F = 1.390; p = 0.172) and F2 (F = 0.295; p = 0.284) observed non-significant differences. Female adult longevity for F0 (F = 0.412; p = 0.368), F1 (F = 0.095; p = 0.468) and F2 (F = 1.894; p = 0.943) remained non-significant (Table 3).

3.3. Effect of Chlorantraniliprole on Demographic Traits of F0, F1, and F2 Generations

Demographic characters calculated using two sex stage-specific life tables are shown in Table 4. For the F0 generation, the intrinsic rate of increase (r) was directly proportional to concentration which significantly decreased in LC10 and LC25 compared to the control (Table 4).

The finite mean rate of increase (λ) was significantly different in LC10 and LC25 compared to the control (Table 4) and changed with increased concentration. The net reproductive rate (R0) was higher in control and decreased significantly with increased concentration in LC10 and LC25. The mean generation time (T) was prolonged in LC10, and LC25 treated insects compared to the control (Table 4). The GRR was significantly low in LC10 and LC25-treated insects compared to the control (Table 4).

For the F1 generation, r was directly proportional to concentration which significantly decreased in LC10 and LC25 compared to the control (Table 4). The λ was significantly different in LC10 and LC25 compared to the control (Table 4) and changed with increased concentration. The R0 was higher in control and decreased significantly with increased concentration in LC10 and LC25. The T was prolonged in the LC10 and LC25-treated insects compared to the control (Table 4). The GRR was significantly low in the LC10 and LC25-treated insects compared to the control (Table 4).

For the F2 generation, r was directly proportional to concentration which significantly decreased in LC10 and LC25 compared to the control (Table 4). The λ was significantly different in LC10 and LC25 compared to the control (Table 4) and changed with increased concentration. The R0 was higher in control and decreased significantly with increased concentration. The T was prolonged in LC10 and LC25-treated insects compared to the control (Table 4). The GRR was significantly low in LC10 and LC25-treated insects compared to the control (Table 4).
Table 4. Transgenerational effects of chlorantraniliprole on demographic traits of *Spodoptera frugiperda* for the F₀, F₁, and F₂ generations.

|       | F₀             | F₁             | F₂             |
|-------|----------------|----------------|----------------|
|       | LC₁₀           | Control        | LC₂₅           |
|       | r              | 0.172 ± 0.0036 ab | 0.194 ± 0.0040 a | 0.160 ± 0.0034 b |
|       | λ              | 1.188 ± 0.0043 ab | 1.215 ± 0.0048 a | 1.174 ± 0.0039 b |
|       | R₀             | 185.544 ± 18.16 b | 206.19 ± 21.006 a | 196.02 ± 18.074 b |
|       | T              | 30.259 ± 0.26 a  | 27.347 ± 0.184 b | 32.903 ± 0.375 a  |
|       | GRR            | 196.990 ± 18.24 b | 214.849 ± 21.13 a | 211.319 ± 18.43 b |
|       | F₁             |                |                |
|       | r              | 0.170 ± 0.0036 ab | 0.199 ± 0.0036 a | 0.157 ± 0.0029 ab |
|       | λ              | 1.186 ± 0.0042 ab | 1.220 ± 0.0044 a | 1.170 ± 0.0034 ab |
|       | R₀             | 182.322 ± 18.26 b | 213.33 ± 19.597 a | 196.122 ± 18.34 b |
|       | T              | 30.472 ± 0.232 a  | 26.866 ± 0.173 b | 33.564 ± 0.153 a  |
|       | GRR            | 198.209 ± 18.702 b | 220.959 ± 19.69 a | 215.759 ± 18.82 ab |
|       | F₂             |                |                |
|       | r              | 0.183 ± 0.0049 b  | 0.211 ± 0.0062 a | 0.158 ± 0.0029 b  |
|       | λ              | 1.201 ± 0.0059 a  | 1.235 ± 0.0077 a | 1.171 ± 0.0034 b  |
|       | R₀             | 213.77 ± 19.11 ab | 217.34 ± 19.35 a | 193.83 ± 17.30 b  |
|       | T              | 29.26 ± 0.599 a  | 25.42 ± 0.601 b  | 33.266 ± 0.265 a  |
|       | GRR            | 226.73 ± 19.48 ab | 229.19 ± 19.65 a | 201.04 ± 17.47 b  |

Here, r—intrinsic rate of increase, λ—finite rate of increase, R₀—net reproduction rate, T—mean length of a generation, GRR— gross reproduction rate; values are means ± SE (standard errors of the means). The means followed by different letters are significantly different from each other (p < 0.05).

Age-stage specific survival rate (sₓj) of the F₀ generation denoted that the overall life span of the F₀ (filial generation) prolonged in LC₁₀ and LC₂₅ as compared to the control (Figure 1).

![Figure 1](image1.png)

**Figure 1.** Age stage-specific survival rate (sₓj) of the F₀ generation in *Spodoptera frugiperda*.

Age-stage specific life expectancy (eₓj) was higher in LC₁₀ and LC₂₅-treated insects than in the control (Figure 2).

![Figure 2](image2.png)

**Figure 2.** Age stage life expectancy (eₓj) of the F₀ generation in *Spodoptera frugiperda*. 

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Age-stage specific reproductive rate \( (v_{xj}) \) of the F\(_0\) generation denoted that the overall reproductive rate reduced in LC\(_{25}\)-treated insects, and the LC\(_{10}\)-treated insects also had less reproductive rate as compared to the control (Figure 3).

![Figure 3. Age stage reproductive value \( (v_{xj}) \) of the F\(_0\) generation in *Spodoptera frugiperda*.](image)

The \( s_{xj} \) of F\(_1\) (first filial generation) denoted that the overall life span was prolonged in LC\(_{10}\) and LC\(_{25}\) compared to the control (Figure 4).

![Figure 4. Age stage-specific survival rate \( (s_{xj}) \) of the F\(_1\) generation in *Spodoptera frugiperda*.](image)

The \( e_{xj} \) was higher in LC\(_{10}\) and LC\(_{25}\)-treated insects compared to the control (Figure 5).

![Figure 5. Age stage life expectancy \( (e_{xj}) \) of the F\(_1\) generation in *Spodoptera frugiperda*.](image)

The \( v_{xj} \) of the F\(_1\) generation denoted that the overall reproductive rate was reduced in LC\(_{25}\)-treated insects, and LC\(_{10}\)-treated insects had less reproductive rate as compared to the control (Figure 6).
Figure 6. Age stage reproductive value ($v_{xj}$) of the F$_1$ generation in *Spodoptera frugiperda*.

The $s_{xj}$ of F$_2$ (second filial generation) denoted that the overall life span was prolonged in LC$_{10}$ and LC$_{25}$ compared to the control (Figure 7).

Figure 7. Age stage-specific survival rate ($s_{xj}$) of the F$_2$ generation in *Spodoptera frugiperda*.

The $e_{xj}$ was higher in LC$_{10}$ and LC$_{25}$-treated insects than in the control (Figure 8).

Figure 8. Age stage life expectancy ($e_{xj}$) of the F$_2$ generation in *Spodoptera frugiperda*.

The $v_{xj}$ of the F$_2$ generation denoted that the overall reproductive rate was reduced in LC$_{25}$-treated insects, and LC$_{10}$-treated insects had less reproductive rate as compared to the control (Figure 9).

Figure 9. Age stage-specific reproductive rate ($v_{xj}$) of the F$_2$ generation in *Spodoptera frugiperda*. 
4. Discussion

By comprehending the life table of insects, effective management techniques may be created to control insects that are infesting agricultural plants. A greater understanding of the life cycle, survival rate, and reproduction may aid in managing insect pests [67,68]. In the context of muscle function, chlorantraniliprole is an anthranilic diamide that acts as a target for ryanodine receptors. After ingesting anthranilic pesticides, insects experience calcium loss, which leads to muscular contractions.

According to the current research findings, exposure to sublethal quantities of chlorantraniliprole led to a considerable reduction in both fecundity and fertility (egg hatch). On the other hand, Teixeira et al. [69] found that eating chlorantraniliprole at a concentration of 500 mg L\(^{-1}\) did not have a significant impact on the quantity of eggs deposited by apple maggot fly or the percentage of eggs that hatched. Knight and Flexner [70] similarly found that chlorantraniliprole had only a little impact on the adult \(C.\) pomonella population’s capacity to survive and reproduce. It is possible that the varying quantities of pesticides used cause variations between earlier and current findings, the various species of insects tested, and the technique used to apply the pesticides. Aside from that, the sublethal concentrations of chlorantraniliprole significantly extended the preoviposition of adults. This was in agreement with the observations made by Teixeira et al. [69], which stated that chlorantraniliprole-exposed insects begin egg-laying later than non-exposed adults do.

In accordance with the findings of Han et al. [71], who found that fecundity was dramatically decreased in \(LC_{10}\) and \(LC_{30}\)-treated groups in comparison to the control group, our findings show that fecundity was severely reduced. Similar results were seen in our experiments, in which groups treated with \(LC_{10}\) and \(LC_{25}\) had a considerably lower fecundity than the control. Our findings are in further accord with Lutz et al. [72], who found that the lifespan of larvae and pupae was far longer than previously estimated. In the same way, the duration of the larval and pupal stages was lengthened in \(LC_{10}\) and \(LC_{25}\)-treated groups compared to the control group in the present research. It’s possible that the disruption to the ryanodine receptors caused the patient to stop eating, which contributed to the protracted duration. Our findings are similarly in accordance with those of Ali et al. [5], who found that the development stages of the larval and pupal stages were severely altered in comparison to the control.

Compared to the control group, the length of time spent as a larva in the group of insects that had been treated with chlorantraniliprole for the present research was much longer. However, in our studies, pupal and adult emergence were not significantly altered in chlorantraniliprole-sprayed insects as compared to the control. Similar results have been reported for \(S.\) exigua where chlorantraniliprole decreased larval weight, pupal weight, and pupation rate. Nawaz et al. [73] reported that \(R_0\), \(r\), and \(\lambda\) significantly decreased in chlorantraniliprole-treated groups compared to the control. Similar results for these parameters were recorded in the current study.

Similarly, Han et al. [71] observed a reduced survival rate and less fecundity in chlorantraniliprole-treated insects compared to control. Our study also recorded a lower survival rate and less fecundity in the chlorantraniliprole-treated insects compared to the control. Similar findings have also been reported by Wang et al. [74], where early-instar larvae of \(P.\) xylostella were affected more at 14 DAT when exposed to chlorantraniliprole-treated radish seedlings using the field rate. Long-lasting residual efficacy of chlorantraniliprole has also been observed against other pests like oblique banded leafroller [75], the grapevine moth and white grubs.

According to Han et al. [71], the values of \(R\), \(r\), and \(\lambda\) were considerably lower in chlorantraniliprole-treated groups compared to the control. These metrics showed a considerable drop in severity in the groups treated with chlorantraniliprole, which produced similar results as seen in the present investigation. According to Fernandes et al. [76], sublethal poisoning might affect an insect’s overall fitness and its reproductive capabilities. This notion was reinforced by the findings of the current study with \(P.\) xylostella. Yin et al. [77] reported quite similar findings to these, and observed that sublethal doses
of Spinosad inhibited the population growth of *P. xylostella* by impairing the organism’s ability to survive, develop, and reproduce.

5. Conclusions

This is the first study that provides important basic time-specific, age-specific, and reproduction-specific data for understanding a *S. frugiperda* attack on maize with chlorantraniliprole. The impacts on their development and fecundity resulted in a decreased population of *S. frugiperda*. The results revealed that fecundity was mainly affected by chlorantraniliprole in the second filial generation, which suggests that chlorantraniliprole spraying in the spring season will save maize crops from *S. frugiperda* during the autumn, which is as the main attacking season of the fall armyworm.

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