

Effects of Mixing Methods of Aerial Application Adjuvants and Insecticides on Control Efficacy Against Striped Stem Borer (*Chilo suppressalis*) Using Plant Protection UAVs: Postprint

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Abstract

To investigate the influence of aerial application adjuvant types and their mixing compatibility with insecticides on the control efficacy against rice stem borer (*Chilo suppressalis*), this study employed a three-factor, three-level L₉(3⁴) orthogonal experimental design, with insecticides (10% emamectin benzoate · indoxacarb SC, 5% chlorantraniliprole SC, and 0.8% rotenone SC), aerial application adjuvants (silicone adjuvant, mineral oil adjuvant, and lecithin adjuvant), and spray application volumes (21, 24, and 27 L/hm²) as the experimental factors. Significance levels of each factor were analyzed using analysis of variance (ANOVA). The results demonstrated that under the experimental conditions of this study, on the 14th day post-application, insecticides exerted a significant effect on rice stem borer control efficacy ($P < 0.05$), while aerial application adjuvants exhibited an extremely significant effect ($P < 0.01$). Within the designated spray volume range (21-27 L/hm²), application volume showed no significant influence on control efficacy. Mixing method 7 (0.8% rotenone SC, silicone adjuvant, and 27 L/hm² spray volume) demonstrated favorable initial and residual efficacy, achieving 81.45% control efficacy on the 14th day post-application. Mixing method 4 (5% chlorantraniliprole SC, silicone adjuvant, and 24 L/hm² spray volume) exhibited significant residual efficacy, with 79.30% control efficacy on the 14th day post-application. The findings of this study can serve as a reference for spray solution mixing protocols in rice stem borer management.

Full Text

Effects on Control Efficacy of Pesticide-Adjuvants Mixture against Rice *Chilo suppressalis* (Walker) Based on Plant Protection Unmanned Aerial Vehicle

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Abstract: To investigate the effects of pesticide-adjuvant mixture methods on the control efficacy against rice *Chilo suppressalis* (Walker), this study designed orthogonal experiments with three factors (pesticide type, spray volume, and aerial application adjuvant) at three levels each. The factors included pesticides (10% emamectin benzoate·indoxacarb SC, 5% chlorantraniliprole SC, and 0.8% rotenone SC), spray volumes (21, 24, and 27 L/hm²), and aerial application adjuvants (organosilicon, mineral oil, and lecithin). A blank factor was included as an error term to verify the rationality of the orthogonal design. Analysis of variance (ANOVA) was used to assess the significance of each factor. The results showed that under the experimental conditions, both pesticide type ($P < 0.05$) and adjuvant type ($P < 0.01$) had significant effects on control efficacy 14 days after application, while spray volume showed no significant effect ($P > 0.05$) within the tested range. The optimal mixture was 0.8% rotenone SC with organosilicon adjuvant at 27 L/hm² spray volume, achieving 81.45% control efficacy 14 days after application with both rapid and persistent effects. A satisfactory alternative was 5% chlorantraniliprole SC with organosilicon adjuvant at 24 L/hm², which achieved 79.30% control efficacy 14 days after application. These findings provide valuable references for optimizing pesticide-adjuvant mixtures in UAV-based control of rice stem borer.

Keywords: plant protection UAV; *Chilo suppressalis*; aerial application adjuvant; pesticide; control efficacy

1 Introduction

Chilo suppressalis (Walker), commonly known as the rice stem borer, is one of the most destructive pests in rice production and is widely distributed across China [1, 2]. Its larvae damage rice plants by causing dead sheaths, dead hearts, and white panicles [3], leading to significant yield losses. With the increasing rate of land transfer and the trend toward large-scale agricultural production in China [4], unmanned aerial vehicle (UAV) application has developed rapidly due to its high operational efficiency, low cost, and improved safety [5]. However, the quality of UAV spraying is influenced by multiple factors, including the physical and chemical properties of the spray solution [6], aerial application adjuvants [7], spraying technology [8], and meteorological conditions [9].

Adjuvants can modify the physicochemical properties of spray solutions to enhance droplet spreading, penetration, and deposition on target crops [10], while reducing drift [11], thereby improving both application quality and pesticide efficacy. This approach has advanced considerably in recent years [12, 13]. Naue et al. [14] found that a novel organosilicon adjuvant containing lecithin could effectively wet waxy plant surfaces that are difficult to wet, improving solution spreadability, penetration, and coverage. Gaskin et al. [15] investigated the effects of adjuvants on insecticide retention and found that adjuvants significantly increased retention on hydrophobic crops (by up to fivefold) but had no significant effect on hydrophilic crops. Wang et al. [16] evaluated five adjuvants (Silwet408, NF-100, Beidatong, Maidao, and Sujie) and found that all significantly reduced surface tension and increased maximum retention on crop leaves, thereby enhancing the efficacy of azoxystrobin against plant diseases. Hong et al. [17] studied the synergistic effects of four adjuvants with 10% tetra-chlorantraniliprole SC against rice stem borer, finding that organosilicon oil and water-based formulations were most effective. Yang et al. [18] reported that the Anringle adjuvant increased the efficacy of 25% methoxyfenozide · indoxacarb WG by 10.13%. Sun et al. [19] found that adding the Huainongte vegetable oil adjuvant did not significantly improve control of rice stem borer.

Most previous studies have focused on comparing multiple adjuvants for a single pesticide, while the combined effects of different pesticides, adjuvants, and spray volumes require further investigation. This study employed orthogonal experimental design and statistical analysis to examine how these three factors affect control efficacy against rice stem borer, aiming to identify optimal mixture strategies.

2 Materials and Methods

2.1 Experimental Equipment and Materials

(1) Application equipment. A DJI T16 plant protection UAV (Shenzhen DJI Innovations Technology Co., Ltd.) was used, with a maximum payload of

16 L, eight XR11001VS nozzles, and a maximum flow rate of 3.6 L/min [20].

(2) Test pesticides. Three insecticides were tested: 10% emamectin benzoate·indoxacarb SC (EBI, containing 1% emamectin benzoate and 9% indoxacarb, Dongguan Ruidefeng Biotechnology Co., Ltd.), a locally recommended product; 5% chlorantraniliprole SC (CHI, Shenzhen Noposion Agrochemicals Co., Ltd.); and 0.8% rotenone SC (ROT, containing 0.5% fenvalerate, Guangdong Xinxiutian Chemical Co., Ltd.), used only for experimental testing and not for commercial rice production.

(3) Test adjuvants. Three adjuvant types were evaluated: organosilicon adjuvant (Quanfeng, Anyang Quanfeng Biotechnology Co., Ltd.), which provides super spreadability for improved wetting and coverage [21]; lecithin-based adjuvant (Lingkong Feidu, Nileke Bioengineering (Guangzhou) Co., Ltd.), which offers good biocompatibility to facilitate transport and translocation within plants and pests [22]; and mineral oil adjuvant (Weichi, Total Fluides, France), which provides anti-evaporation properties to extend droplet-crop contact time [23].

2.2 Experimental Environment and Methods

The field experiment was conducted at the teaching and research base of South China Agricultural University in Ningxi Town, Zengcheng District, Guangzhou, Guangdong Province. The rice variety was Meixiangzhan 2, sown on June 24, 2020, and used at the late tillering stage with an average plant height of 55 cm. The experimental field had uniform fertility, good irrigation and drainage conditions, and no obstacles around the plots, making it suitable for UAV operations.

A DJI T16 UAV was used for spraying with a 5 m swath width, flight speed of 4.5 m/s, and altitude of 1.8 m above the crop canopy. Pre-treatment surveys were conducted on August 20, 2020, from 8:00–11:30. Applications were made on the same day from 17:00–19:00 and the following day from 8:00–9:30 under conditions of $29\pm 1^{\circ}\text{C}$ temperature, 65–70% relative humidity, and wind speed < 2 m/s, meeting the requirements of the “Guidelines for Field Efficacy Trials of Pesticide Application by Plant Protection UAVs” (draft). The pest population was rice stem borer, with dead heart rates exceeding 10% in some areas.

Pesticide type, adjuvant type, and spray volume were selected as experimental factors (Table 1). The orthogonal experimental design followed the $L_9(3^4)$ array, with a blank factor included as an error term to verify design rationality (Table 2). Ten mixture treatments were established, each corresponding to one plot without replication. Each plot covered approximately 525 m^2 ($15\text{ m} \times 35\text{ m}$), as shown in Figure 1 [Figure 1: see original paper]. Treatments 1–9 comprised the orthogonal design combining three pesticides (EBI, CHI, ROT), three adjuvants (organosilicon, mineral oil, lecithin), and three spray volumes (21, 24, 27 L/hm²), while Treatment 10 served as the blank control. Application rates were 675 mL/hm² for emamectin benzoate·indoxacarb and chlorantraniliprole, and 1350 mL/hm² for rotenone, with adjuvants added at 1% of solution volume based on local recommendations.

2.3 Control Efficacy Investigation and Statistics

Pest surveys were conducted before application and at 6, 10, and 14 days after application. In each plot center, 18 sampling points were selected in a 3×6 grid pattern (3 rows × 6 columns). At each point, 5 rice hills were examined to record total plant number and dead heart number. Following pesticide field efficacy trial guidelines [24] and longitudinal comparisons within plots, control efficacy was calculated using formulas (1)-(3). Phytotoxicity was also observed.

2.4 Data Processing

SPSS 23.0 software was used to calculate 95% and 99% confidence intervals. Duncan's new multiple range test and Duncan's multiple comparison method were applied for significance testing and level optimization [25]. P-values, F-values, and mean squares are primary statistical indicators in ANOVA for testing model and coefficient significance. The P-value indicates the probability of error when significant differences exist among factor levels; smaller P-values denote more significant differences. Larger F-values indicate more significant factor effects. For an orthogonal experiment to be valid, the error term mean square must be smaller than those of experimental factors [26, 27].

3 Results

3.1 Control Efficacy of Different Mixtures

Control efficacy was calculated for each plot at 6, 10, and 14 days after application, as shown in Figure 2 [Figure 2: see original paper]. At 6 days after application, efficacy ranged from 64.20% to 86.74%, with substantial variation among mixture treatments. At 10 days after application, average efficacy in plots treated with emamectin benzoate · indoxacarb and rotenone decreased by 3.78% and 2.10%, respectively, while chlorantraniliprole plots showed a slight increase of 2.54%. At 14 days after application, emamectin benzoate · indoxacarb and rotenone plots continued to decline (by 1.53% and 1.56%, respectively), whereas chlorantraniliprole plots continued to improve (by 2.52%). All rice plants grew normally without phytotoxicity symptoms.

3.2 Significance Analysis of Factors

Single-factor ANOVA using Duncan's new multiple range test was performed to analyze the significance of pesticides, adjuvants, and spray volume on control efficacy (Table 3). The error term mean square was smaller than those of all three factors at 6, 10, and 14 days after application, confirming the orthogonal design was valid. Under the experimental conditions, at 6 days after application, both pesticide type ($P < 0.05$) and adjuvant type ($P < 0.05$) had significant effects, while spray volume ($P > 0.05$) showed no significant effect. At 10 days after application, only adjuvant type ($P < 0.05$) remained significant, with pesticide

type and spray volume showing no significant effects ($P>0.05$). At 14 days after application, pesticide type showed a significant effect ($P<0.05$), adjuvant type showed a highly significant effect ($P<0.01$), and spray volume remained non-significant ($P>0.05$).

The F-values consistently ranked as: adjuvants > pesticides > spray volume at all three time points, indicating that adjuvant type was the primary factor affecting control efficacy, followed by pesticide type, while spray volume was a secondary factor with non-significant differences among levels within the 21-27 L/hm² range.

3.3 Optimization of Mixture Methods

Duncan's multiple comparison was performed for the three factors at 14 days after application (when efficacy was relatively stable) to identify optimal mixture methods (Table 4). For pesticide type, level 3 (rotenone) performed best, with the ranking: rotenone SC > chlorantraniliprole SC > emamectin benzoate · indoxacarb SC. For adjuvant type, level 1 (organosilicon) performed best, with the ranking: organosilicon > lecithin > mineral oil. For spray volume, the three levels showed no significant differences, though level 3 (27 L/hm²) performed slightly better.

Therefore, the optimal mixture was 0.8% rotenone SC with organosilicon adjuvant at 27 L/hm² spray volume, achieving 81.45% control efficacy at 14 days after application with both rapid and persistent effects. A satisfactory alternative was 5% chlorantraniliprole SC with organosilicon adjuvant at 24 L/hm², which achieved 79.30% control efficacy at 14 days after application with good persistence.

4 Discussion and Conclusion

This study used a DJI T16 UAV to investigate how different combinations of pesticides, adjuvants, and spray volumes affect control efficacy against rice stem borer through orthogonal experimentation.

The observed trend of decreasing efficacy over time for emamectin benzoate · indoxacarb and rotenone, versus increasing efficacy for chlorantraniliprole, can be attributed to chlorantraniliprole's systemic properties [28, 29]. Compared with the contact-action pesticides emamectin benzoate · indoxacarb and rotenone, chlorantraniliprole provides longer residual activity. At 6 days after application, emamectin benzoate · indoxacarb showed significantly higher efficacy than chlorantraniliprole; by 10 days, their efficacy was similar; and by 14 days, chlorantraniliprole showed significantly higher efficacy. This explains why pesticide effect changed from significant to non-significant and back to significant over time, demonstrating the advantage of systemic insecticides for long-term control. Although rotenone efficacy also declined over time, it remained higher

than chlorantraniliprole at 14 days, showing both rapid and persistent effects.

Among the three adjuvants tested, the performance ranking was: organosilicon > lecithin > mineral oil. Organosilicon adjuvants provide super spreadability, reducing surface tension below the leaf wetting critical pressure and enabling stomatal penetration [21]. They also significantly decrease contact angles, allowing droplets to spread on leaf surfaces [30] and improving deposition on hydrophobic rice plants [14]. Lecithin, as a cell membrane component, offers excellent biocompatibility that facilitates pesticide transport and distribution within plant tissues, enhancing sustained release [22]. Mineral oil adjuvants extend droplet evaporation time and improve penetration [23] but are less effective for deposition and retention compared to the other two adjuvants.

Spray volume directly affects solution concentration and droplet density, influencing pest control efficacy [31, 32]. Within the 21-27 L/hm² range tested, higher volumes tended to produce better control, though the trend was not significant. However, increasing spray volume reduces UAV operational efficiency. Therefore, spray volume selection should balance efficiency and efficacy.

This study provides valuable references for optimizing pesticide-adjuvant mixtures in UAV applications for rice stem borer control. Future research should further investigate the mechanisms underlying the superior performance of specific pesticide-adjuvant combinations and evaluate their economic viability for practical application.

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