Entomology and Applied Science Letters
Volume 10, Issue 3, Page No: 18-28
Copyright CC BY 4.0
Available Online at: www.easletters.com

ISSN No: 2349-2864

Beta-cyfluthrin Resistance of Cigarette Beetle *Lasioderma serricorne* (F.) (Coleoptera: Anobiidae) and its Control Using Imidacloprid Space Sprays

Zan Su[1], Qian Sun[2], Xinsheng Cheng[2*], Yichao Hu[1]

[1]China Tobacco Guangxi Industrial Co., Ltd, Nanning, China.
[2]Department of Applied Chemistry, University of Science and Technology of China, Hefei, China.

ABSTRACT

Lasioderma serricorne (F.) (Coleoptera: Anobiidae), is generally considered to be one of the most destructive insects in cigarette manufacturing. Beta-cyfluthrin, as a synthetic pyrethroid, has always been an effective insecticide to manage *L. serricorne* in cigarette manufacturing factories and food storage or processing factories. In this study, bioassays were conducted to assess the sensitivity of *L. serricorne* (LS_H) collected from Hefei Cigarette Manufacturing Factory, to beta-cyfluthrin and its alternative to imidacloprid. Results revealed that the LS_H strain had developed high resistance to beta-cyfluthrin, but was highly susceptible to imidacloprid. LS_H strain exhibited no cross-resistance to imidacloprid with a cross-resistance ratio only as 1.00 - 1.33 folds. In addition, results of field trials showed that space sprays with beta-cyfluthrin aerosol had failed to kill insects in the cigarette manufacturing area. Imidacloprid, as a substitute for beta-cyfluthrin, showed a high pest control effect with a decreased rate of detected *L. serricorne* up to 100%. Our work is significant in recognizing insect resistance at an early age, developing corresponding tactics to control insects effectively, and providing more potential insecticide options for managing other Coleoptera insects resistant to pyrethroid. Results also implied that space spray with imidacloprid aerosol in a confined space had significant potential to control stored-product pests.

Keywords: Beta-cyfluthrin, Imidacloprid, Aerosol, Resistance.

HOW TO CITE THIS ARTICLE: Su Z, Sun Q, Cheng X, Hu Y. Beta-cyfluthrin Resistance of Cigarette Beetle *Lasioderma serricorne* (F.) (Coleoptera: Anobiidae) and its Control Using Imidacloprid Space Sprays. Entomol Appl Sci Lett. 2023;10(3):18-28. https://doi.org/10.51847/PvKX7T8pen

Corresponding author: Xinsheng Cheng
E-mail ✉ xscheng@ustc.edu.cn
Received: 30/03/2023
Accepted: 07/09/2023

INTRODUCTION

The cigarette beetles, *Lasioderma serricorne* (F.) (Coleoptera: Anobiidae), belong to a group of insects that infest stored products, and feed and live in many kinds of dried substances, such as cloth, paper, furniture, grain, coffee, and tobacco [1]. As the cosmopolitan and polyphagous pests, *L. serricorne* is generally considered to be one of the most destructive insects in tobacco processing and cigarette manufacturing, due to the capacity to develop in tobacco which is toxic for most other species [2-6]. In addition to weight losses of tobacco leaves caused by larvae feeding during tobacco processing and storage, if beetles get into final cigarette products, it can lead to customer complaints and even cause a cigarette brand to disappear from the market, resulting in huge economic losses [3, 7].

Like pest control in food processing and stored factories, management of *L. serricorne* in cigarette manufacturing areas has always depended heavily on sanitation, including promptly removing waste material and eliminating infected tobacco shreds [8]. However, merely cleaning in cigarette manufacturing area is not enough to control the pest completely, and the application of space aerosol insecticide is often used as a supplementary method [8, 9]. Application of residual and contact insecticide aerosols can effectively prevent pest infestation in food-processing facilities with several advantages, including low cost, short treatment time, and can be integrated with other management tactics such as sanitation [10, 11]. The application of insecticides as aerosols for

© 2023 Entomology and Applied Science Letters
This is an open access journal, and articles are distributed under the terms of the Creative Commons Attribution-Non Commercial-ShareAlike 4.0 License, which allows others to remix, tweak, and build upon the work non-commercially, as long as appropriate credit is given and the new creations are licensed under the identical terms.

managing stored-product pests is a well-established technique and was initially used for controlling *L. serricorne* in tobacco warehouses in the 1950s with dichlorvos (DDVP) aerosol [12]. It was reported that DDVP aerosol could effectively control stored-product pests, including black carpet beetles *Attagenus megatoma* (Fab.) (Coleoptera: Dermestidae), confused flour beetles *Tribolium confusum* (Jacquelin du Val) (Coleoptera: Pseudodontidae), *Lasioderma serricorne*, red flour beetles *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) and almond moths *Cadra cautella* (Walker) (Lepidoptera: Pyralidae) in laboratory and field [10, 12-15]. However, DDVP aerosol has been discontinued because of the development of pest resistance and its high toxicity to mammals and the environment. At present, widely used pesticides for such applications mainly include pyrethroids and insect growth regulators. There have been quite a few reports on successful control of various insects, for example, prallethrin aerosol for *Cadra cautella*, Indian meal moths *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae), saw-toothed grain beetles *Oryzaephilus surinamensis* (L.) (Coleoptera: Silvanidae), *Trogoderma variabile* Ballion (Coleoptera: Dermestidae) and *Tribolium castaneum* under laboratory conditions [16], cyfluthrin aerosol for *Tribolium castaneum* under laboratory conditions [17], esfenvalerate aerosol for *Plodia interpunctella* under laboratory conditions [18], and pyrethrin aerosol for *Tribolium castaneum* and *Tribolium confusum* in laboratory and in a commercial food-storage factory [11, 19-22].

It's well known that beta-cyfluthrin is a synthetic pyrethroid with low environmental persistence, low toxicity to non-target organisms, and no bioaccumulation. In addition, this pesticide is also a broad-spectrum neurotoxin with a demonstrable effect in killing *L. serricorne* [20, 23]. In fact, a chemical insecticide that can be used in cigarette manufacturing factories is limited, and the insecticide resistance of *L. serricorne* is of great concern. Beta-cyfluthrin aerosol, as an assistant to sanitation, has been used for years to control *L. serricorne* in Hefei Cigarette Manufacturing Factory (Hefei City, Anhui province, China). Therefore, it is imperative to determine the sensitivity level of *L. serricorne* to beta-cyfluthrin for maintaining control efficiency and resistance management.

Herein, we assessed beta-cyfluthrin susceptibility level in the population of *L. serricorne* collected from Hefei Cigarette Manufacturing Factory. After multiple rounds of bioassays with different insecticides (not shown in this paper except imidacloprid), we finally selected imidacloprid as an alternative insecticide. Subsequent field trials were carried out in the cigarette manufacturing area of Hefei Cigarette Manufacturing Factory to evaluate the control effect of space spray with imidacloprid aerosol in practice. Our study is conducive to timely recognizing the development of insecticide resistance of *L. serricorne* in cigarette manufacturing factories and provides key suggestions for pest resistance management.

MATERIALS AND METHODS

Insecticide, pheromone trap, atomizer, and spray tower

Insecticides used in this study were commercial formulations, as follows: beta-cyfluthrin (12.5% [a.i.]), suspension concentrate (SC), provided by Jiangsu Yangnong Chemical Co. LTD. (Jiangsu, China), imidacloprid (100g [a.i] L^{-1}, SC), provided by Zhejiang Haizheng Chemical co. LTD. (Zhejiang, China).

Pheromone traps were used to monitor the number of insects captured in the cigarette manufacturing area of Hefei Cigarette Manufacturing Factory, provided by Japan Fuji Flavor Co. LTD. (Japan). A lure permitting the controlled release of sex pheromones is mounted on the sticky board that catches beetles for counting.

Electric atomizer (Nanjing Minghai Health Technology Development Co. LTD., Nanjing, China) was used in field trials for delivering spray particles of 50 ± 10 μm in size, with spray efficiency of 500 mL/min, Hand-held ultra-low volume atomizer gun (Aima Instrument Factory, Guangdong, China) with calibration was used to produce mist in spray toxicity bioassay.

The cylindrical glass spray tower was made by Beijing Wuyi Glass Instrument Factory (Beijing, China) with spray settings at a volume of 10 L and, a height of 40 cm. The inner diameter of the tower bottom is 20 cm, and 3 cm for the tower mouth. The Spray tower has no upper and lower bases, but has a glass tower cap.

Insect strains and rearing conditions

Tobacco leaf fragments and tobacco shorts were carefully collected from processing machinery in the cigarette manufacturing area of Hefei Cigarette Manufacturing Factory and brought back to the laboratory. With the aid of a stereoscopic microscope, larvae of *L. serricorne* were searched and collected from fragments and tobacco shorts and reared into adults (LS_H). LS_H strain was cultured for more than three generations in the laboratory before bioassays. Reference susceptible strain (LS_{LAB}) was obtained from our laboratory with no pesticide exposure for several years. Both strains were maintained in dark incubators with a temperature of 28 ℃ and relative humidity of 65-75%. Wheat raw material, previously frozen for more than 7 days under -18 degrees, was crushed into small particles. *L. serricorne* was reared on wheat particles mixed with active yeast (10:1, w/w). Unsexed adults of 1-3 days were used for the following bioassays.

Spray toxicity bioassay

In this study, spray toxicity bioassays were conducted to study the toxicity of beta-cyfluthrin and imidacloprid against *L. serricorne* in the laboratory as suggested by relative literature [24, 25]. Preliminary trials were carried out to determine appropriate ranges of testing concentration, with 156.25 mg mL^{-1}, 83.64 mg mL^{-1}, 41.82 mg mL^{-1}, 13.94 mg mL^{-1}, 6.35 mg mL^{-1}, 3.17 mg mL^{-1} for LS_H strain, and 57.11 mg mL^{-1}, 19.04 mg mL^{-1}, 6.35 mg mL^{-1}, 3.17 mg mL^{-1}, 0.63 mg mL^{-1}, 0.13 mg mL^{-1}, 0.03 mg mL^{-1} for LS_{LAB} strain, and distilled water as the control in beta-cyfluthrin spray toxicity bioassay. In imidacloprid spray toxicity bioassay, testing concentrations of LS_H strain and LS_{LAB} strain were 1.75 mg mL^{-1}, 0.35 mg mL^{-1}, 3.50×10^{-2} mg mL^{-1}, 3.50×10^{-3} mg mL^{-1}, 3.50×10^{-4} mg mL^{-1} and 3.50×10^{-5} mg mL^{-1}, and distilled water as the control. In the laboratory, at 27 °C, the spray tower was placed on a flat marble tabletop to ensure that the bottom of the spray tower fitted perfectly with the tabletop to prevent insects from escaping. After slowly introducing 20 adults to the tower bottom from the tower mouth, 0.5 mL liquid was sprayed into the spray chamber at the tower mouth with a hand-held ultra-low volume atomizer gun, at a distance of 35 cm. The tower mouth was covered with a glass cap immediately (not sealed). Dead individuals were documented 2 and 24 hours after treatment under dark conditions. An adult was considered dead if its appendages did not move when prodded with a hairbrush [26]. Three replicates were conducted for each dose.

Field trials

Field trials were carried out in the cigarette manufacturing area (shred-making section, storage section, blending section, cigarette-making section, and ripper section) of Hefei Cigarette Manufacturing Factory in Hefei, Anhui, China. Before the test, five sections worked normally and were cleaned normally following written sanitation procedures. Pheromone traps were used to monitor the number of insects captured [8, 11, 27-31]. The number and hanging height of the pheromone trap in each section were based on CORESTA [8]. Traps were placed on steel nails of the wall or column and marked for position. The numbers of *L. serricorne* caught by traps were recorded once a week, and traps were replaced every 30 days.

The details of the cigarette manufacturing area in the Hefei Cigarette Manufacturing Factory and the locations of traps in each section can be seen in **Figure 1**. Shred shredding section has a construction area of 1600 m^2 (20 m × 80 m), a height of 10 m, and thus, a volume of 16000 m^3. A total of 9 pheromone traps were placed evenly in this section, with 8 traps placed on 80-meter-long walls, at 1.5 m above the ground, and one trap placed on the center column at 5 m above the ground. The storage section has a construction area of 600 m^2 (20 m × 30 m), a height of 5 m, thus, a volume of 3000 m^3. A total of 3 pheromone traps were placed evenly on three non-entrance walls, at 1.5m above the ground. The blending section has a construction area of 600 m^2 (20 m × 30 m), a height of 5m, thus, a volume of 3000 m^3. A total of 3 pheromone traps were placed evenly on three non-entrance walls, at 1.5m above the ground. The cigarette-making section has a construction area of 1200 m^2 (20 m × 60 m), a height of 5 m, thus, a volume of 6000 m^3. A total of 6 pheromone traps were placed evenly on 60-meter-long walls, at 1.5 m above the ground. The ripper section has a construction area of 200 m^2 (20 m × 10 m), and a height of 5m, thus, a volume of 1000 m^3. Only one pheromone trap was placed on the center column, at 1.5 m above the ground. Temperature was at 26 ± 2℃ and relative

humidity was 60 ± 5% in all, but the ripper section.

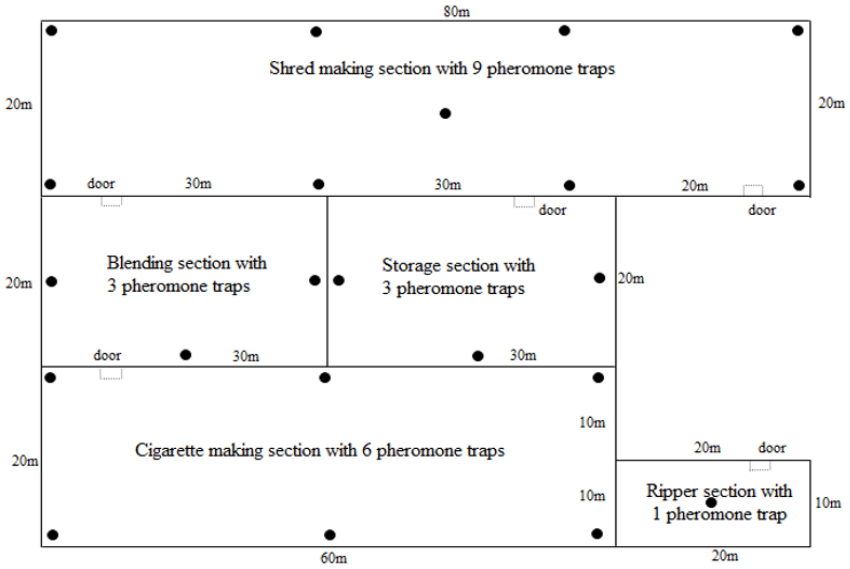


Figure 1. Plant of cigarette manufacturing area in Hefei Cigarette Manufacturing Factory, and locations of traps in each section, (•) showing pheromone trap position.
Note: shred-making section: the place for cutting tobacco leaves into tobacco shreds; blending section: the place for blending tobacco shreds with different grades; storage section: the place for storing tobacco shreds; cigarette-making section: the place for making cigarette products; ripper section: the place for dealing with an unqualified cigarette. Five sections together make up the cigarette manufacturing area of Hefei Cigarette Manufacturing Factory.

In field trials, the application concentration and dose of beta-cyfluthrin and imidacloprid were determined according to the guidelines for the use of commercial pesticides and pre-experiment. Beta-cyfluthrin aerosols were sprayed in the space of five sections with a dose of 10 L/3000 m^3(1 L of beta-cyfluthrin commercial formulation in 9 L water). Seven weeks later, imidacloprid aerosols were sprayed in the space of five sections with a dose of 10 L/3000 m^3 (0.5 L of imidacloprid commercial formulation in 9.5 L water). Both applications were conducted during the factory break time, and with doors and windows closed. The next morning, windows (equipped with insect-proof gauze net) were opened for ventilation, and sanitation, following standardized sanitation protocols. The people spraying and counting are skilled workers in the factory.

Data analyses

Probit analysis (IBM SPSS® Statistics 25, IBM Corp., NY, USA) was used for analyzing the bioassay data to estimate the concentration of killing 50% (LC_{50}) of *L. sericorne*. The chi-square test was applied to ensure the goodness-of-fit of the model.

In field trials, monitoring data of *L. sericorne* in five sections were analyzed by graphing software (Origin 2018, OriginLab Corp., Northampton, Massachusetts, USA).

$$Decrease\ rate\ of\ detected\ L.sericorne\ in\ week\ n = \frac{Nw0-Nwn}{Nw0} \times 100\%, \quad (1)$$

$Nw0$ is the number of detected *L. sericorne* in the week before application, *Nwn* is the number of detected *L. sericorne* in week n after application.

RESULTS AND DISCUSSION

Spray toxicity bioassay

Results of spray toxicity bioassay are shown in **Table 1**. At 2 h after beta-cyfluthrin application, the LC_{50} value of the LS_H strain was 71.98 mg mL^{-1}, which was 7.48 folds that of the LS_{LAB} strain. At 24 h, the LC_{50} value of the LS_H strain was 19.78 mg mL^{-1}, which was 15.10 folds that of the LS_{LAB} strain. In addition, LC_{50} values of LS_H strain were 1.33-fold and 1.00-fold that of LS_{LAB} strain at 2 h and 24 h after imidacloprid application, respectively.

Table 1. Toxicity of insecticides to LS_{LAB} strain and LS_H strain of *L. serricorne* at 2 h and 24 h in bioassays (in the laboratory, at 27 ℃)

Exposure time	Insecticide	Strains[a]	LC_{50} (95%FL[b])/ (mg mL^{-1})	Slope ± SE	χ^2	Df[c]	P[d]	N[e]	RR[f]
2 h	Beta-cyfluthrin	LS_{LAB}	9.62 (6.63-12.98)	-6.64 ± 1.07	12.17	18	0.84	800	-
		LS_H	71.98 (34.81-122.24)	-5.73 ± 1.17	14.24	13	0.36	1400	7.48
	Imidacloprid	LS_{LAB}	0.15 (0.04-0.40)	-1.13 ± 0.31	12.68	14	0.55	700	-
		LS_H	0.20 (0.08-0.44)	-1.30 ± 0.27	8.17	14	0.88	600	1.33
24 h	Beta-cyfluthrin	LS_{LAB}	1.31 (0.57-2.23)	-3.88 ± 0.72	12.68	18	0.81	800	-
		LS_H	19.78 (0.41-76.26)	-4.63 ± 1.02	32.17	13	0.002	1400	15.10
	Imidacloprid	LS_{LAB}	0.03 (0.01-0.06)	-0.95 ± 0.26	6.06	14	0.97	700	-
		LS_H	0.03 (0.01-0.07)	-0.93 ± 0.27	8.67	14	0.85	600	1

[a]LS_{LAB}, reference susceptible strain; LS_H, *L. serricorne* collected from Hefei Cigarette Manufacturing Factory.
[b]Fiducial Limit.
[c]Degree of freedom.
[d]P ≥ 0.05 indicates a significant fit between the observed data and the expected linear regression model in Probit analysis.
[e]Number of insects used totally
[f]Resistance Ratio: LC_{50} of LS_H strain/LC_{50} of LS_{LAB} strain.

Field trials

Quantitative change of detected L. serricorne in the shred-making section

As shown in A1 of **Figure 2**, the number of monitored *L. serricorne* increased in the first five weeks after beta-cyfluthrin application from 17 in week 0 to 116 in week 5 and then decreased in week 6 and week 7. Compared to the beetle count in week 0, the numbers increased by 0%, 41.18%, 82.35%, -282.35%, -582.35%, -341.18%, and -300.0% for weeks 1-7 after application, respectively. As shown in A2 of **Figure 2**, the number of monitored *L. serricorne* decreased rapidly after application from 68 in week 0 to 7 in week 1, a decrease rate of 89.71%. In the following weeks, the decrease rate was 95.58%, 94.12%, 95.58%, 91.18%, 83.82%, and 69.12%, respectively.

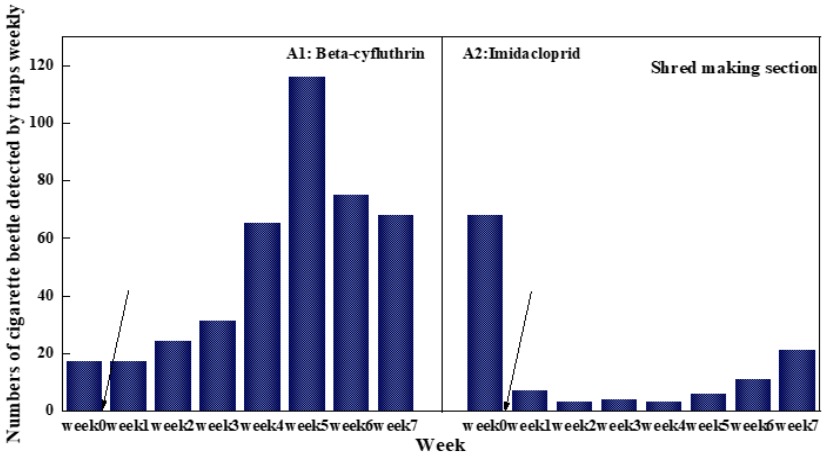


Figure 2. Quantitative change of detected *L. serricorne* weekly before and after application of insecticide in shred making section, the week before application was recorded as week 0 and an arrow indicated the application time (the last day of the week). A1) application with beta-cyfluthrin; A2) application with imidacloprid.

Quantitative change of detected L. serricorne in the storage section

Results of B1 **(Figure 3)** showed that the decrease rate of detected *L. serricorne* in Week 1-7 was -15.91%, -11.36%, 11.36%, 68.18%, -50.0%, -20.45%, and -9.1%, respectively. It could be seen from B2 **(Figure 3)** that the number of monitored *L. serricorne* decreased obviously after imidacloprid application. The decrease rate of detected *L. serricorne* in weeks 1-7 were 95.83%, 95.83%, 95.83%, 100.0%, 97.92%, 100.0%, and 97.92%, respectively. The storage section has a construction area of 600 m^2 and a volume of 3000 m^3. After imidacloprid treatment, only at most two *L. serricorne* were detected every week. This section is for storing shreds, as a Hazard Analysis

Critical Control Point, with the greatest risk of *L. serricorne* invading cigarette products. Therefore, the fewer *L. serricorne* in this plant, the less risk of *L. serricorne* infecting products. In addition, none of the complicated machines and fewer shelters for *L. serricorne* in this plant were also the factors for the high control effect.

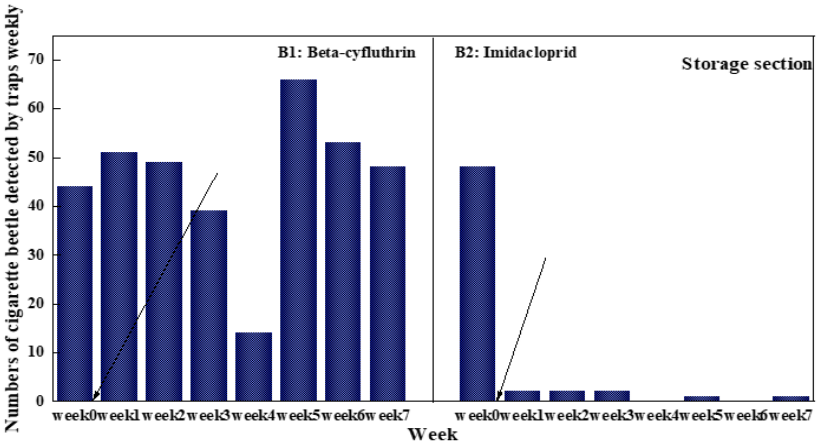


Figure 3. Quantitative change of detected *L. serricorne* weekly before and after application of insecticide in the storage section, the week before application was recorded as week 0 and an arrow indicated the application time (the last day of the week). B1) application with beta-cyfluthrin; B2) application with imidacloprid.

Quantitative change of detected L. serricorne in the blending section

After the application of beta-cyfluthrin, except in week 4 with decrease rate of detected *L. serricorne* of 89.47%, decrease rate in other weeks was maintained at 26.32%-47.37% **(Figure 4)**. As shown in C2 **(Figure 4)**, within 7 weeks after imidacloprid application, decrease rate of detected *L. serricorne* was maintained at 70.0%-100.0%. Only at most three *L. serricorne* were captured per week.

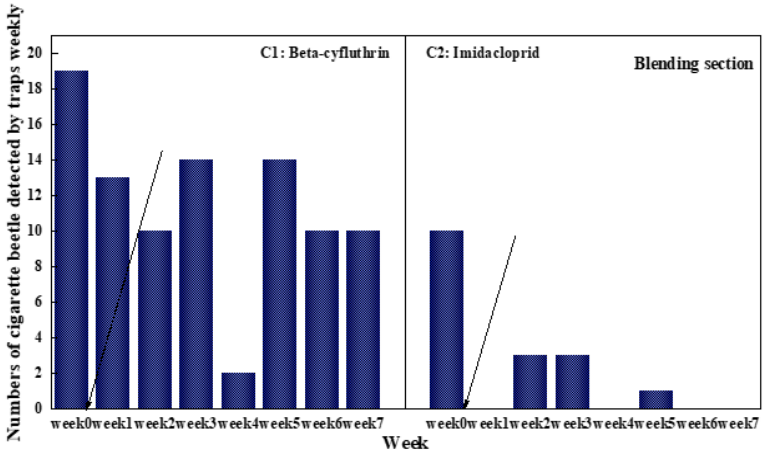


Figure 4. Quantitative change of detected *L. serricorne* weekly before and after application of insecticide in the blending section, the week before application was recorded as week 0 and an arrow indicated the application time (the last day of the week). C1) application with beta-cyfluthrin; C2) application with imidacloprid.

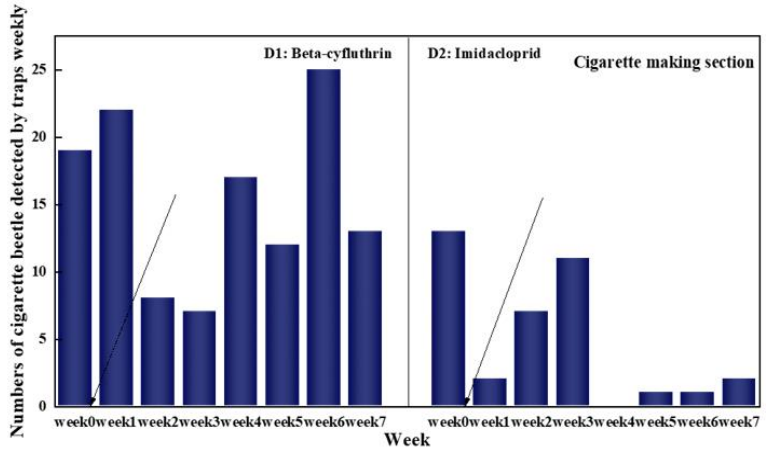
Quantitative change of detected L. serricorne in the cigarette-making section

This section has a complex structure, large space, and a high degree of machine integration, which is the last risk point for *L. serricorne* to invade cigarette products. The tobacco industry has strict requirements for pest control and sanitation. D1 in **Figure 5a** showed a weekly quantitative change of detected *L. serricorne* before and after the application of beta-cyfluthrin. As a whole, number of captured *L. serricorne* did not change obviously, and decrease rate of detected *L. serricorne* in week 1-7 was -15.79%, 57.89%, 63.16%, 10.53%, 36.84%, -31.58%,

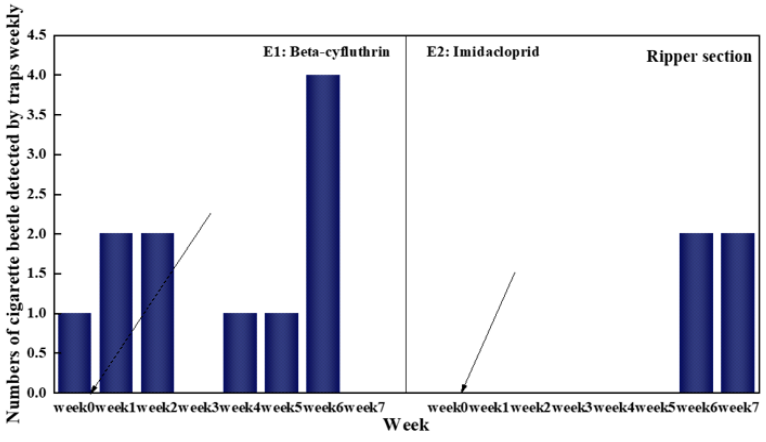
31.58%, respectively. It could be seen from D2 **(Figure 5a)** that, the decrease rate of detected *L. serricorne* in week 1 was 84.62%, but only 46.15% and 15.38% in week 2 and week 3. We realized that the treatment effect differed significantly with other sections and adults were only found in a pheromone trap, and thus carried out an inspection immediately. After careful examination, it was found that most beetles were in obsolete equipment covered with plastic film that pesticide could not reach. Only those beetles that came out from the not-well sealing of the plastic cover were attracted and landed in the trap. Therefore, the obsolete equipment was removed and imidacloprid was applied again. Decreased rate of detected *L. serricorne* in weeks 4-7 was maintained at 84.62-100.0%, which reached the threshold index of pest control in this section (≤ one *L. serricorne*/week/trap).

Quantitative change of detected L. serricorne in ripper section

In the cigarette manufacturing area, this section is relatively independent, and isolated from other plants in architecture and space. E1 **(Figure 5b)** showed that the number of *L. serricorne* in this section was few, but did not decrease obviously after application. E2 **(Figure 5b)** showed that after the application of imidacloprid, none of *L. serricorne* was detected in week 1-5, and only two were detected in week 6 and week 7.



a)



b)

Figure 5. Quantitative change of detected *L. serricorne* weekly before and after application of insecticide in cigarette making section (a) and ripper section (b), the week before application was recorded as week 0 and an arrow indicated the application time (the last day of the week). D1) application with beta-cyfluthrin; D2) application with imidacloprid.

Decrease rate of detected L. serricorne in cigarette manufacturing area after application with different insecticides

The decreased rate of detected *L. serricorne* weekly in cigarette manufacturing areas after application with different insecticides is shown in **Table 2**. After space spraying with beta-cyhalothrin aerosol, the decreasing rate of detected *L. serricorne* in the cigarette manufacturing area was maintained at -109%

and 9%, with an average decreasing rate of -29%. After application of imidacloprid, the decreasing rate was maintained at 81.29-97.84%, with an average rate of 89.93%.

Table 2. Decrease rate of detected *L. serricorne* weekly in cigarette manufacturing area (five sections overall) after application

Insecticide	Week after insecticide application							Average
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	
Beta-cyfluthrin	-5.00%	7.00%	9.00%	1.00%	-109.00%	-67.00%	-39.00%	-29%
Imidacloprid	92.09%	89.21%	85.61%	97.84%	93.53%	89.93%	81.29%	89.93%

Pyrethroids are the widely used insecticides to control *L. serricorne* in cigarette manufacturing in China, but given that pyrethroids have been used for a long time, it is imperative to investigate the control effect in the laboratory and field. Our study indicated that the LS_H strain had developed high resistance (up to 15.10-fold) to beta-cyfluthrin after years of exposure, and this insecticide failed to control pests in the laboratory and field. In this case, pyrethroids were incapable of being used for suppressing *L. serricorne* for a while. Our study also showed that the LS_H strain had high sensitivity to the neonicotinoid insecticide, imidacloprid. As we know, cross-resistance of insects to insecticides must be taken into account when selecting alternation of insecticides in insecticide resistance management programs. Metabolic mechanisms of insect resistance to pyrethroid and neonicotinoids have been extensively studied. Widespread resistance to neonicotinoid insecticides was associated with the elevation of cytochrome P450 activity and overexpression of cytochrome P450 genes [32]. Research also suggested that enhanced cytochrome P450 activity contributed to the development of pyrethroid resistance and that might be the main factor of pyrethroid resistance. In addition, the decrease in sodium channel sensitivity was also an important pyrethroid resistance mechanism that could not be ignored [33-37]. In this study, although these two insecticides have similar metabolic mechanisms of resistance, our results indicated that the LS_H strain exhibited no cross-resistance to imidacloprid with a cross-resistance ratio of only 1.00 - 1.33 folds **(Table 1)**, which was an important factor that imidacloprid was able to effectively suppress *L. serricorne* in the field. Several studies have shown that there was no cross-resistance between insecticides that had similar metabolic mechanisms of resistance. Chen *et al*. (2020) suggested that the overexpression of three cytochrome P450 genes and enhanced cytochrome P450 activity contributed to metabolic resistance to neonicotinoid dinotefuran in *Aphis gossypii* Glover (Lepidoptera: Noctuidae) [38], and leaf-dipping bioassay results revealed that *Aphis gossypii* with 74.67 folds resistance to dinotefuran showed only 1.1 folds resistance to imidacloprid (no cross-resistance), but 15.3 folds resistance to neonicotinoid thiamethoxam. Ling and Zhang (2011) indicated that *Nilaparvata lugens* (Hemiptera: Delphacidae) showed 7.42 folds resistance to nereistoxin bisultap, but only 1.02 folds resistance to imidacloprid (no cross-resistance) [39], and results of the biochemical analysis showed that cytochrome P450 played roles in metabolizing bisultap in *Nilaparvata lugens.* The above situations may be attributed to the fact that although the increased activity of cytochrome P450 was the main reason for the resistance of insects to insecticides, the ultimate result of insect resistance may be jointly determined by metabolic mechanism, target site sensitivity, and body surface penetration [35, 40]. Several pieces of literature have reported that imidacloprid, as a systemic neonicotinoid insecticide, could effectively control sap-sucking pests including thrip, aphids, and mosquitoes [41-43]. However, only a few pieces of literature reported the use of imidacloprid for controlling stored-product pests. Wakil and Schmitt (2015) conducted field trials on farms and implied that imidacloprid could be effectively used for the protection of wheat stored against four major grain pests [44]. Nayak and Daglish (2006) studied the control effect of imidacloprid against four species of psocids and indicated that imidacloprid had the potential as a grain protectant to control stored-product pests [45]. Athanassiou, Kavallieratos, Arthur, and Throme (2013) reported that simultaneous use of beta-cyfluthrin with imidacloprid was not more effective than beta-cyfluthrin alone to control stored-product pests, and the efficacy of both

formulations varies with target species [46]. Arthur and Fontenot (2013) studied the effectiveness of spray and dust formulations of dinotefuran (another nicotinoid insecticide) to kill pests, and indicated that dinotefuran could be incorporated into management plans for the control of stored product insects [47]. In these studies, imidacloprid or other nicotinoid insecticides were added to the grain as a protectant, or used for warehouse surface spraying to control stored-product pests. Different from above, in our work, we sprayed imidacloprid aerosols into a confined space to knock down and kill *L. serricorne*. In field trials, imidacloprid aerosol droplets produced by atomizer were thin and suspended in space for a certain period, which could effectively kill *L. serricorne* by using its knockdown effect and touch-killing effect.

CONCLUSION

Integrated Pest Management for food and tobacco industries mainly focuses on source control of raw materials, physical prevention, and sanitation. Meanwhile, space spray with insecticide aerosol can also be used as a supplementary means for pest control. Our work indicated that when *L. serricorne* develops resistance to pyrethroids, and the use of organophosphate and carbamate insecticides is limited due to toxicity or odor, application of space spray with imidacloprid aerosol in a confined space is a sensible and reliable choice for pest control. Our findings implied that, in addition to cigarette beetles, imidacloprid had significant potential to manage other Coleoptera insects resistant to pyrethroids in processing and stored facilities.

ACKNOWLEDGMENTS: We are grateful for the support of Hefei Cigarette Manufacturing Factory (Hefei, Anhui) for monitoring the amounts of L. serricorne in five plants and this work was supported by a grant from the Guangxi Province Tobacco Corporation (2021450000340033).

CONFLICT OF INTEREST: None

FINANCIAL SUPPORT: Guangxi Province Tobacco Corporation (2021450000340033).

ETHICS STATEMENT: None

REFERENCES

1. Howe RW. A laboratory study of the cigarette beetle, Lasioderma serricorne (F.)(Col., Anobiidae) with a critical review of the literature on its biology. Bull Entomol Res. 1957;48(1):9-56.
2. Sivik FP, Tenhet JN, Delamar CD. An ecological study of the cigarette beetle in tobacco storage warehouses. J Econ Entomol. 1957;50(3):310-6.
3. Edde PA. Biology, ecology, and control of Lasioderma serricorne (F.)(Coleoptera: Anobiidae): A review. J Econ Entomol. 2019;112(3):1011-31.
4. Yamamoto RT, Fraenkel G. The suitability of tobaccos for the growth of the cigarette beetle, Lasioderma serricorne. J Econ Entomol. 1960;53(3):381-4.
5. Papadopoulou SC, Buchelos CT. Definition of the flight period of Lasioderma serricorne (F.) in stored tobacco. J Pest Sci. 2002;75:81-3.
6. Hori M, Miwa M, Iizawa H. Host suitability of various stored food products for the cigarette beetle, Lasioderma serricorne (Coleoptera: Anobiidae). Appl Entomol Zool. 2011;46:463-9.
7. Kazutaka S, Kenji F. Effect of adult feeding on longevity and fecundity of the cigarette beetle, Lasioderma serricorne F.(Coleoptera: Anobiidae). Appl Entomol Zool. 2001;36(2):219-23.
8. Ryan L. Post-harvest Tobacco Infestation Control. Chapman & Hall, London, UK; 1995.
9. Childs DP, Phillips GL, Press Jr AF. Control of the cigarette beetle in tobacco warehouses with automatic dichlorvos aerosol treatments. J Econ Entomol. 1966;59(2):261-4.
10. Cogburn RR, Simonaitis RA. Dichlorvos for control of stored-product insects in port warehouses: low-volume aerosols and commodity residues. J Econ Entomol. 1975;68(3):361-5.
11. Arthur FH. Aerosol distribution and efficacy in a commercial food warehouse. Insect Sci. 2008;15(2):133-40.
12. Tenhet JN, Bare CO, Childs DP. Further studies on the control of the cigarette beetle with DDVP. Tobacco Sci. 1958;147:106-10.

13. Jay EG, Gillenwater HB, Harein PK. The toxicity of several dichlorvos (DDVP) and nailed formulations to the adult confused flour beetle. J Econ Entomol. 1964;57:415-6.
14. Harein PK, Gillenwater HB, Jay EG. Dichlorvos: methods of dispensing, estimates of concentration in air, and toxicity to stored-product insects. J Econ Entomol. 1970;63(4):1263-8.
15. Gillenwater HB, Harein PK, Loy Jr EW, Thompson JF, Laudani H, Eason G. Dichlorvos applied as a vapor in a warehouse containing packaged foods. J Stored Prod Res. 1971;7(1):45-56.
16. Arthur FH. Evaluation of prallethrin aerosol to control stored product insect pests. J Stored Prod Res. 1993;29(3):253-7.
17. Arthur FH. Evaluation of an aerosol formulation containing cyfluthrin against three species of stored-product insects. J Entomol Sci. 1988;23(3):257-63.
18. Arthur FH, Campbell JF, Fontenot EA, Toews MD. Assessing effects of esfenvalerate aerosol applications on resident populations of Tribolium castaneum (Herbst), the red flour beetle, through direct and indirect sampling. J Stored Prod Res. 2013;53:1-6.
19. Kharel K, Arthur FH, Zhu KY, Campbell JF, Subramanyam B. Influence of temperature and artificially-created physical barriers on the efficacy of synergized pyrethrin aerosol. J Stored Prod Res. 2015;60:36-42.
20. Arthur FH, Campbell JF, Donaldson JE. Laboratory evaluation of particle size, food contamination, and residual efficacy of pyrethrin+ methoprene aerosol. J Stored Prod Res. 2017;72:100-10.
21. Arthur FH, Scheff DS, Brabec D, Bindel J. Aerosol concentration, deposition, particle size, and exposure interval as mortality factors Tribolium confusum Jacquelin du Val (Coleoptera: Tenebrionidae). J Stored Prod Res. 2019;83:191-9.
22. Boina DR, Subramanyam B. Insect management with aerosols in food-processing facilities. InTech, Rijeka, CRO; 2012.
23. Paloukas YZ, Agrafioti P, Rumbos CI, Schaffert S, Sterz T, Bozoglou C, et al. Evaluation of Carifend® for the control of stored-product beetles. J Stored Prod Res. 2020;85:101534.
24. Silva DE, do Nascimento JM, da Silva RT, Juchem CF, Ruffatto K, da Silva GL, et al. Impact of vineyard agrochemicals against Panonychus ulmi (Acari: Tetranychidae) and its natural enemy, Neoseiulus californicus (Acari: Phytoseiidae) in Brazil. Crop Prot. 2019;123:5-11.
25. Zhu YC, Adamczyk J, Rinderer T, Yao J, Danka R, Luttrell R, et al. Spray toxicity and risk potential of 42 commonly used formulations of row crop pesticides to adult honey bees (Hymenoptera: Apidae). J Econ Entomol. 2015;108(6):2640-7.
26. Kim SI, Park C, Ohh MH, Cho HC, Ahn YJ. Contact and fumigant activities of aromatic plant extracts and essential oils against Lasioderma serricorne (Coleoptera: Anobiidae). J Stored Prod Res. 2003;39(1):11-9.
27. Campbell JF, Mullen MA, Dowdy AK. Monitoring stored-product pests in food processing plants with pheromone trapping, contour mapping, and mark-recapture. J Econ Entomol. 2002;95(5):1089-101.
28. Roesli R, Subramanyam B, Fairchild FJ, Behnke KC. Trap catches of stored-product insects before and after heat treatment in a pilot feed mill. J Stored Prod Res. 2003;39(5):521-40.
29. Buchelos CT, Levinson AR. Population dynamics of Ephestia elutella (Hübner) in tobacco stores with and without insecticidal treatments: a survey by pheromone and unbaited traps. Z Angew Entomol. 1985;100(1-5):68-78.
30. Levinson AR, Buchelos CT. Population dynamics of Lasioderma serricorne F.(Col., Anobiidae) in tobacco stores with and without insecticidal treatments: a three year-survey by pheromone and unbaited traps. J Appl Entomol. 1988;106(1-5):201-11.
31. Trematerra P. Combined control of Lasioderma serricorne (F.) and Ephestia elutella (Hbn.) in a tobacco processing facility by attracticide method. J Appl Entomol. 2020;144(7):598-604.
32. Karunker I, Morou E, Nikou D, Nauen R, Sertchook R, Stevenson BJ, et al. Structural

model and functional characterization of the Bemisia tabaci CYP6CM1vQ, a cytochrome P450 associated with high levels of imidacloprid resistance. Insect Biochem Mol Biol. 2009;39(10):697-706.
33. Bass C, Schroeder I, Turberg A, Field LM, Williamson MS. Identification of mutations associated with pyrethroid resistance in the para-type sodium channel of the cat flea, Ctenocephalides felis. Insect Biochem Mol Biol. 2004;34(12):1305-13.
34. Boaventura D, Buer B, Hamaekers N, Maiwald F, Nauen R. Toxicological and molecular profiling of insecticide resistance in a Brazilian strain of fall armyworm resistant to Bt Cry1 proteins. Pest Manag. Sci. 2020;33:101-9.
35. RosE RL, Barbhaiya L, Roe RM, Rock GC, Hodgson E. Cytochrome P450-associated insecticide resistance and the development of biochemical diagnostic assays in Heliothis virescens. Pestic Biochem Physiol. 1995;51(3):178-91.
36. Sayani Z, Mikani A, Mosallanejad H. Biochemical resistance mechanisms to fenvalerate in Plutella xylostella (Lepidoptera: Plutellidae). J Econ Entomol. 2019;112(3):1372-7.
37. Scott JG, Leichter CA, Rinkevihc FD, Harris SA, Su C, Aberegg LC, et al. Insecticide resistance in house flies from the United States: resistance levels and frequency of pyrethroid resistance alleles. Pestic Biochem Physiol. 2013;107(3):377-84.
38. Chen A, Zhang H, Shan T, Shi X, Gao X. The overexpression of three cytochrome P450 genes CYP6CY14, CYP6CY22 and CYP6UN1 contributed to metabolic resistance to dinotefuran in melon/cotton aphid, Aphis gossypii Glover. Pestic Biochem Physiol. 2020;167:104601.
39. Ling S, Zhang R. Cross-resistance of bisultap resistant strain of Nilaparvata lugens and its biochemical mechanism. J Econo Entomol. 2011;104(1):243-9.
40. Ahmad M, McCaffery AR. Penetration and metabolism of trans-cypermethrin in a susceptible and a pyrethroid-resistant strain of Helicoverpa armigera. Pestic Biochem Physiol. 1999;65(1):6-14.
41. Cao Y, Yang H, Li J, Wang C, Li C, Gao Y. Sublethal effects of imidacloprid on the population development of western flower thrips Frankliniella occidentalis (Thysanoptera: Thripidae). Insects. 2019;10(1):3.
42. Machida H, Kondo T, Kanehira K, Hagimori I, Kamio T. The inhibitory effect of a combination of imidacloprid and permethrin on blood feeding by mosquitoes in dogs raised under outdoor conditions. Vet Parasitol. 2008;154(3-4):318-24.
43. Yuan WL, Bo XU, Ran GC, Chen HP, Zhao PY, Huang QL. Application of imidacloprid controlled-release granules to enhance the utilization rate and control wheat aphid on winter wheat. J Integr Agric. 2020;19(12):3045-53.
44. Wakil W, Schmitt T. Field trials on the efficacy of Beauveria bassiana, diatomaceous earth and Imidacloprid for the protection of wheat grains from four major stored grain insect pests. J Stored Prod Res. 2015;64:160-7.
45. Nayak MK, Daglish GJ. Potential of imidacloprid to control four species of psocids (Psocoptera: Liposcelididae) infesting stored grain. Pest Manag Sci. 2006;62(7):646-50.
46. Athanassiou CG, Kavallieratos NG, Arthur FH, Throne JE. Efficacy of a combination of beta-cyfluthrin and imidacloprid and beta-cyfluthrin alone for control of stored-product insects on concrete. J Econ Entomol. 2013;106(2):1064-70.
47. Arthur FH, Fontenot EA. Efficacy of dinotefuran (Alpine® spray and dust) on six species of stored product insects. J Stored Prod Res. 2013;55:55-61.