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ARTICLE

A Preliminary Study on Controlling *Chilo suppressalis* in Rice Fields Using Precision Timing and Insecticide Combinations

Li Wang[1,2], Jinfeng Zhang[2], Binbin Li[2], Zhengbo Pen[3], Zhiyuan Yang[3,*] and Anshu Rastogi[4,*]

[1]Department of Municipal and Ecological Engineering, Shanghai Urban Construction Vocational College, Shanghai, China
[2]Department of Modern Agriculture, Meishan Vocational and Technical College, Sichuan, China
[3]Rice Research Institute, Sichuan Agricultural University, Sichuan, China
[4]Department of Bioclimatology, Poznan University of Life Sciences, Poznan, Poland
*Corresponding Authors: Zhiyuan Yang. Email: yang@sicau.edu.cn; Anshu Rastogi. Email: anshu.rastogi@up.poznan.pl

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ABSTRACT: *Chilo suppressalis* (Walker) is one of the most important rice pests worldwide, posing a significant challenge to effective control. To develop a precision-timed, eco-friendly management strategy, overwintering population investigation and dynamic monitoring of *C. suppressalis* populations were conducted in the Meishan region of Sichuan, China, from 2023 to 2024. The optimal timing for insecticide application was estimated, followed by field trials evaluating the efficacy of different insecticides. Results demonstrated that the peak emergence of first-generation adults typically occurred in early July (under the environmental conditions of the Meishan region), with the ambient humidity below 75% and temperature around 29°C. Pesticide efficacy trials show that insecticide combinations exhibited superior control. Notably, a combined treatment of *emamectin benzoate·methoxyfenozide + chlorantraniliprole* achieved the highest control efficacy (90.05%) and a corresponding yield of 12,491.55 kg/ha. All tested treatments were determined to be safe for rice growth. Furthermore, this optimized strategy resulted in notable economic benefits, including a 50% reduction in pesticide usage and cost savings of 4796.15 CNY compared to conventional practices. This study provides valuable insights into sustainable rice production and pest management and, for the first time, proposes a precision application time window based on intelligent monitoring.

KEYWORDS: *Chilo suppressalis*; rice; precision timing; *emamectin benzoate*; chlorantraniliprole

1 Introduction

Chilo suppressalis (Walker) (Lepidoptera: Crambidae) is one of the most destructive insect pests in rice ecosystems across Asia and Europe, posing a persistent threat to global rice production and food security [1,2]. During the tillering stage in rice, the larvae severely damage the vascular system, causing the interior leaf to wilt and resulting in dead hearts. During the flowering stage, panicles are severed at their base, creating white heads with unfilled grains, which cause annual economic losses estimated up to $40 million [3,4]. *C. suppressalis* is widely distributed across major rice-growing regions of Asia and parts of Europe, where it causes substantial yield losses [5,6]. The pest is particularly prevalent in East and Southeast Asia, including China, Japan, Korea, Vietnam, the Philippines, and Thailand, where climatic conditions favor multiple generations per year and persistent infestations [7,8]. In China, *C. suppressalis* is recognized as one of the most destructive rice pests across the Yangtze River Basin, Sichuan Basin, and southern rice-growing provinces. Beyond Asia, established populations have also been reported in parts of southern

Europe, including Spain and Italy, highlighting its expanding geographic footprint [5]. This underscores the seriousness of *C. suppressalis* infestations. Moreover, economic impacts are likely to intensify under climate change scenarios, as rising temperatures and altered humidity patterns can increase pest survival and outbreak frequency. Given the potential escalation of damage under these changing conditions, there is an urgent need to develop effective management practices to prevent losses and enhance productivity.

For decades, the primary strategy for controlling *C. suppressalis* has largely depended on chemical pesticides [9], thereby substantially mitigating yield losses resulting from the borer's infestation. The long-term, excessive, or indiscriminate use of pesticides can lead to increased pest resistance [10]. Additionally, the overuse of chemical pesticides in rice cultivation results in measurable residue accumulation that compromises grain quality and poses health risks. In China, the toxicological studies indicated a surge of 17.7% of brown rice samples contained multiple residues exceeding maximum limits in Guilan Province [11], in Iran, the average concentration of the organophosphorus pesticide diazinon in rice reached 31.91 mg/kg, far above EU safety standards [9]; and in Nigeria, rice samples exceeded permissible thresholds with hazard quotients [12]. More critically, field populations of *C. suppressalis* have developed high levels of resistance. Studies indicate that resistance ratios have reached up to 461.7-fold for *chlorantraniliprole* compared to susceptible strains [13]. This escalating resistance not only renders chemical treatments ineffective but also exacerbates environmental pollution and poses risks to food safety and ecosystem health.

In response to these challenges, Integrated Pest Management (IPM) has emerged as the cornerstone of modern, sustainable crop protection to manage pest populations in an economically and ecologically sound manner [14]. Applying physical and chemical control measures, at the most vulnerable stage of a pest's life cycle can dramatically increase efficacy while minimizing the number of applications, thereby reducing selection pressure for resistance and lowering costs [15]. However, the effective timing of interventions against *C. suppressalis* has been hampered by a lack of precise, real-time data on its population dynamics. Traditional forecasting methods often rely on historical data and manual scouting, which are labor-intensive and often fail to capture the fluctuating local weather conditions on pest development [16]. To overcome these limitations, the intelligent monitoring systems, which combine automated trapping with spray timing analytics, offer a transformative opportunity to overcome this limitation. Dynamic monitoring employs continuous, real-time data collection through advanced sensors, remote sensing. This approach provides a granular, temporally dense picture of pest populations and environmental conditions, enabling the identification of early warning signals before pest populations reach damaging thresholds. When integrated with intelligent decision-support systems, pest management transforms from reactive to proactive, enabling interventions tailored precisely to current pest pressure [17–19].

In China, the convergence of pesticide-reduction policies and the widespread resistance of *C. suppressalis* to common insecticides necessitates optimized management strategies [20,21]. To advance the sustainable production of rice, this study was designed to precisely determine the optimal timing for pesticide application against *C. suppressalis* based on real-time adult population dynamics and evaluate the efficacy of different insecticide combinations applied, aiming to identify strategies that reduce overall insecticide dependency. This approach provides a comprehensive evaluation of its viability for sustainable rice farming. This research fills critical gaps by demonstrating how sensor-based, real-time monitoring coupled with intelligent decision-making can revolutionize *C. suppressalis* management, offering a novel, precise, and adaptive framework that differs fundamentally from conventional, threshold-based IPM practices.

2 Materials and Methods

2.1 Overwintering Population Determination and Adult Monitoring of C. suppressalis

To ascertain the baseline overwintering population data of *C. suppressalis*, representative winter fallow rice fields were surveyed across various locations in Meishan County, Sichuan Province, China (Table 1). A jumping multi-point sampling method was employed, wherein rice stubble from a total area of 10 m^2 was excavated at each site. Approximately 100 rice stubbles per site were randomly selected, dissected, and examined for live overwintering larvae to determine the initial insect population density. This density was then extrapolated to estimate the population per hectare, providing a standardized baseline for subsequent assessments [22].

To monitor adult population dynamics, an intelligent insect monitoring and reporting system (BA-T/CBX, Chengdu Bian Technology Co., Ltd.) was deployed in the surveyed areas (Fig. S1). This system operated continuously from June to August 2023 to monitor the adult moth population dynamics based on an artificial intelligence framework that integrates machine vision for species identification with real-time environmental data acquisition. It automatically captures images of trapped insects and identifies and counts adult *C. suppressalis*. Concurrently, the system records key meteorological variables, including daily average temperature (°C) and relative humidity (%), to analyze the relationship between environmental factors and pest population fluctuations.

2.2 Experimental Material and Field Management

The rice variety 'Zheyou 210' selected by Zhejiang Academy of Agricultural Science, which exhibited the highest susceptibility to overwintering *C. suppressalis* infestation based on preliminary surveys, was suitable for evaluating control efficacy. 'Zheyou 210'seedlings were sown on March 17 and manually transplanted on April 18, 2024, into experimental plots covering an area of 0.1 ha. The field was prepared by rotary tilling to a depth of 20 cm, followed by flooding for one week before harrowing and transplanting. A standardized fertilization was applied to all plots to ensure uniform crop nutrition. This included a basal application of a compound fertilizer (N-P-K = 15-15-15) at a rate of 300 kg/ha before transplanting, followed by two topdressings of urea at 150 kg/ha each, applied at the mid-tillering and panicle initiation stages, respectively.

The chemical insecticides used in the study were 1.8% *Avermectin* (EC), 40% *Chlorantraniliprole* (DPC), 34% *Spinetoram* (SC), 9% *Emamectin Benzoate · Methoxyfenozide* (SC), and 16% *Avermectin · Indoxacarb* (SC). Detailed information regarding the registration and manufacturing of these products is provided in the Supplementary Material (Table S1).

2.3 Pesticide Treatment and Application

Based on the dynamic monitoring data of *C. suppressalis* adult populations from 2023, pesticide applications were timed to precede the predicted peak of the first-generation larval hatching. Seven pesticide treatment groups (T1-T7) and an untreated group (control; CK) were established in a randomized complete block design. The recommended dosage of pesticides is based on instructions, and the dosage of compound pesticides is halved as follows: T1 = 2.7 g a.i. ha^{-1}, *Avermectin*, T2 = 60 g a.i. ha^{-1}, *Chlorantraniliprole*, T3 = 51 g a.i. ha^{-1}, *Spinetoram*, T4 = 1.35 g a.i. ha^{-1}, *Avermectin* + 30 g a.i. ha^{-1}, *Chlorantraniliprol*, T5 = 6.75 g a.i. ha^{-1}, *Emamectin Benzoate · Methoxyfenozide* + 60 g a.i. ha^{-1}, *Chlorantraniliprole*, T6 = 25.5 g a.i. ha^{-1}, *Spinetoram* + 30 g a.i. ha^{-1}, *Chlorantraniliprole*, T7 = 24 g a.i. ha^{-1}, *Avermectin·Indoxacarb*, CK = Untreated Control. Pesticide applications were applied twice at the tillering stage and the heading stage. A backpack electric sprayer (3WBD-20) equipped with a fan-shaped nozzle was used, operating at a pressure of 0.3 MPa and an application speed of approximately 1 m/s to ensure uniform coverage of the rice canopy.

2.4 Assessment of Withered Heart Rate and Control Efficacy

Fourteen days after each pesticide application, the efficacy of the treatments was assessed. In each plot, 100 rice tillers were randomly sampled using a parallel jumping sampling method. The number of tillers showing 'withered heart' symptoms was recorded. The withered heart rate (%) and control efficacy (%) were calculated using the following formulas: Eqs. (1) and (2) [16,23].

$$Withered\ Heat\ Rate\ (\%) = [\frac{Number\ of\ withered\ tillers}{Total\ Number\ of\ Tillers\ Investigated}] \times 100 \quad (1)$$

$$Control\ Effect\ (\%) = [\frac{Withered\ Heart\ Rate\ in\ CK\text{-}Withered\ Heart\ Rate\ in\ Treatment}{Withered\ Heart\ Rate\ in\ CK}] \times 100 \quad (2)$$

2.5 Analysis of Rice Yield and Economic Benefit

During the rice maturity period, five rice panicles were randomly selected from each treatment, dried, and evaluated. The number of productive panicles, total grains per panicle, seed setting rate (%), and thousand-grain weight TGW (g) were recorded to calculate the theoretical yield (Eq 3). The experiment was replicated thrice for accuracy.

$$Theoretical\ Yield\ (\mathrm{kg/ha}) = \frac{Panicles/\mathrm{m}^2 \times Grains/paniclee \times Seed\ setting\ (\%) \times TGW\ (\mathrm{g})}{100} \quad (3)$$

An economic analysis was conducted by calculating the total cost of pest management, including insecticides and labor, for the average of pest prevention areas and control areas based on the actual yield and the prevailing market price of rice. The net economic benefit was then determined to evaluate the cost-effectiveness of each control strategy.

2.6 Determination of Heavy Metal and Pesticide Residues

For residue analysis, a composite sample of rice grains was prepared for each treatment by combining grains collected from all three replicates. 200 g of powdered rice from each composite sample was sent to the Sichuan Zhong'an Testing Center for analysis. The contents of lead (Pb), cadmium (Cd), and total mercury (Hg) were determined using atomic fluorescence spectrometry ICP-MS (7900, Agilent) and AFS (9700, Beijing Titan Instrument Co., Ltd.) after microwave digestion. The limits of detection (LOD) were 0.02, 0.002, and 0.001 mg/kg, respectively. Residues of organophosphate and pyrethroid insecticides were analyzed using GC-MS (7010D, Agilent), while carbamate insecticides were analyzed using LC-MS/MS (6470, Agilent).

2.7 Statistical Analysis

The experiment was conducted using a randomized complete block design with three replications. Data on withered heart rate, yield components, and final yield were subjected to analysis of variance using SPSS Statistics (Version 26.0, IBM Corp.). The assumptions of ANOVA were checked prior to analysis. When the F-test indicated significant differences among treatment means ($p < 0.05$), Duncan's multiple range test was employed for post-hoc pairwise comparisons to separate the means.

3 Results

3.1 Overwintering C. suppressalis Population in Rice Fields

The investigation of overwintering baseline survey data of *C. suppressalis* across nine locations in Sichuan Province revealed significant variation in residual insect densities (Table 1). The average overwintering population was estimated at 4515 heads, with an average natural mortality rate of 10.25%. Notably, the highest population densities were recorded in Songjiang (10,890 heads) and Qinjia (9405 heads), both of which were planted with the rice variety 'Zheyou 210'. The survival rates in these high-density locations were 87.34% and 91.66%, respectively, indicating a substantial carryover population and posing a high risk for pest outbreaks in the subsequent rice-growing season. In contrast, locations such as Simeng and Duoyue, planted with 'Pin Xiang You', exhibited the lowest population density, suggesting varietal or micro-environmental influences on overwintering success.

Table 1: Overwintering population of *C. suppressalis* in different locations of Sichuan province.

Survey Location	GPS Coordinates for Samples	Rice Varieties	Investigated Rice Stubble/Panicle	Overwintering Insect (heads/ha)	Mortality Rate (%)
Simeng	29°53′55″ N, 103°46′41″ E	Pin Xiang You	216	495	0
Funiu	30°7′104″ N, 103°78′2″ E	Quanyou 1606	312	3960	10
Shangyi	30°5′31″ N, 103°46′19″ E	Linliang You	149	2475	8.34
Qinjia	29°56′24″ N, 103°51′26″ E	Zheyou 210	191	9405	8.34
Yongshou	29°58′52″ N, 103°51′39″ E	Unknown	194	3960	0
Duoyue	30°5′31″ N, 103°46′19″ E	Pin Xiang You	141	495	0
Wansheng	30°0′21″ N, 103°51′47″ E	Unknown	203	6930	15.39
Songjiang	29°59′49″ N, 103°42′17″ E	Zheyou 210	280	10,890	12.66
Taihe	30°6′30″ N, 103°48′5″ E	Linliang You	168	1980	37.50
	Average		206	4515	10.25

Note: The survey baseline data are used to inform the selection of treatment plots rather than to draw a direct comparison.

3.2 Population Dynamics and Forecasting of C. suppressalis Adults

According to the intelligent insect monitoring results from June to August 2024, adult *C. suppressalis* showed dynamic population fluctuations. As shown in Fig. 1, the first-generation adults peaked between 1 and 7 July, with the highest count of 66 on the night of 5 July. The second generation reached its peak on 24 July, with 75 adults, followed by a smaller peak from 3 to 7 August. The first-generation peak lasted about 5 days, indicating a prolonged or multi-phased emergence. Monitoring ended on 10 August, with adults still present.

Further analysis of the relationship between moth emergence and meteorological factors indicated a strong correlation. As shown in Fig. 1, the two major population peaks occurred at average daily temperatures of 28~30°C with relative humidity below 75%, suggesting that warm and dry conditions trigger synchronized pupal eclosion in *C. suppressalis.* This information is crucial for determining the optimal window for applying control measures, targeting the subsequent larval stage before significant crop damage occurs.

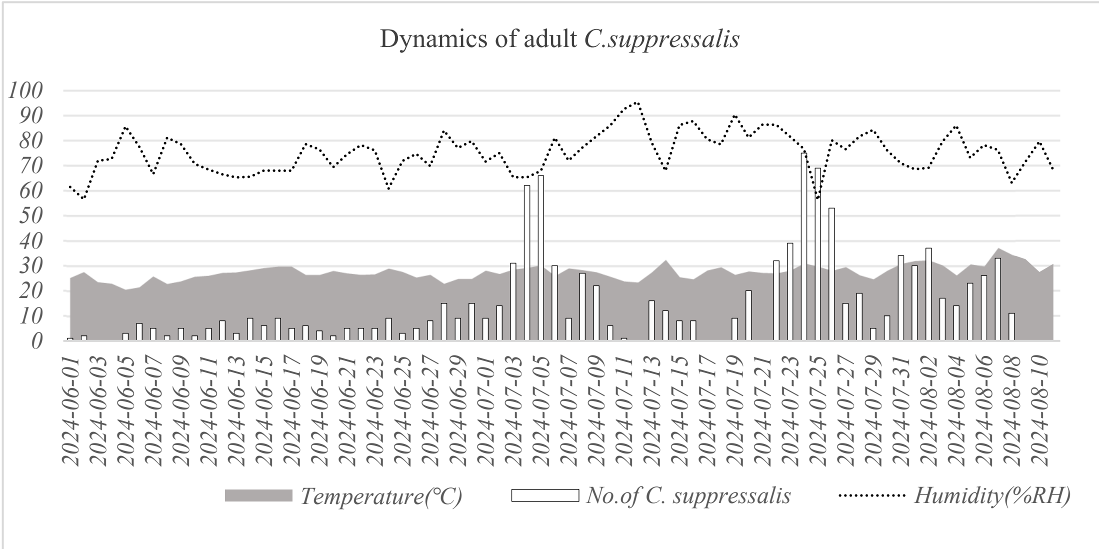

Figure 1: Dynamic monitoring of the occurrence of *C. suppressalis* adults.

3.3 Effect of Different Pesticide Treatments on C. suppressalis

The effectiveness of seven pesticide treatments against *C. suppressalis* was evaluated using withered heart rate and white panicle number (Table 2). The results clearly demonstrate that combination treatments were more effective than single-agent applications. Among the single-agent treatments, *Abamectin* (T1), *Chlorantraniliprole* (T2), and *Spinetoram* (T3) exhibited the lowest control efficacy, at 50.41%, 60.63%, and 65.10%, respectively. This relatively low performance suggests the potential development of resistance to these insecticides in the local *C. suppressalis* population.

In comparison to single-agent treatment, the combination of pesticides (T4–T7) achieved significantly better results. Notably, the treatment combining *Emamectin Benzoate·Methoxyfenozide* + *Chlorantraniliprole* (T5) and the one combining *Spinetoram* + *Chlorantraniliprole* (T6) were the most effective. These treatments resulted in the lowest withered heart rates, which were 0.96% and 1.27%, respectively. Furthermore, T5 significantly reduced the number of white panicles compared to the untreated control group. The T5 group retains the lowest withered heart rate in rice fields, with the control effect reaching 90.05%.

Table 2: Control effects of different pesticide treatments on *C. suppressalis*.

Treatment	No. of Effective Panicles	No. of White Panicles	Withered Heart Rate%	Control Effect%
T1	22.48 ± 1.91a	0.93 ± 0.24a	4.18 ± 1.36a	50.41
T2	19.90 ± 2.13ab	0.74 ± 0.28ab	3.77 ± 1.54ab	60.63
T3	19.47 ± 0.90ab	0.65 ± 0.20ab	3.34 ± 0.99ab	65.10
T4	22.55 ± 3.30a	0.49 ± 0.04ab	2.20 ± 0.13a	77.04
T5	21.79 ± 2.36a	0.21 ± 0.06b	0.96 ± 0.28abc	90.05
T6	22.23 ± 1.75a	0.28 ± 0.09b	1.27 ± 0.40ab	86.80
T7	19.93 ± 0.85ab	0.49 ± 0.18ab	2.48 ± 0.94a	74.08
CK	21.45 ± 0.92a	2.06 ± 0.34a	9.58 ± 1.30a	

Note: Values are Means ± SD. Within a column, the same lowercase letters of data indicate that the difference between different treatments is not significant at the level of 5%.

3.4 Phytotoxicity and Residue Analysis

Throughout the experiment, no signs of phytotoxicity, such as leaf discoloration, stunting, or other abnormal growth, were observed in any of the pesticide-treated plots when compared to the untreated control group. This shows that all tested insecticides were safe for the 'Zheyou 210' rice variety at the applied doses. Residue analysis of the harvested rice grains revealed that Pb and Hg were not detected in any sample (Table 3). Cd was detected in all samples, including the control, but the concentrations in all treatment groups were well below the national food safety standard permissible limit of ≤0.2 mg/kg. Furthermore, no residues of the applied pesticides were detected in the final grain products. These results confirm that the tested pest management strategies are safe for consumers and do not lead to the accumulation of harmful residues in rice.

Table 3: Detection of heavy metals and pesticide residues in rice.

Treatment Group	Pb mg/kg	Cd mg/kg	Hg mg/kg	Pesticide Residues mg/kg
T1	Not detected	0.0517	Not detected	Not detected
T2	Not detected	0.0103	Not detected	Not detected
T3	Not detected	0.0118	Not detected	Not detected
T4	Not detected	0.0278	Not detected	Not detected
T5	Not detected	0.0373	Not detected	Not detected
T6	Not detected	0.0172	Not detected	Not detected
T7	Not detected	0.0100	Not detected	Not detected
CK	Not detected	0.0147	Not detected	Not detected

Note: The national standard limits for Pb, Cd, and Hg in rice are ≤0.2 mg/kg, ≤0.2 mg/kg, and ≤0.02 mg/kg, respectively (Sichuan Zhong'an Testing Center).

3.5 Impact of Insecticide Treatments on Rice Yield and Economic Efficiency

The application of effective pesticide treatments translated directly into improved yield-related traits and higher grain yield (Table 4). The T5 treatment, *emamectin benzoate·methoxyfenozide + chlorantraniliprole*, which demonstrated the highest pest control efficacy, also produced the best agronomic results. It recorded the highest seed setting rate (91.23%), a significantly higher 1000-grain weight (26.3 g), and the highest grain yield (12,491.55 kg/ha). Representing a 27.95% yield increase compared to the untreated control. Other combination treatments (T4, T6, T7) also showed positive trends in yield components and delivered substantial yield gains over the control. The average yield across all pesticide treatments was 11,737.65 kg/ha.

Table 4: Rice yield and related traits under different pesticide treatment groups.

	No. of Effective Panicles	No. of Grains per Panicle	Seed Setting Rate/%	1000-Grain Weight/g	Theoretical Yield//kg ha^{-1}	Yield/kg ha^{-1}
T1	22.48 ± 1.91a	199 ± 65.94ab	83.96 ± 4.14b	24.24 ± 0.62abc	10,917.3 ± 217.28a	11,049.60
T2	19.90 ± 2.13ab	191.6 ± 33.45ab	83.09 ± 8.02cd	20.91 ± 1.60c	11,390.4 ± 225.07a	11,099.25
T3	19.47 ± 0.90ab	196.2 ± 24.39ab	85.72 ± 3.35abc	21.44 ± 4.33bc	12,272.1 ± 181.26a	11,354.25
T4	22.55 ± 3.30a	241.4 ± 7.13a	86.42 ± 5.81abc	19.69 ± 3.56c	12,700.8 ± 138.93a	12,193.65
T5	21.79 ± 2.36a	218.80 ± 62.18ab	91.23 ± 2.24a	26.3 ± 3.29ab	13,725.6 ± 222.97a	12,491.55
T6	22.23 ± 1.75a	240.20 ± 76.39a	84.18 ± 4.84bcd	21.75 ± 2.73bc	13,268.7 ± 306.89a	12,459.75
T7	19.93 ± 0.85ab	224.80 ± 73.31ab	89.76 ± 2.91ab	22.95 ± 1.34abc	12,406.8 ± 297.70a	11,515.05
CK	21.45 ± 0.92a	160.80 ± 41.28b	78.27 ± 2.10d	27.39 ± 6.58a	10,220.7 ± 220.01ab	9762.60

Note: Values are Means ± SD. The same lowercase letters after the same column of data indicate that the difference between different treatments is not significant at the level of 5%.

The economic benefit analysis hinges on the market price of paddy rice. By comparing yield data and input versus benefits under the three management models, the results shown in Table 5 indicate that the net profits for pesticide-treated areas amounted to 29,943.44 CNY/ha. Notably, compared to traditional pesticide application areas, the pesticide-treated areas reduced pesticide usage by half, significantly decreasing both pesticide and labor costs, resulting in savings of 4796.15 CNY/ha.

Table 5: Economic benefit analysis (Unit: CNY/ha).

Treatment	Yield/kg	Rice Price	Revenue	Fertilizer Cost	Pesticide Cost	Labor/ Mechanical Cost	Total Cost	Net Profit	Efficiency
Non-Pesticide area	11,737.65	2.96	34,743.44	2250	750	1800	4800	29,943.44	
Pesticide-treated area	9762.6	2.96	28,897.30	2250	0	1500	3750	25,147.30	4796.15
Conventional pesticide application area	11,262.6	2.96	33,337.30	2250	1125	2550	5925	27,412.30	2531.15

Note: Market prices for inputs and outputs are subject to fluctuation. The 'Efficiency' for the pesticide-treated area represents the reduction in total costs compared to the Non-Pesticide area.

4 Discussion

To control *Chilo suppressalis*, it is necessary to understand its occurrence pattern. *C. suppressalis* is a holometabolous insect with four stages throughout its life cycle, including the egg stage, the larval stage, the pupal stage, and the adult stage. Damage occurs when larvae bore into the stem, resulting in withered seedlings during the tillering stage of rice, withered ears during the booting stage, and withered hearts during the mature stage [13,15]. The disaster in crop growth caused by the *C. suppressalis* is mainly due to the rapid growth of its population and the limitations of comprehensive control. During the egg and larval stages, the rice stem borer typically infests the rice panicles, causing brick damage, making chemical control ineffective. Therefore, control of the rice stem borer can only be implemented during the adult stage, including the mating period. The outbreak of this pest is closely related to farming systems, rice varieties, cultivation techniques, climate change, and the pest's resistance to commonly used insecticides [24,25]. In recent years, the mechanized harvesting method has largely retained rice stumps, and the surplus rice stumps are too high, resulting in an increase in the survival rate of overwintering larvae of the *C. suppressalis* [13]. The trials survey results indicated that the overwintering *C. suppressalis* population in the Songjiang region reached 10,890 heads, significantly increasing the baseline population for the subsequent year. This highlights the necessity of integrating cultural practices, like deep tillage and stubble management, to reduce the initial pest pressure.

Our research demonstrates the pivotal role of intelligent monitoring systems in modern pest management. By providing real-time data on adult moth populations, these systems enable precise timing of interventions. We identified a peak emergence of the first-generation adults around July 5th, which correlated with an average daily temperature of approximately 29°C and ambient humidity below 75%. Similar results for the increase in adult moth emergence were observed by Xiang et al. [15], who also noted the influence of temperature on adult emergence. The lower humidity might reduce fungal pathogens or natural enemies, thereby favoring adult emergence, and that temperature thresholds align with the insect's thermally driven development cycles [26]. This synergistic effect of optimal temperature and lower humidity facilitates the synchronized emergence of mature pupae, resulting in a concentrated population peak. The ability to pinpoint this peak activity is crucial for scheduling pesticide applications just before larval hatching, thereby maximizing efficacy and minimizing the number of treatments. The

IoT-based smart traps using machine or deep learning for automatic pest identification and counting offer a major improvement over traditional labor-intensive scouting methods [27]. Using these insights, we formulated a decision-support guideline: insecticide application application should be triggered when ambient temperature reaches ~29°C with humidity below 75%, or when monitored adult counts exceed defined economic threshold.

So far, the control measures for the rice stem borer in agriculture mainly rely on chemical pesticides [28]. The effectiveness of pesticide control has gradually decreased, accompanied by an increase in dosage, which has exacerbated the formation of drug resistance and caused a vicious cycle, leading to an increase in the number of residual pests in the field and a growing population year by year. Mao et al. (2019) used rice stem soaking and drip methods to determine the resistance levels of 20 field populations of *C. suppressalis* developed resistance to *triazophos*, *chlorpyrifos*, and *avermectin* at 64.5~461.3 times, 10.1~125.0 times, and 6.5~76.5 times, respectively, through the LD_{50} of the topical application test [29]. The resistance levels of the *C. suppressalis* population to *avermectin* in some areas of Jiangxi Province range from 74.8 to 108.7 times [30]. Seed treatments of *chlorantraniliprole* just provide 30% control of *C. suppressalis* infestations [31]. Monitoring the development of *C. suppressalis* resistance to *diamide* and *abamectin* insecticides. The *emamectin benzoate* became a key insecticide for the control of this species in China. However, with the widespread use of *emamectin benzoate*, resistance has developed rapidly in some field populations of *C. suppressalis* [26]. In the present investigation, the chemical combination *emamectin benzoate · methoxyfenozide + chlorantraniliprole* retains the lowest withered heart rate in rice fields, with the control effect reaching 90.05%. This superior performance is likely attributed to the synergistic action of the ingredients The *chlorantraniliprole* and *emamectin benzoate* target the insect's muscular and nervous systems, respectively, while *methoxyfenozide* acts as a molting hormone agonist to disrupt development. This coordinated, multi-target approach not onlyensures rapid control but also helps delay the evolution of resistance.

The decision-making process, therefore, could be strengthened following this workflow: 1) Monitoring: Regular collection of temperature, humidity, and adult pest counts. 2) Analysis: Compare current environmental data and pest numbers to established thresholds. 3) Action: Scheduling insecticide application at the optimal time (shortly before peak emergence) if thresholds are met; and 4) Evaluation: Assessing efficacy to adjust future strategies. Integrating these steps into a practical pest management calendar, as supported by Cui et al. [24], enables farmers to make informed decisions based on real-time cues. By optimizing insecticide timing to coincide with peak adult emergence and utilizing synergistic chemical combinations, this strategy contributes significantly to sustainable rice pest management.

5 Conclusion

Effective management of *C. suppressalis* during rice cultivation hinges on the precise timing of interventions. This requires dynamic monitoring to apply treatments before the peak of adult infestation. While cultural practices like deep tillage and post-harvest irrigation contribute to reducing overwintering pest populations, our study specifically demonstrates the efficacy of a targeted chemical strategy. The combined application of *emamectin benzoate·methoxyfenozide + chlorantraniliprole*, timed just before July 1st in the Songjiang region, effectively controlled *C. suppressalis* populations. This approach led to a significant rice yield increase of over 27.95%, minimized the withered heart rate, and allowed for a 50% reduction in pesticide usage compared to conventional methods. Economically, this strategy resulted in an additional income of 4796.15 CNY per hectare while halving pesticide costs, highlighting its potential to enhance profitability and mitigate environmental impact. In line with the principles of green agriculture, future research should focus on optimizing this integrated approach and validating the adaptability of this strategy across different rice-growing regions with varying ecological conditions.

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Availability of Data and Materials: We confirm that the data is available within the article or its Supplementary Materials.

Ethics Approval: Not Applicable.

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Supplementary Materials: The supplementary material is available online at https://www.techscience.com/doi/10.32604/phyton.2026.075709/s1. Figure S1: The intelligent insect monitoring and reporting system. Table S1: The registration and manufacturing details of insecticides used.

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