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Control of *Spodoptera frugiperda* on Fresh Corn via Pesticide Application before Transplanting

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Abstract: Background: Pesticide application before transplanting crops has been widely used in rice as an economical and effective method for reducing the use of chemical pesticides. This study focused on the feasibility of the application of pesticides before transplanting in a fresh corn nursery to control *Spodoptera frugiperda*. Methods: Three pesticides, including 35% Chlorantraniliprole WDG, 6% Spinetoram SC, and 3% Emamectin Benzoate WDG, combined with Polyorganosilicon (HTY-A8) or special flight additives (MF) as synergists were used and their toxicity was determined in the larvae of *S. frugiperda* feeding on sweet corn in the third leaf stage treated with 5 and 25 times the conventional field application concentration. The best combinations were tested in the field. The results showed that *S. frugiperda* exhibited high sensitivity to the three pesticides. The period of pest control validity of 35% Chlorantraniliprole WDG and 6% Spinetoram SC in the larvae was about 20 days, while that of 3% Emamectin Benzoate WDG was much shorter. The active component content of Chlorantraniliprole in the corn leaves was significantly higher than that of Emamectin Benzoate and Spinetoram. The pest control effects of Chlorantraniliprole were significantly promoted by HTY-A8 and MF. The field experiment showed that the control effect on *S. frugiperda* could last for 17 days by spraying Chlorantraniliprole or Spinetoram at 25 times the conventional concentration before transplanting, Furthermore, this method could reduce the amount of active ingredient to 4/5 or 3/4 of that found in a single field spray or seed coating treatment, respectively. Conclusions: This study puts forward a new method to effectively control *S. frugiperda* in the seedling stage of fresh corn.

Keywords: *Spodoptera frugiperda*; pesticide application before transplanting; fresh corn; seedling stage; additive; Chlorantraniliprole

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1. Introduction

Due to its strong long-distance migration ability, the fall armyworm (*Spodoptera frugiperda*) has spread rapidly throughout China since it invaded Yunnan Province in December 2018. It has been listed as a class A national crop pest since 15 September 2020 [1,2]. The larvae of *S. frugiperda* can feed on 353 species of plants in 42 genera, including corn, rice, wheat, and sorghum [3]. However, *S. frugiperda* mainly harms corn in China, damaging an area of 1.07 million hectares in 2019 and 1.33 million hectares in 2020 [4,5]. Fresh corn, including sweet corn, waxy corn, and sweet-waxy corn, has higher sugar and protein content than grain corn [6,7]. Studies have shown that fresh corn is more beneficial to the development and reproduction of *S. frugiperda*, and sweet corn is better than waxy corn [8,9]. Field studies have also confirmed that *S. frugiperda* prefers fresh corn to grain corn for feeding [10–12].

Fresh corn can be planted twice a year in southern China, and even three times a year in Hainan Province, which can result in perennial damage by *S. frugiperda* [13]. Chemical pesticides must be sprayed on the plants 4-6 times from emergence to maturity for *S. frugiperda* control [14,15]. Due to the mechanism of action of the pesticides in *S. frugiperda*—which mainly involves contact and stomach toxicity—and the fact that small leaves cannot adhere enough pesticides, the effect of spraying pesticides is very poor at the early planting stage. The application of seed-coating agents to control diseases and insect pests at the corn seedling stage has been widely used [16–18]. Research has shown that *S. frugiperda* can be controlled at the corn seedling stage from 10 to 25 days after planting by seed coating with chemical pesticides, among which 50% Chlorantraniliprole FSC (flowable concentrate for seed coating) and 40% Bromothiazine FSC have been shown to exhibit good effects [19–21]. However, the germination rate and vigor of coated seeds can be significantly reduced after long-term storage [22]. In particular, the germination rate of sweet corn was shown to decrease more rapidly after coating treatment [23]. Accordingly, few seed coating agents have been applied to fresh corn, especially sweet corn.

The growth vigor of fresh corn is weaker at the seedling stage than that of grain corn. In order to improve the tidiness and robustness of fresh corn field seedlings and ensure consistency during the whole growth period, the production of fresh corn is generally based on seeding and transplanting [24,25]. The application of high-concentration pesticides (10–40 times that of conventional spray) in crop seeding areas before transplanting could be conducive to the construction and restoration of field biodiversity and enhance the biological control of pests by natural enemies by reducing pesticide use in the field at the early stage. This economical and effective chemical pesticide reduction technique has been widely used for pest control in rice; for example, the delivery of Avermectin Chlorantraniliprole is used to prevent first-generation *Chilo suppressalis* [26,27]; Armistar Top (Syngenta) is used to counteract rice sheath blight disease [28]; a combination of four insecticides and three fungicides at a concentration of 40 times is used to control *C suppressalis*, *Cnaphalocrocis medinalis*, and rice leaf blast disease [29]; and Pymetrozine and Dinotefuran are used to prevent rice virus disease [30]. The control effect of this method can last for more than 40 days. However, few studies have reported on corn pest control using this method. Therefore, we explored the feasibility of the application of high-concentration pesticides in a fresh corn nursery to control *S. frugiperda*. The results of this study contribute to a better understanding of the effective control of *S. frugiperda* through the application of high-concentration pesticides to fresh corn in the seedling stage.

2. Materials and Methods

2.1. Materials

2.1.1. Plants

The corn cultivars used were Zhetian 19 and Zhenuoyu 18, which were bred by the Institute of Corn and Featured Upland Crops, Zhejiang Academy of Agricultural Sciences.

2.1.2. Insects

S. frugiperda pupae were purchased from Henan Jiyuan Baiyun Industry Co., Ltd., Jiyuan, China. The newly emerged (<12 h) moths were paired to lay eggs. After hatching, the newly hatched (<12 h) larvae were fed with Zhetian 19 leaves in an incubator (28 ± 1 °C, L:D = 16:8, humidity of 80%). The leaves were changed each day until the first-generation larvae were ready for experiments.

2.1.3. Pesticides

The experimental pesticides included 35% Chlorantraniliprole water-dispersible granules (WDG) (Bayer Crop Science Co., Ltd. (Hangzhou, China)); 3% Emamectin Benzoate WDG (Hailir Pesticides and Chemical Group); 6% Spinetoram suspension concentrate (SC) (US Dow AgroSciences Biological Chemistry Company, Indianapolis, IN, USA); 50% Chlorantraniliprole FSC (LMW) (Corteva Agriscience, Johnston, IA, USA); Polyorganosilicon (HTY-A8) (Nanjing Hongyang Agricultural Material Chain Group Co., Ltd. Nanjing, China); and special flight additives (MF) (Beijing Grand AgroChem Co., Ltd., Beijing, China), all commercially available.

2.2. Methods

2.2.1. Determination of Insecticide Toxicity to Newly Hatched or Third Instar *S. frugiperda* Larvae

The toxicities of 35% Chlorantraniliprole WDG, 3% Emamectin Benzoate WDG, and 6% Spinetoram SC in the newly hatched and third instar larvae of *S. frugiperda* were determined singularly via the leaf dipping method. The sensitive baseline method was used [31]. A series of pesticide concentration gradients were set for biological determination in pre-experiments. For newly hatched larvae, the active ingredient (a.i.) concentrations of 35% Chlorantraniliprole WDG and 6% Spinetoram SC were set as 1.62 mg/L, 0.24 mg/L, 0.048 mg/L, 0.00192 mg/L, 0.000384 mg/L, and 0 mg/L, and the concentrations of 3% Emamectin Benzoate WDG were set as 1.2 mg/L, 0.24 mg/L, 0.048 mg/L, 0.0096 mg/L, 0.00192 mg/L, and 0 mg/L. For third instar larvae, the concentrations of 35% Chlorantraniliprole WDG and 6% Spinetoram SC were set as 4.86 mg/L, 1.62 mg/L, 0.54 mg/L, 0.18 mg/L, 0.06 mg/L, 0.02 mg/L, and 0 mg/L, while the 3% Emamectin Benzoate WDG concentrations were set as 1.2 mg/L, 0.24 mg/L, 0.048 mg/L, 0.0096 mg/L, 0.00192 mg/L, and 0 mg/L. Each pesticide was prepared with deionized water to the highest concentration first, and then diluted to the lowest concentration through a gradient. Each treatment had 3 repetitions, and a total of 72 newly hatched or third instar larvae were used for each concentration.

The first leaf from the top of 5-7-leaf stage corn was gently scrubbed in 1% detergent solution then washed with clearwater and soaked in the configured solution for 20 s. The leaves, when dried, were cut into small squares (1 cm × 1 cm) and moved into a 24-cell incubator (1 cm × 1 cm × 1 cm for each cell, moisturized by 0.5 mL 1.5% water agar), with 2 small square leaves per cell. One newly hatched or third instar larva of *S. frugiperda* was introduced into each cell, which was then covered and fastened to prevent the larvae from escaping. The deaths of the newly hatched and third instar larvae were recorded at 48 h and 72 h after introduction, respectively. Death was judged as immobility when touched by a brush.

2.2.2. Toxicity of Pesticides to *S. frugiperda*

The three insecticides described in Section 2.2.1 were used accompanied by special flight additives, MF or Polyorganosilicon HTY-A8. Chlorantraniliprole FSC (50%) was used as a positive control (CK+) and clearwater as a negative control (CK−). Based on the recommended and production concentrations of the insecticides, two high concentrations of insecticides (5 and 25 times that of conventional spray) were used, accompanied by the additives (Table 1). The cultivar of corn was Zhetian 19, raised on a 75-well tray (540 mm × 280 mm). The test was carried out in a ventilated plastic greenhouse in early summer with natural light. The temperature and humidity in the greenhouse were basically consistent with the natural environment. The insecticides were sprayed on the corn plants at the 3-leaf stage (V3) (8 days after emergence) using a small hand-squeezed spray pot (250 mL) until water droplets on the leaf edge streamed down, ensuring the same squeeze time for each treatment. The seedlings were cultured on the trays using bottom irrigation to replenish water, with 8 trays per treatment. The changes in plant harm caused by the insecticides, including leaf shape and color and plant height, were observed 14 days after spraying.

Table 1. Combinations of insecticides and additives.

Treatment Number	Treatment	Times of Conventional Spray	Application Concentration
1	LCB	5	330 mg/L
2	LCB + HTY-A8	5	330 mg/L + 0.02% HTY-A8
3	LCB + MF	5	330 mg/L + 0.02% MF
4	LCB	25	1650 mg/L
5	LCB + HTY-A8	25	1650 mg/L + 0.02%HTY-A8
6	LCB + MF	25	1650 mg/L + 0.02% MF
7	YJD	5	400 mg/L
8	YJD + HTY-A8	5	400 mg/L + 0.02%HTY-A8
9	YJD + MF	5	400 mg/L + 0.02% MF
10	YJD	25	2000 mg/L
11	YJD + HTY-A8	25	2000 mg/L + 0.02%HTY-A8
12	YJD + MF	25	2000 mg/L + 0.02% MF
13	JWY	5	50 mg/L
14	JWY + HTY-A8	5	50 mg/L + 0.02%HTY-A8
15	JWY + MF	5	50 mg/L + 0.02% MF
16	JWY	25	250 mg/L
17	JWY + HTY-A8	25	250 mg/L + 0.02%HTY-A8
18	JWY + MF	25	250 mg/L + 0.02% MF
CK+	LMW	/	6.8 g/kg seed coating
CK−	water	/	0.0

Note: LCB—35% Chlorantraniliprole WDG; JWY—3% Emamectin Benzoate WDG; YJD—60 g/L Spinetoram SC; LMW—50% Chlorantraniliprole FSC; HTY-A8—Polyorganosilicon HTY-A8; MF—flight additives.

On the 2nd, 10th, and 20th day after being sprayed, all of the corn leaves were taken in batches to test the mortality of the newly hatched and third instar larvae. The leaves from the different treatments were cut into 1 cm sections, then two pieces and one larva were placed into each cell in a 24-cell incubator; each treatment was repeated 3 times. The deaths of the newly hatched and third instar larvae were recorded at 48 h and 72 h after introduction, respectively.

Furthermore, 500 g of fresh leaves was taken from each treatment and frozen at −20 °C on the 2nd, 10th, and 20th day after being sprayed. After all the samples were collected, they were sent to Zhejiang Greentown Agricultural Science Monitoring Technology Co., Ltd. to detect residual pesticides.

2.2.3. Control Effect of *S. frugiperda* in the Field

The field experiment was carried out at the Zhejiang Academy of Agricultural Sciences (120.23 E, 29.28 N) in the autumn of 2022. After a comprehensive comparison of the results of the lab bioassay and leaf residual pesticides determination, field experiments were conducted with treatment 3 (5 × Chlorantraniliprole + MF), treatment 5 (25 × Chlorantraniliprole + HTY-A8), treatment 11 (25 × Spinetoram + HTY-A8), and treatment 12 (25 × Spinetoram + MF). Chlorantraniliprole FSC (50%) 6.8 g/kg seed coating (CK+) and water (CK−) were used as controls. Zhenuoyu 18 cultivars were raised from seedlings in 128-well trays (size 54.9 cm × 27.8 cm). The insecticides were sprayed when the seedlings grew to the V3 stage; then, the seedlings were transplanted into the field on the second day. Ternary compound fertilizer (N:P:K = 15:15:15, 600 kg/hm^2) was used as the base fertilizer before plowing. The transplanting density was 65 cm × 32 cm. The seedlings were watered continuously for 3 days after being transplanted. Treatments were arranged in random blocks and repeated 3 times. Each plot area was 95 m^2. The percentage of plants damaged by *S. frugiperda* in the field was investigated on the 8th, 11th, 14th, 17th, and 22nd day after transplantation, where corn leaves with holes were considered as damaged. Then, the relative pest control effect was calculated. On the 22nd day, the pest index of each treatment was investigated according to the Davis grading standard [32].

2.3. Statistical Analysis

In the laboratory bioassay, the effective determination was that the negative control mortality had to be less than 10%. The control mortality was used to correct the treatment mortality, that is:

$$C = \frac{(A - B)}{(100 - B)} \times 100 \quad (1)$$

where C is the corrected mortality, *A* is the mortality of the treatment group, and *B* is the mortality of the negative control (CK−) group.

$$R = \frac{Ni}{N} \times 100 \quad (2)$$

In the equation above, R is the damage rate of corn plants in the field, *Ni* is the number of damaged corn plants in the investigation, and *N* is the total number of corn plants in the investigation.

$$P = \frac{(Rck - Rt)}{Rck} \times 100 \quad (3)$$

In Equation (3), P is the relative control effect on the plant, *Rck* is the damage rate of the control plants, and *Rt* is the damage rate of the treatment plants.

The original data were preliminarily sorted using Excel 2019, and the toxicity of the different pesticides was analyzed using the Polo plus software (LeOra software Inc., Berkeley, CA, USA). The lethal median concentration (LC_{50}) and 95% confidence interval were calculated. After the corrected mortality and field relative control effect values were transformed by arcsine square root, SAS V8 (SAS Institute, INC., Cary, NC, USA) was used for a one-way analysis of variance (ANOVA), and the differences among treatments were compared via Tukey's HSD method.

3. Results

3.1. Determination of Insecticide Toxicity in Newly Hatched and Third Instar Larvae of *S. frugiperda*

The *S. frugiperda* larvae exhibited high sensitivity to 35% Chlorantraniliprole WDG, 3% Emamectin Benzoate WDG, and 6% Spinetoram SC. The LC_{50} value in the newly hatched larvae was 0.011–0.065 mg/L, while the LC_{50} value in the third instar larvae was 0.014–0.144 mg/L. Among the insecticides, the larvae were most sensitive to 3% Emamectin Benzoate WDG, with LC_{50} values of 0.011 mg/L in the newly hatched larvae and 0.014 mg/L in the third instar larvae. Both LC_{50} values of 3% Emamectin Benzoate WDG were much lower than those of 6% Spinetoram SC or 35% Chlorantraniliprole WDG (Table 2).

Table 2. Susceptibility of newly hatched and third instar *S. frugiperda* larvae to insecticides.

Tested Insects	Insecticides	Number of Tested Insects	Treatment Time	Slope ± SE	LC_{50} (95% CL) (mg/L)	χ^2	*df*
Newly hatched larvae	3% Emamectin Benzoate WDG	432	48 h	2.108 ± 0.302	0.011 (0.005–0.018)	59.822	13
	6% Spinetoram SC	504	48 h	1.220 ± 0.127	0.040 (0.026–0.057)	22.673	16
	35% Chlorantraniliprole WDG	432	48 h	1.483 ± 0.181	0.065 (0.035–0.102)	32.329	13
Third instar larvae	3% Emamectin Benzoate WDG	432	72 h	1.002 ± 0.121	0.014 (0.009–0.020)	7.085	13
	6% Spinetoram SC	504	72 h	1.210 ± 0.111	0.089 (0.061–0.124)	19.253	16
	35% Chlorantraniliprole WDG	432	72 h	1.174 ± 0.100	0.144 (0.081–0.235)	43.928	16

Note: CL—confidential limit.

3.2. Toxicity of Corn Leaves in *S. frugiperda* Larvae with Different Pesticides Treatments

All the treatments resulted in no significant damage to the three-leaf stage corn seedlings. All the seedlings grew normally, and no signs of drug damage were found, such as spots on leaves, curled leaves, yellowing leaves, and dwarfing plants.

The corrected mortalities of the newly hatched and third instar *S. frugiperda* larvae were 100% for all treatments, and the mortality of the 50% Chlorantraniliprole FSC coating (CK+) was also 100% on the 2nd day after the application of pesticides (Table 3). However, on the 10th day after the application of pesticides, the corrected mortalities of the newly hatched larvae with the 35% Chlorantraniliprole WDG and 60 g/L Spinetoram SC treatments were both over 95%, while the corrected mortality of the newly hatched larvae with treatment 16 (25 × Emamectin Benzoate) was 98.51%; this value showed no significant difference from that of the 35% Chlorantraniliprole WDG and 60 g/L Spinetoram SC treatments, but was significantly higher than that of the 3% Emamectin Benzoate WDG treatment. The corrected mortalities of the third instar larvae with the 35% Chlorantraniliprole WDG and 6% Spinetoram SC treatments were all over 80%, except for treatment 2 (5 × Chlorantraniliprole + HTY-A8). Among them, the corrected mortalities of the third instar larvae with treatment 2 (5 × Chlorantraniliprole + HTY-A8) and treatment 3 (5 × Chlorantraniliprole + MF) were significantly lower than with the other treatments using these two pesticides. The corrected mortality of the newly hatched larvae with the 3% Emamectin Benzoate WDG treatment was more than 74%, while the corrected mortality for the third instar larvae was less than 60%. Meanwhile, the corrected mortality of the third instar larvae with the 50% Chlorantraniliprole FSC coating (CK+) treatment was only 66.31%. Only treatment 5 (25 × Chlorantraniliprole + HTY-A8), treatment 6 (25 × Chlorantraniliprole + MF), and CK + (50% Chlorantraniliprole FSC coating) exhibited high toxicity towards the newly hatched *S. frugiperda* larvae on the 20th day after application. The corrected mortalities of the three treatments were all over 81%; this value was significantly higher than the other treatments, but there was no significant difference among the three treatments. The corrected mortality of the third instar larvae decreased significantly on the 20th day compared with that on the 10th day, and only the corrected mortalities of treatment 5 (25 × Chlorantraniliprole + HTY-A8) and 50% Chlorantraniliprole FSC coating (CK+) were over 66%, significantly higher than those of other treatments (Table 3).

3.3. Pesticide Residues in Corn Leaves with Different Pesticide Treatments

The active ingredient content in leaves from the 35% Chlorantraniliprole WDG treatment group reached the highest value on the second day after application of pesticides, while the active ingredient content of 50% Chlorantraniliprole seed coating treatment was the lowest, at only 0.25 mg/kg. The active ingredient contents in the leaves of all treatment groups on the 10th day after the application of pesticides decreased sharply compared with those on the 2nd day. The largest decrease was observed in the 3% Emamectin Benzoate WDG treatment group, which decreased to 1/202 of the last sampling, and the 6% Spinetoram SC group, which decreased to 1/11 of the previous sampling. The active ingredient content in leaves from the 35% Chlorantraniliprole WDG treatment group decreased slightly to 1/6 of the last sampling. However, the active ingredient content of the 50% Chlorantraniliprole FSC coating (CK+) group only decreased to 1/3 of the last sampling. The addition of auxiliaries slowed down the degradation of the effective ingredient among the same active ingredient application groups. Although the active ingredient contents in the leaves from the three pesticide treatment groups were very low on the 20th day after the application of pesticides, the active ingredient content remained stable in the leaves of the 50% Chlorantraniliprole FSC coating (CK+) group when compared to the preceding 10 days (Table 4).

Table 3. Mortalities of *S. frugiperda* larvae after being fed corn leaves with different pesticide treatments.

Treatment Number	Corrected Mortality %					
	2nd Day		10th Day		20th Day	
	Newly Hatched Larvae	Third Instar Larvae	Newly Hatched Larvae	Third Instar Larvae	Newly Hatched Larvae	Third Instar Larvae
1	100.00	100.00	100.00 a	95.45 ± 4.55 ab	42.46 ± 7.09 cde	11.14 ± 4.50 f
2	100.00	100.00	100.00 a	70.78 ± 1.35 cdef	47.84 ± 4.07 cde	41.81 ± 5.87 bc
3	100.00	100.00	100.00 a	83.12 ± 2.93 bcde	58.75 ± 5.58 bc	28.87 ± 4.52 cde
4	100.00	100.00	100.00 a	96.97 ± 3.03 a	45.888 ± 4.77 cde	39.56 ± 8.53 bcd
5	100.00	100.00	100.00 a	92.35 ± 1.44 ab	95.38 ± 2.62 a	73.08 ± 9.46 a
6	100.00	100.00	100.00 a	98.48 ± 1.52 a	87.51 ± 3.90 a	29.34 ± 5.57 cde
7	100.00	100.00	95.52 ± 2.51 bc	90.84 ± 2.56 abc	37.71 ± 8.43 cde	30.33 ± 8.96 cd
8	100.00	100.00	100.00 a	87.81 ± 3.94 abcd	28.32 ± 9.05 efg	27.64 ± 2.11 cde
9	100.00	100.00	100.00 a	86.22 ± 2.50 abcde	31.64 ± 2.40 def	12.22 ± 1.12 ef
10	100.00	100.00	98.51 ± 1.45 ab	92.35 ± 2.99 ab	28.09 ± 9.05 efg	19.69 ± 5.39 def
11	100.00	100.00	100.00 a	96.97 ± 3.03 a	52.22 ± 7.78 cd	19.89 ± 3.76 edf
12	100.00	100.00	100.00 a	95.45 ± 2.62 ab	14.46 ± 3.15 gh	35.08 ± 5.91 bcd
13	100.00	100.00	80.60 ± 1.66 fg	63.35 ± 10.25 efgh	30.05 ± 3.62 def	22.92 ± 6.76 cdef
14	100.00	100.00	89.55 ± 1.58 de	58.51 ± 6.78 fgh	25.28 ± 2.67 efg	28.67 ± 9.59 cde
15	100.00	100.00	94.03 ± 1.59 cd	41.78 ± 14.09 hi	15.69 ± 10.78 gh	24.41 ± 8.68 cdef
16	100.00	100.00	98.51 ± 1.51 ab	43.15 ± 10.73 hi	15.36 ± 10.23 gh	19.25 ± 10.91 def
17	100.00	100.00	74.63 ± 5.65 g	44.23 ± 19.15 ghi	31.80 ± 1.86 def	27.48 ± 4.78 cde
18	100.00	100.00	85.07 ± 2.91 ef	26.19 ± 1.77 i	7.94 ± 3.32 h	25.97 ± 3.41 cde
CK+	100.00	100.00	100.00 a	66.31 ± 6.32 defg	81.08 ± 2.23 ab	66.82 ± 14.24 a

Note: Data in the table are average values. Different letters in the same column indicate significant differences at $p < 0.05$ using Tukey's HSD test.

Table 4. Active ingredient content in corn leaves with each pesticide treatment.

Treatment Number	Pesticide Active Ingredient	Pesticide Content in Leaves (mg/kg)		
		2nd Day	10th Day	20th Day
1	Chlorantraniliprole	47.4 (5.44)	8.71 (13.83)	0.63
2		126 (5.94)	21.2 (52.29)	0.37
3		88.6 (3.32)	26.7 (51.35)	0.52
4		394 (12.75)	30.9 (34.33)	0.9
5		700 (5.15)	136 (53.98)	2.52
6		394 (6.46)	60.9 (52.95)	1.15
7	Spinetoram	2.27 (24.67)	0.092 (/)	<0.01
8		2.8 (21.54)	0.13 (10.83)	0.012
9		1.25 (1.95)	0.64 (/)	<0.01
10		10 (12.66)	0.79 (/)	<0.01
11		6.32 (4.05)	1.56 (53.79)	0.029
12		7.1 (2.42)	2.93 (244.17)	0.012
13	Emamectin Benzoate	5.35 (232.61)	0.023 (/)	<0.005
14		1.46 (66.36)	0.022 (/)	<0.005
15		3.13 (69.56)	0.045 (/)	<0.005
16		26.1 (483.33)	0.054 (/)	<0.005
17		12.5 (208.33)	0.06 (6.00)	0.01
18		12.5 (156.25)	0.08 (/)	<0.005
CK+	Chlorantraniliprole	0.25 (3.01)	0.083 (1.00)	0.083

Note: The numbers in parentheses are the multiples of the content of the effective components in the leaves compared to the next time point.

3.4. Field Control Effects of Different Pesticide Treatments on S. frugiperda

On the 8th day after transplanting, the corn was at the 4-5-leaf stage (V4–V5). The plant damage rate caused by *S. frugiperda* in the water treatment (CK−) group reached 15.99%. Interestingly, the plant damage rate in each of the pesticide treatment groups was less than 5% (Figure 1). Moreover, the plant damage rate with treatment 12 (25 × Spinetoram + MF) was 0, and the relative control effect of treatment 12 was 100%; in addition, the relative control effect of treatment 5 (25 × Chlorantraniliprole + HTY-A8) and 11 (25 × Spinetoram + HTY-A8) were both higher than 90% (Table 5). The relative control effect of the three treatments exhibited no significant difference from that of the 50% Chlorantraniliprole FSC coating (CK+) but was significantly higher than that of treatment 3 (5 × Chlorantraniliprole + MF) (Figure 1, Table 5). The plant damage caused by *S. frugiperda* in the control group (CK−) reached 20.6% on the 11th day after transplanting. With treatment 3, the plant damage rate reached 9.48% and the relative control effect was only 49.10%, which was not significantly different from that of the CK+ group but was significantly lower than that observed with treatment 11 (25 × Spinetoram + HTY-A8) (94.23%) and treatment 12 (25 × Spinetoram + MF) (100%) (F = 4.56, *df* = 4, p = 0.0235). On the 14th day after transplantation with treatment 3, the plant damage rate continued to increase rapidly; it was not significantly different from that of the CK− treatment but was significantly lower than that of the other four treatments (F = 5.51, *df* = 4, p = 0.0132). On the 17th day after transplanting, the relative control effect of treatment 12 decreased to 62.34%, which was not significantly different from that of treatment 5, treatment 11, and CK + (F = 2.86, *df* = 4, p = 0.0811). On the 22nd day after transplanting, the corn was at the 8-9-leaf stage (V8–V9) and grew vigorously. The plant damage rate in the field increased significantly compared with the last time point. The plant damage rate in the CK− group reached 57.80%, and the relative control effects of all treatments were less than 40% (Figure 1, Table 4).

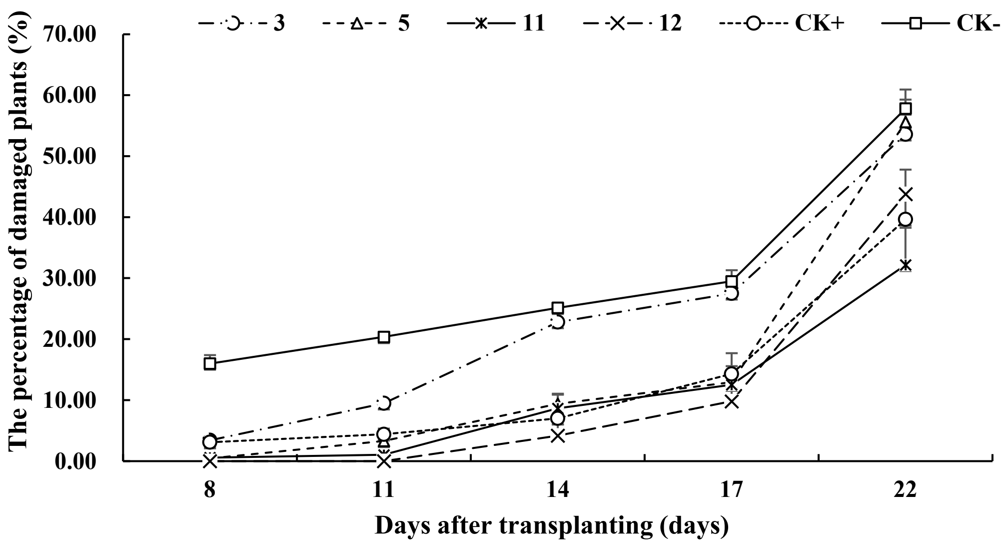

Figure 1. Plant damage caused by *S. frugiperda* in the field after transplanting with different treatments at different times. Note: 3—5 × Chlorantraniliprole + MF; 5—25 × Chlorantraniliprole + HTY-A8; 11—25 × Spinetoram + HTY-A8; 12—25 × Spinetoram + MF.

Table 5. Relative control effect on *S. frugiperda* with different pesticide treatments after transplanting.

Treatment	Relative Control Effect %				
	8th Day	11th Day	14th Day	17th Day	22nd day
3	60.32 ± 28.20 b	49.10 ± 13.63 c	8.81 ± 18.33 b	4.83 ± 8.11 b	3.17 ± 12.10 a
5	92.01 ± 7.99 ab	79.25 ± 14.20 abc	62.47 ± 8.49 a	53.01 ± 15.68 a	7.71 ± 13.05 a
11	90.08 ± 9.91 ab	94.24 ± 3.44 ab	65.66 ± 11.08a	55.27 ± 15.42 a	37.42 ± 27.70 a
12	100.00 ± 0.00 a	100.00 ± 0.00 a	83.31 ± 9.14 a	62.34 ± 15.83 a	16.67 ± 22.11 a
CK+	74.05 ± 11.00 ab	75.72 ± 9.46 bc	71.81 ± 11.50 a	47.25 ± 19.82 ab	28.08 ± 14.23 a

Note: Data in the table are mean ± SE. Different letters in the same column indicate significant differences at $p < 0.05$ using Tukey's HSD test.

3.5. Average Pest Damage Level

The oldest larvae in the field were at the fifth–sixth instar on the 22nd day after transplanting, while the newest larvae were still at the first–second instar. The progress of larval development in the field was uneven. The plant damage level with treatment 11 (25 × Spinetoram + HTY-A8) was the lowest on the 22nd day after transplanting and was significantly lower than that in the treatment 3 (5 × Chlorantraniliprole + MF) and CK− (water) groups (F = 3.66, *df* = 5, *p* = 0.0304) (Figure 2).

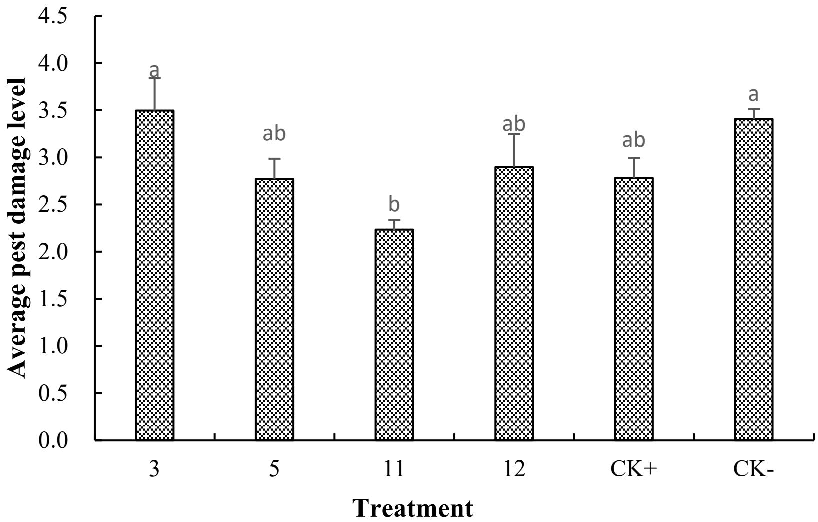

Figure 2. Degree of plant damage by *S. frugiperda* with different treatments on the 22nd day after transplanting. Note: 3—5 × Chlorantraniliprole + MF; 5—25 × Chlorantraniliprole + HTY-A8; 11—25 × Spinetoram + HTY-A8; 12—25 × Spinetoram + MF. Note: Different letters on the column indicate significant difference at $p < 0.05$ level by Tukey's HSD test.

3.6. Economic Estimates

Taking Chlorantraniliprole as an example, the amount of active ingredient and labor cost of the different application methods were calculated (Table 6). The results showed that the method of pesticide application before transplanting reduced the amount of chemical control used in the field and decreased the amount of effective ingredient by 4/5 and 3/4 when compared to field spraying and seed coating, respectively. In addition, the labor cost associated with the application of pesticides before transplanting was only 1/4 and 1/6 that of field spraying and seed coating, respectively.

Table 6. Pesticide dosage and labor cost for different methods of application.

Method of Application	Number of Field Sprays	Single Dose	Active Ingredient Required for Single Control/Hectare	Labor Cost of Application (RMB)
35% Chlorantraniliprole field spray	1	150 g/hectare	52.5 g	300
50% Chlorantraniliprole FSC seed coating	0	6.8 g/kg seed	38.25 g	50
35% Chlorantraniliprole application before transplanting (25 times that of field spray concentration)	0	3750 g/ hectare	9.84 g	70

Note: One hectare of sweet corn seedlings requires 11.25 kg seeds, and the seedling area required for planting 1 hectare in the field is 75 m^2. The active ingredient required for a single control was calculated as follows: 52.5 = 150 × 0.35; 38.25 = 6.8 × 11.25 × 0.5; 9.84 = 3750 × 75/10,000 × 0.35. The labor cost of application was calculated as follows: labor cost is CNY 20 per hour, 300 = 20 × 15; 50 = 20 × 2.5; 70 = 20 × 3.5.

4. Discussion

This study showed that the efficacy and persistence of the application of 35% Chlorantraniliprole WDG before transplanting was the best for controlling *S. frugiperda*. The effective control time of treatment 5 (25 × Chlorantraniliprole + HTY-A8) in newly hatched larvae and third instar larvae could extend over 20 days, better than that observed with CK+. The effective control time of 6% Spinetoram SC was shorter than that of 35% Chlorantraniliprole WDG at about 10 days after application, decreasing rapidly at 20 days. The persistence of 3% Emamectin Benzoate WDG was the worst, with its effectiveness in the third instar larvae decreasing significantly on the 10th day after application. The special flight additives MF and Polyorganosilicon HTY-A8 showed different synergistic effects on the agents.

Many studies have shown that Emamectin Benzoate, Spinetoram, and Chlorantraniliprole exhibit strong insecticidal activity against Lepidoptera insects, such as *S. frugiperda* [33–36]. In this study, the bioassay results for these three insecticides showed that the experimental insect population (*S. frugiperda*) was extremely sensitive, and the LC_{50} was lower than that of field populations reported by Lu et al. [37], Chen et al. [38], and Wang et al. [31]. This might be related to the long-term artificial diet that was fed to the test insects indoors. On the other hand, the commercial insecticides used in this experiment were different than the original compounds, as their activity was increased by the addition of a surfactant and emulsifier [39]. The results of the laboratory bioassay showed that the persistence period of 35% Chlorantraniliprole WDG and 6% Spinetoram SC was about 20 days, while the persistence period of 3% Emamectin Benzoate WDG was only 10 days in newly hatched larvae and even shorter in third instar larvae.

The internal absorption, conductivity, and chemical stability of different pesticides can affect their absorption by corn leaves and the degradation rate in leaves [40]. The determination of the active ingredient contents in corn leaves on the second day after the application of pesticides showed that the absorption capacity of Chlorantraniliprole was greater than that of Spinetoram and Emamectin Benzoate. That might be related to the strong internal absorption of Chlorantraniliprole itself [41,42]. The results from the 10th and 20th day showed that Chlorantraniliprole exhibited the slowest degradation rate, followed by Spinetoram and Emamectin Benzoate. The contents of the active ingredients of the three pesticides at 25 times concentration were significantly higher than those at 5 times concentration, indicating that the concentration increase may increase the absorption of the active ingredient by corn leaves, thus indirectly increasing the residues and prolonging the presence of the insecticides. Our results were consistent with the experimental results of Chen et al. [29], who studied rice. Our field experiment also verified our findings; however, attention should be paid to crop safety when utilizing high-concentration application.

Pesticide additives play an important role in improving pest control efficacy and performance, stabilizing the quality of preparations, and reducing the harm caused by active components [43]. The addition of Polyorganosilicon Silwet 408 was found to significantly improve the leaf protection and insecticidal effect of Chlorantraniliprole on *Cnaphalocrocis medinalis* [44]. It also significantly increased the retention of Chlorantraniliprole in corn leaves and increased its control effect on *S. frugiperda* [45]. The control effect of Tetrachloroacetamide on *Pieris rapae* was also improved by adding Polyorganosilicon Silwet 408 and Greebwet 7618 [46]. In this study, Polyorganosilicon HTY-A8 and special flight additives (MF) both significantly promoted the absorption of 35% Chlorantraniliprole WDG, but did not promote the absorption of 6% Spinetoram SC and 3% Emamectin Benzoate WDG. On the 10th day after the application of pesticides, the two additives slowed the degradation rate of the active ingredient.

The field study results showed that the control effect of spraying 35% Chlorantraniliprole at five times the conventional dosage was considerably decreased on the 14th day after transplanting. Conversely, the control effect on *S. frugiperda* achieved by spraying 35% Chlorantraniliprole WDG or 6% Spinetoram SC at 25 times the conventional dosage was still over 50% on the 17th day after transplanting, better than 50% Chlorantraniliprole FSC coating treatment. This indicates that spraying 35% Chlorantraniliprole WDG and 6% Spinetoram SC at 25 times the conventional concentration before transplanting fresh corn could effectively control *S. frugiperda* in the early plant stage. With the growth of the corn, we suggest using additional insecticides to control the damage caused by *S. frugiperda* in the later stage.

5. Conclusions

The use of pesticides before transplanting represents a simple and efficient method for the control of *S. frugiperda* at the seedling stage that can be improved by increasing the concentration of pesticides and introducing additives to increase the absorption of the pesticides, which will delay the degradation of the effective components in leaves and prolong the effective control time. In addition, pesticide use and labor cost were greatly reduced with the application of pesticides before transplanting. This study puts forward a new method to effectively control *S. frugiperda* at the seedling stage in fresh corn.

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