agriculture

MDPI

Article

Design of and Experimentation with a Suction-Based Pest-Capture Machine for the Tea Pest *Empoasca vitis*

Yu Han [1,*], Zhiyu Song [1], Wenyu Yi [2] and Caixue Zhan [1]

[1] Nanjing Institute of Agricultural Mechanization, Ministry of Agricultural and Rural Affairs, Nanjing 210014, China
[2] Key Laboratory of Agricultural Equipment Technology for Hilly and Mountainous Areas, Ministry of Agriculture and Rural Affairs, Chengdu 610066, China
* Correspondence: hanyu@caas.cn

Abstract: To investigate an effective physical pest control method for tea trees, we designed and manufactured a suction-based pest-capture machine (hereafter labeled the "pest vacuum") and conducted a test and field experiment to evaluate its effectiveness in the control of *Empoasca vitis* Göthe (*E. vitis*). Based on the proposed model, the minimum practical air velocity of the pest vacuum was 5.85 m s^{-1}. The field experiment included two treatments and a blank control. In treatment 1, we used the pest vacuum along tea trees only once, while in treatment 2, the pest vacuum was used along trees twice, separately, in 2 consecutive periods, and with an interval of more than 30 min. The results show that a highly significant difference arose among the dropping rates of the two treatments and the blank control instantly after suction, a significant difference among the dropping rates 7 days later, and no significant difference 14 days later. The dropping rate and the effective rate of prevention of treatment 2 reached 81.87% and 80.60% instantly after suction. Moreover, the effective rate of prevention of nymphs was slightly higher than that of adults. Overall, the pest vacuum had a prominent, albeit short-term, effect on the control of *E. vitis*. Seven days after the suction, it is better to repeat the suction five days after the first suction. The pest vacuum provides a valid physical method for pest control, so more attention should be paid in future investigations to reducing the weight and working noise of the pest vacuum.

Keywords: pest control; tea garden; modeling; design; *Empoasca vitis Göthe*; field experiment

check for updates

Citation: Han, Y.; Song, Z.; Yi, W.; Zhan, C. Design of and Experimentation with a Suction-Based Pest-Capture Machine for the Tea Pest *Empoasca vitis*. *Agriculture* **2024**, *14*, 964. https://doi.org/10.3390/agriculture14060964

Academic Editor: Jacopo Bacenetti

Received: 14 December 2023
Revised: 14 May 2024
Accepted: 4 June 2024
Published: 19 June 2024

1. Introduction

Pests pose great risks to agricultural production worldwide. The tea plant, for example, is highly vulnerable to and a common target of the insect pest *Empoasca vitis Göthe* (*E. vitis*). The nymphs and adults of *E. vitis* suck the sap of tender tea shoots, seriously affecting the tea quality and yield [1]. Insect pest control is a vital procedure in the agricultural industry, and its methods include agricultural control, chemical control, biological control, and physical control. Chemical control plays a key role in achieving a high agricultural yield owing to its low cost and effective pest control compared with other methods. However, chemical pest control has an adverse effect on the ecological environment, threatening food security, human health, and environmental safety. Modern physical control technologies break through the traditional patterns of pest control and production, which reduces the application of chemical pesticides and effectively avoids environmental pollution, ensuring ecology and food security, and promoting the economic benefits of agriculture [2]. Thus, physical technology for pest control has become a modern agricultural development trend.

Although chemical pesticide is still the main pest control method, many physical technologies for pest control have been investigated and applied to agriculture, including new physical technologies. Bian et al. [3] applied colored sticky card traps to monitor and capture yellow tea thrips in the garden. Moreover, De Guzman et al. [4] used olfactory cues as visual stimuli to trap the beetle *Aethina tumida* Murray (Coleoptera: Nitidulidae). Marco et al. [5] applied UV LEDs as light sources for trapping macro-moths (Lepidoptera). Salehi et al. [6] used ultrasonic signals to study the Mediterranean flour moth and the repellency and biological effects of various ultrasonic signals with different frequencies and wave shapes on adults, larvae, and pupae of the pest. They found that ultrasound signals in the frequency range 43–45 kHz and the Sin (x) or Cos (x) wave shape had the greatest deterrent effects on the moths. Keller et al. [7] examined the use of short (<25 ms) laser pulses to kill or disable anesthetized female *Anopheles stephensi* mosquitoes, and the green and far-infrared wavelengths were found to be more effective than the near- and mid-infrared wavelengths. Moreover, Liao et al. [8] used a push–pull inset removal fan to reduce the population quantity of *E. vitis*. Xiang et al. [9] reported that bud green, olive green, and yellow boards had a significant trapping effect on the larvae and nymphs of *E. vitis*. As reported by Luo et al. [10], black light, electric light, and a frequency trembler grid lamp could be used to effectively trap tea pests. Mazzoni V. et al. [11] conducted dynamic analyses for the optimization of a pest control system based on vibrations.

In addition, the application of computer vision and artificial intelligent technologies in pest management has been investigated more in recent years. Image-processing and CNN technologies have been widely used in pest recognition. For example, Wen et al. [12] investigated the image recognition of navel orange diseases and insect pests based on compensatory fuzzy neural networks. Wu et al. [13] used the SVM method to classify leaf-miner-infected leaves. In addition, Wu et al. [14] constructed a visualization domain-specific knowledge graph of crop diseases and pest fields with deep-learning technology. Wen et al. [15] conducted multi-fractal analysis of Fourier transform spectra to recognize citrus fruit insects. Zhao et al. [16] investigated an image recognition method for cotton pests based on transfer learning. Wang et al. [17] forecasted a cotton pest disaster with an adaptive discriminant deep-belief network. Furthermore, Zhao et al. [18] established a pest information collection system for cotton based on mobile GIS. Zhou et al. [19] investigated an electronic nose for cotton pest detection. Yao et al. [20] have designed an image collection and diagnosis system for agricultural diseases and pests with distributed and mobile devices. Hadipour-Rokni, R., et al. [21] detected the citrus fruit pests using a machine vision system and convolutional neural network through the transfer-learning technique.

Although widely used, the abovementioned physical technologies for pest control cannot be applied in all situations; for example, they cannot be effectively used in capturing *E. vitis* and tea geometrids, the main pests in tea gardens. Similarly, the application of computer vision and artificial intelligent technologies in pest management is still in the research stage.

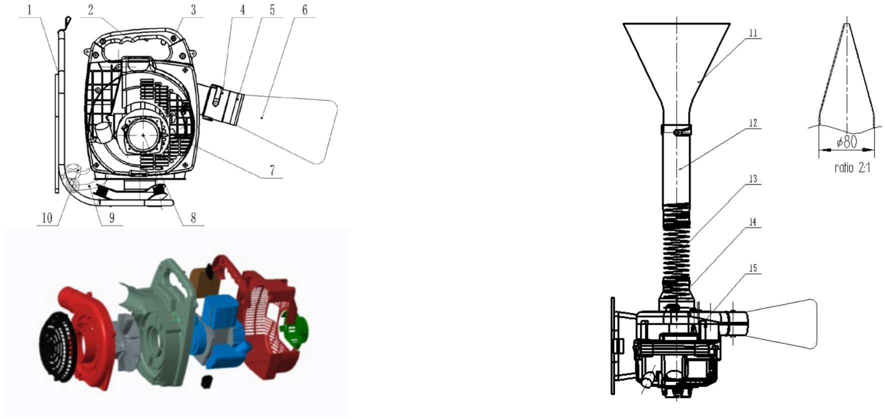
Therefore, the objective of this study was to design a pest vacuum with a negative-pressure fan to control *E. vitis* in a tea garden. The rest of this paper is structured as follows. First, the structure and principles of the pest vacuum are introduced in Section 2. Section 3 details the parameter test carried out. In Section 4, the method and procedures for a field experiment in a tea garden are introduced. In Section 5, the results are provided and analyzed. Section 6 provides a discussion and conclusion.

2. The Principle and Structure of the Pest Vacuum

2.1. Structure and Principle

The main principle of the proposed insect-trapping device is vacuum adsorption, and its main component is a spiral flow fan by which a vacuum space is formed. The vacuum produces suction to capture the pests.

As shown in Figure 1, the pest vacuum mainly comprises a gasoline engine (power: 2.8 kW), a spiral flow fan (power: 800 W), a piece of housing, a suction port, and a vent. The suction port is coaxial with the fan, and the vent is tangent to the outline of the fan. Connected to the suction port is a flexible pipe. The suction port starts off circular and tends to become oblate at the end, where the flow pressure increases dramatically.



(**a**) (**b**)

Figure 1. The structure of the pest vacuum. Note: 1 back rack, 2 handlebar, 3 flame rollout switch, 4 vent connector, 5 lathe dog, 6 collection bags, 7 housing, 8 gasoline engine, 9 accelerator flexible shaft, 10 accelerator switch, 11 suction port, 12 suction pipe, 13 flexible suction pipe, 14 connection pipe, 15 top cover. (**a**): Front view; and (**b**): vertical view.

The principle of this pest vacuum is as follows. (1) When the fan blades spin at high speed, the air in the fan cavity is compressed and pushed out via the vent, and a negative pressure cavity is produced in the fan cavity. (2) Because of the differential pressure between the fan, which links to the air outside with the suction port, wind forms from outside to inside, which exerts a suction force on the target pest. (3) The pest collides with the high-speed spinning fan blades after being sucked into the fan, dying in the collision owing to the impact force. (4) The killed pest is then flushed out through the vent to the mesh bag, terminating the process.

2.2. Suction Mechanism

No relevant research has been performed on the aerodynamic behavior of the *E. vitis*'s flight. The force between the *E. vitis* and the tea surface is difficult to quantify, so the calculation of the suction force, by which the *E. vitis* is sucked into the fan inside the machine, is simplified here. We take the *E. vitis* as a particle, in which the reaction force between the *E. vitis* and the tea leaf is neglected. Hence, the *E. vitis* is subjected to gravity and the suction force during suction. If only the suction force is greater than the gravity, the *E. vitis*'s suction will be successful. Therefore, the suspended velocity of the *E. vitis* can be calculated as follows:

$$v_t = \sqrt{\frac{2m_{max}g}{C_d \rho S_i}} \tag{1}$$

where m_{max} is the maximum mass of the *E. vitis*, kg; g is the gravity acceleration, m s^{-2}; C_d is a constant resistance, N; ρ is the air density, kg/m^3; and S_i is the maximum projection area of the *E. vitis* along the flight direction.

In practice, the air velocity should be extended with the air coefficient, yielding the practical velocity that the pest vacuum should have:

$$v = kv_t \tag{2}$$

where k is the air velocity coefficient, and its value is 1.2, as in Wang's work [22]. Other parameters were determined with some tests, as shown in Table 1. The weight was tested directly, and the maximum projection area was calculated based on the size and the structure of the *E. vitis*.

Table 1. Main aerodynamic parameters.

Parameters	m_{max}/kg	g/(m s^{-2})	C_d	k	ρ/kg m^{-3}	S_i/m^2
Value	3.4×10^{-5}	9.8	0.6	1.2	1.3	1.8×10^{-5}

While the pest vacuum was working, the *E. vitis* would be disturbed and fly; hence, these pests were sucked in the flying state. Therefore, the maximum projected area is defined as the area projected vertically from the back of the small green leafhopper when its wings are fully opened. The calculating model is shown in Figure 2, where the main body structure parameters are the head diameter and body length (i.e., d and h). The main parts of the *E. vitis* that affect the projection are the body and wings. Here, we assume that the wing has approximately the same area as the body and that they are simplified as rectangular with the width of the head diameter (d) and the length of the body length (h). Therefore, the whole area can be calculated as the model shown in Figure 2d, which models the area as a rectangle with a width and length of three times d and h, respectively. The amateur *E. vitis*, through testing, yielded d = 2 mm, h = 3 mm. Consequently, the whole projected area is 1.8×10^{-5} m^2.

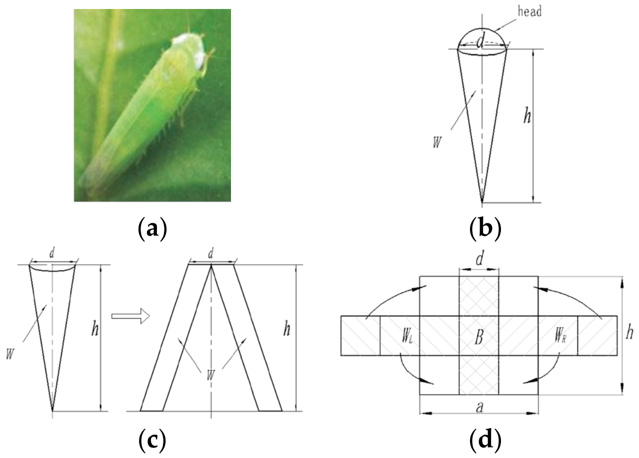


Figure 2. Projection area model. Note: W denotes the wing, h denotes the body length, d denotes the head diameter, B denotes the body, W_L and W_R denote the left and the right wing, respectively, and a denotes the side length of the equivalent rectangle. (**a**): *E. vitis*; (**b**): *E. vitis* model; (**c**): wing model; and (**d**): calculating model.

Therefore, the practical air velocity can be calculated from Equations (1) to (2) with those parameters, yielding $v = 1.2 \times 4.875 = 5.85$ m/s. That is, the minimum air velocity should be more than 5.85 m/s so that the *E. vitis* can be captured.

3. Test for Parameters

The main parameters of the pest vacuum are the pressure, flow velocity, and noise, which have a direct effect on both pest control and use comfort. Therefore, it was necessary to test these parameters of the pest vacuum to assess whether they meet the design requirements and to then comprehensively choose one set of optimal parameters. All these parameters were decided by opening the accelerator, so the set of optimal parameters corresponded to an optimal accelerator opening. The ranges of the three parameters were tested under three states of accelerator opening: maximum, median, and minimum.

3.1. The Pressure Test

The suction force for pests is mainly decided by the pressure. Theoretically, the higher the pressure, the better the pest control effect, but high pressure can also damage the tea shoot. Thus, the pressure cannot be too large for a vacuum. We set out to determine the optimal value. We tested the pressure in the laboratory with a mini pressure measure apparatus, which has a mini wind tunnel (diameter: φ80 mm) and a U-shaped pipe, from which we read the pressure value (see Figure 3). The procedure was as follows: (1) connect the suction port of the pest vacuum to the entrance of the mini wind tunnel, (2) fill the transparent U-shaped pipe with room-temperature water, (3) start the pest vacuum, and (4) read the pressure from the dial gauge when the engine starts to run normally. The pressure test was conducted under three states of the accelerator of the engine: maximum, median, and minimum. The result is shown in Table 2. The differential pressure was 2050 Pa when the accelerator was set to the maximum, while it changed to 1400 Pa when the accelerator was set to the minimum.

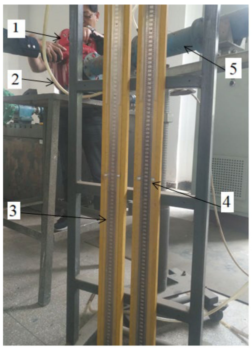


Figure 3. Pressure test. Note: 1 denotes the pest vacuum, 2 denotes the air hose, 3 denotes the U-shaped tube for reading static pressure, 4 denotes the U-shaped pipe for reading differential pressure, and 5 denotes the pipe fitted with a Venturi nozzle, which is connected to the export of the pest vacuum.

Table 2. Main functional parameters of the pest vacuum.

States of Accelerator	Differential Pressure/Pa	Static Pressure/Pa	Flow Speed/m/s	Noise/dB
Maximum	8310/6260	7050/6280	7.7	81
Median	8210/6060	7750/6990	6. 2	70
Minimum	7980/6580	7640/6770	3.5	62
Mean	8167/6300	7480/6680	5.8	71

Based on the test date, we recommend the median opening of the throat as a moderate parameter value while working.

3.2. Flow Velocity Test

The flow velocity is proportional to the pressure once the diameter of the vent has been designed. We tested the flow velocity with a portable anemograph under three states of the accelerator of the engine. We positioned the anemograph 10 cm away from the flow outlet. The result is shown in Table 1. The maximum flow velocity was 7.7 m s^{-2} when the accelerator was set to the maximum value, the minimal flow velocity was 3.5 m s^{-2} when the accelerator was set to the minimum value, and the medium one was 6.2 m s^{-2} when the accelerator was set to the middle position. While the accelerator was set to the middle position, the pest vacuum would work.

3.3. Noise Test

Noise is one of the main indexes for agricultural machinery. It should be under 90 dB, which is the upper limit of the safe noise scope for users, according to the provisions of agricultural machinery standards. Therefore, the noise was tested with a portable noise meter. We tested the noise from four positions separately: front, back, left, and right of the pest vacuum. Moreover, the noise meter was positioned 1 m away from the center of the pest vacuum. The result is shown in Table 2. The maximum noise was 81 dB when the accelerator was set to the maximum, while the minimum noise was 62 dB when the accelerator was set to the minimum.

4. Experiment

The field experiment for pest control was conducted with two treatments and a blank control separately in a tea garden in June 2023. The three treatments were the same as in the test experiment. The target pest was *E. vitis*.

4.1. Pest Vacuum Parameters

The pest vacuum's main technical parameters include the physical size, weight, and working performance. All these parameters are shown in Table 3.

Table 3. Main technical parameters of the pest vacuum.

Engine	Four-Stroke Gasoline Engine/KM139F
Breadth (mm)	300
Size (mm)	500 × 400 × 400
Width of suction port's end edge (mm)	250
Diameter of the suction pipe (mm)	110
Weight (kg)	6.5
Working performance (hectare/h)	0.2–0.33

4.2. Experimental Plot

A mature tea garden was chosen as the experimental field, which is located in Jurong City, Jiangsu Province. The tea trees are ten years old and planted in strips. To test exactly how the pest vacuum works, no other pest control measures were applied to the garden.

4.3. Pest Counting Method

Here, we adopted the tap-basin method that was widely used in plant protection experiments [23]. To be specific, a basin was placed underneath the crown and the crown was tapped three times with the hand [24]. Then, the number of *E. vitis* specimens remaining in the basin was counted as soon as possible. It was better to use a counter to avoid miscounting numbers. Also, a bright light was needed when the test was conducted near or in the evening.

4.4. Experimental Region

Three experimental plots were marked in the selected tea garden, to which two treatments and a blank control were applied. Every experimental plot included at least 10 tea tree rows, each 30 m long. Three tea tree rows existed between each plot, which were taken as a barrier strip to diminish the mutual effects between adjacent plots.

4.5. Experimental Treatment

The experiment included two treatments and a blank control, denoted as treatment 1, treatment 2, and blank. In treatment 1, the insect catching was carried out on the plot with the pest vacuum just once. Two appropriate periods were employed to implement the experiment. The first one was in the early morning, after the dew had dried up; the other one was at dusk. *E. vitis* is active during these periods, which is beneficial to insect catching. During suction, the suction port scanned the whole surface of the tea tree's canopy (see Figure 4) in sequence at a speed of 0.3 m/s, the top first and then the side face. The distance between the suction port and tea leaf had to be less than 3 cm. It is better to suck while slapping the tea tree crown with the other hand in order to dislodge the pest from the crown, which is good for catching pests. In treatment 2, the insect catching was carried out twice, separately, in two consecutive appropriate periods. If the first insect catching had been fulfilled in the morning, then the second one was performed at dusk; otherwise, if the first insect catching had been fulfilled at dusk, then the second one was performed the next morning. The procedure and technical requirements for suction operation are the same as in treatment 1. No pest control measure was applied to the blank control plot. The experiments for all the treatments were conducted in the same period. Each treatment plot was labeled for later statistical purposes.

Figure 4. Field experiment.

4.6. Data Acquisition

We chose five random test sites in every plot, and we counted the quantity of *E. vitis* repeatedly on each chosen site from three different random points. The counting was conducted four times in total. The first counting was conducted before suction to survey the population base of *E. vitis*; the second one, as soon as possible after suction (after the second suction in treatment 2); the third one, 7 days after the last suction; the fourth one, 14 days after the treatments.

4.7. Data Processing

Taking the initial data (population quantity) into Equations (3) and (4) separately, we could obtain a yield-dropping rate of *E. vitis* and a revised effective rate of preventing *E. vitis* on the tea leaf:

$$D = \frac{B - N}{B} \times 100\% \quad (3)$$

where D denotes the dropping rate of E. vitis, B denotes the population base of E. vitis, and N denotes the counted population quantity at the site after prevention and control.

$$E = \frac{N_c \times B_d}{N_d \times B_c} \times 100\% \quad (4)$$

where E denotes the revised effective rate of prevention, N_c denotes the counted population quantity in the treatment plot after prevention and control; N_d denotes the counted population quantity in the blank control plot after the prevention and control on the treatment plot being conducted; B_c denotes the population base of E. vitis in the treatment plot; and B_d denotes the population base of E. vitis in the blank control plot.

5. Results

To study the control effects of the pest vacuum and determine the proper usage, the experiment was carried out from 18 July to 3 August 2023 in a tea garden in Ju Rong City, Jiangsu, China. According to the procedure and methods mentioned in Section 4, the experiment data were acquired (Table 4). In the experiment, adult *E. vitis* and nymphs were counted individually.

Table 4. Experimental data.

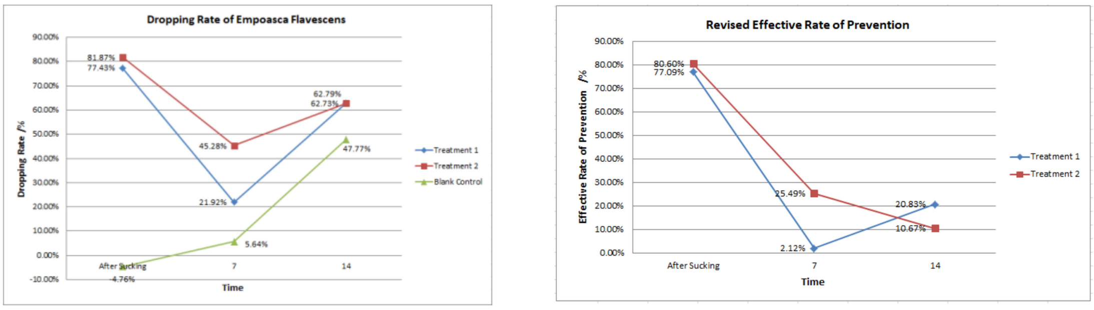
Treatment	Site	Repetition	Population Base		Population Quantity in the Site after Prevention and Control					
					After Suction		7 d		14 d	
			Adult	Nymph	Adult	Nymph	Adult	Nymph	Adult	Nymph
Treatment 1	1	1	13	6	3	0	13	2	7	1
		2	14	13	2	0	6	0	6	2
		3	12	9	5	2	8	1	6	1
	2	1	12	7	4	1	7	3	5	1
		2	14	6	5	1	12	5	6	0
		3	9	5	7	0	13	2	3	3
	3	1	8	10	2	2	6	9	8	1
		2	16	9	2	0	8	5	9	1
		3	10	6	3	0	24	4	16	1
	4	1	19	7	2	1	19	5	7	0
		2	14	6	1	1	15	5	6	2
		3	13	4	3	2	19	2	2	1
	5	1	11	4	3	2	4	3	3	2
		2	12	7	4	3	11	1	4	0
		3	23	5	5	1	9	4	4	0
	Mean		13.33	6.93	3.4	1.07	11.6	3.4	6.13	1.07
Treatment 2	1	1	12	7	2	2	5	1	2	0
		2	13	5	2	0	5	0	5	1
		3	11	9	3	0	3	0	4	1
	2	1	12	6	5	1	15	2	6	1
		2	14	7	3	8	14	1	7	1
		3	11	5	2	0	4	2	2	0
	3	1	11	4	2	0	10	4	4	0
		2	13	6	4	1	10	8	10	1
		3	10	8	1	1	17	3	9	0
	4	1	14	5	2	1	6	2	3	1
		2	15	4	2	3	6	3	4	1
		3	12	7	1	0	5	1	12	0
	5	1	16	8	1	0	6	4	14	3
		2	13	6	1	0	6	4	6	0
		3	14	7	3	1	6	0	10	1
	Mean		12.73	6.26	2.27	1.2	7.87	2. 3	6.53	0.73
Blank control	1	1	13	4	8	3	6	2	10	0
		2	8	5	8	2	7	3	4	0
		3	9	3	11	2	5	2	3	0
	2	1	8	3	11	3	16	6	4	0
		2	8	6	8	3	8	2	4	3
		3	8	4	12	2	15	5	6	1
	3	1	11	3	7	7	4	4	18	3
		2	11	2	12	1	2	2	3	1
		3	15	2	9	3	20	7	12	2
	4	1	13	4	12	4	13	7	8	2
		2	14	5	10	6	17	4	6	1
		3	13	6	16	2	9	2	8	0
	5	1	14	8	12	5	12	4	8	0
		2	15	4	11	7	14	3	6	1
		3	10	2	25	9	9	3	6	0
	Mean		11.33	4.06	11.47	3.93	10.47	3.73	7.07	0.93

Based on the experiment data, both the dropping rate and the effective rate of prevention could reach a high level and then decrease. As shown in Table 5, a highly significant difference was observed among the dropping rates of the two treatments and the blank control instantly after suction, a significant difference was seen among the rates 7 days later, and no significant difference was seen 14 days later. It can be seen from Figure 5a that the dropping rate of treatment 1 and treatment 2 reached 77.43% and 81.87%, respectively, instantly after suction; they decreased to 21.92% and 45.28% 7 days later, but they rebounded to 62.79% and 62.73% after 14 days. Thus, the effect of treatment 2 was better. Its dropping rate was only 13%–17% less than that of the chemical control (3% acetamiprid *EC* 1 500-times dilution) compared with the test results from Xu et al. [25], 3.75% higher than the push–pull inset removal fan (physical control) compared with the test results of Liao et al. [8], and 26.27% less than that of yellow boards (physical control) compared with the test results of Xiang et al. [9]. From Figure 5b, we can also see that the effective rate of prevention of treatment 1 and treatment 2 reached 77.09% and 80.60%, respectively, instantly after suction, and then the rates decreased sharply to 2.12% and 25.49% 7 days later. The control effective rate of prevention in treatment 2 was 30% higher than that of strain LL27 (biological control) compared with the results of the field test conducted by Zhan [26].

Table 5. Variance analysis of the dropping rate.

The Dropping Rate		SS	DF	MS	F	*p*
The dropping rate after suction	Between column	7.140	2	3.570	34.779	0.000
	Interclass	4.311	42	0.103		
	Total	11.452	44			
The dropping rate 7 days later	Between column	1.191	2	0.595	3.742	0.032
	Interclass	6.683	42	0.159		
	Total	7.874	44			
The dropping rate 14 days later	Between column	.225	2	0.112	1.930	0.158
	Interclass	2.443	42	0.058		
	Total	2.667	44			

Note: The level of probability of a significant difference $p < 5\%$.



(**a**) (**b**)

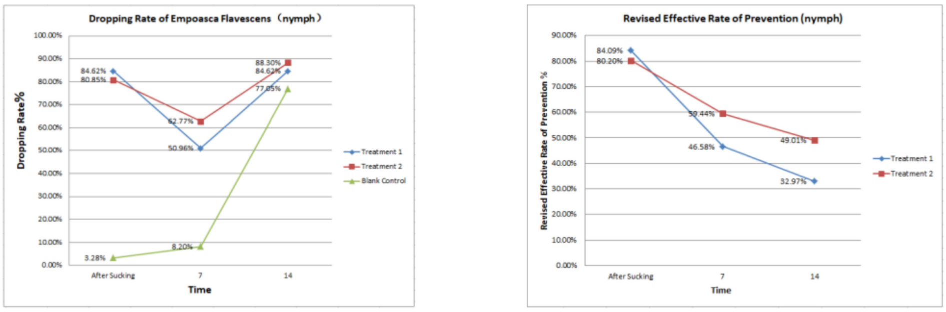
Figure 5. Prevention and control effect of *E. vitis*. (**a**): The dropping rate of *E. vitis*. (**b**) The revised effective rate of prevention.

To investigate the control effect on nymphs, we conducted an analysis confined to nymphs. Similarly, a high significant difference among the dropping rates of the two treatments and the blank control instantly after suction, a significant difference among the rates 7 days later, and no significant difference in rates 14 days later were observed, as shown in Table 6. It can be seen from Figure 6a that the dropping rate of treatment 1 and treatment 2 reached 84.62% and 80.85%, respectively, instantly after suction; it decreased to 50.96% and 62.77% 7 days later. However, it rebounded to 84.62% and 88.30% after 14 days, for a natural decline. From Figure 6b, the effective rate of prevention of treatment 1 and treatment 2 reached 84.09% and 80.20%, respectively, instantly after suction; then, it decreased sharply to 46.58% and 59.44% after 7 days. Comparing Figure 6a,b with Figure 5a,b, both the dropping rate and the effective prevention rate of nymphs were slightly higher than those of adults.

Table 6. Variance analysis of the dropping rate (nymph).

The Dropping Rate		SS	DF	MS	F	*p*
The dropping rate after suction	Between column	9.651	2	4.826	11.113	0.000
	Interclass	18.237	42	0.434		
	Total	27.888	44			
The dropping rate 7 days later	Between column	1.191	2	0.595	3.742	0.032
	Interclass	6.683	42	0.159		
	Total	7.874	44			
The dropping rate 14 days later	Between column	0.225	2	0.112	1.930	0.158
	Interclass	2.443	42	0.058		
	Total	2.667	44			

Note: The level of probability of a significant difference $p < 5\%$.



(**a**) (**b**)

Figure 6. Prevention and control effect for *E. vitis* (nymph). (**a**): The dropping rate of *E. vitis* (nymphs). (**b**): The revised effective rate of prevention (nymphs).

The above results show that the pest vacuum had a very good effect on the control of *E. vitis*, with the dropping rate instantly after suction exceeding 80%.

6. Discussion and Conclusions

The above results show that the pest vacuum had a prominent effect on the control of *E. vitis*; the dropping rate instantly after suction exceeded 80%, although it decreased afterward. The facts show that our simplification and assumption of the suction force are reasonable and effective.

Although the pest vacuum could not achieve an effect as good as that of chemical control, it was more effective than agricultural, biological, and traditional physical control methods, such as insect-attracting boards and frequency trembler grid lamps. Different from pesticides' long-lasting killing, our control method only killed pests while the pest vacuum was working. Then, the uncaptured pests might multiply and the pests from an adjacent area might migrate to this experimental plot, leading to a decrease in the dropping rate. The revised effective rate of prevention decreased from 80.6% instantly after suction to 25.49% 7 days later.

Furthermore, the pest vacuum had a more prominent effect on the control of *E. vitis* nymphs. The maximum of the dropping rate instantly after suction reached 84.62% and increased by 3.25% compared with the general dropping rate of *E. vitis*. Moreover, 7 days after the suction, the maximum of the dropping rate could still reach 62.77%, which is 17.49% higher than the general dropping rate. The revised effective rate of prevention of nymphs declined but still remained at 59.44% 7 days later, which is 33.95% higher than the general dropping rate. The reason for this phenomenon may be that some adult *E. vitis* were disturbed and thus fled to the adjacent plot area while the pest vacuum was working. Then, the captured pests included some adult pests and most pests. After suction, the adult pests from an adjacent area migrated gradually back, so the adult *E. vitis* quantity began to increase. Still, they could not multiply in a short period, so the nymph quantity remained low.

The results indicate that the pest vacuum had a prominent effect on the control of *E. vitis* but that this control was short-term. Seven days after the suction, the revised effective rate of prevention can be expected to decrease sharply to about 25%. Therefore, it is better to perform suction again 5 days after the first suction.

Based on the experiment, we found that the pest vacuum's pressure and flow velocity should be limited. Although it is true that the higher the pressure and flow velocity, the more insects are captured, the tender tea shoots tend to be destroyed when the flow velocity exceeds 10 m/s. In addition, not all the insects should be wiped out, some of which are beneficial for tea trees for they are fed on some pests. It is one of the reasons that the flow speed and vacuum pressure were limited to a certain scope. The pest vacuum only has to act on the pests that have the same body shape and flight characteristics as *E. vitis*. Although *Agelena Labyrinth*, the natural enemy of *E. vitis*, is about the same size as *E. vitis*, it cannot fly; therefore, the machine has little effect on this natural enemy.

Another factor affecting the performance of the machine is the noise from the engine. Firstly, the noise would disturb pests, driving them to fly into the air. This phenomenon affects the machine in two opposite ways. On the one hand, the moderate noise makes it easy for the machine to capture pests, because the pests flying in the air are easier to catch. On the other hand, if the noise is too loud, the pests would fly in advance of the machine arriving, resulting in no pests being left for capture. Secondly, the operator's tolerance to noise should be taken into consideration. It is harmful to human health to be exposed to too much noise for a long period. Therefore, it is wise to choose a proper engine for the pest vacuum. We found that a compromise noise value should be confined to the range of 5080 dB.

In this research, an effective pest vacuum was investigated to provide a valid physical method for pest control, although the pest vacuum has two limitations. First, the pest vacuum should be behind the operator's back while working, which involves intensive labor, especially after a long operating routine. Second, the pest vacuum's working noise is relatively high, which may make the operator uneasy after several hours and also has a bad effect on the capture effect. Fortunately, these two limitations are solvable, although they should be paid more attention in future investigations.

Author Contributions: Validation, Z.S. and C.Z.; Investigation, W.Y.; Writing—original draft, Y.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Research Program: the National Key Research and Development Plan (Grant No. 2016YFD0200902); the Modern Agricultural Technology System of Tea Industry (Grant No. CARS-19, China); and the open subject from Key Laboratory of Agricultural Equipment Technology for Hilly and Mountainous Areas (Grant No. 2022KLOP04, China); The Supported by a grant from Key Laboratory for Crop Production and Smart Agriculture of Yunnan Province (Grant No. 2023ZHNY06).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding authors.

Acknowledgments: We thank Jiangsu Vocational and Technical College of Agriculture and Forestry for providing the experimental tea garden for us, and thank Lilin Chen From Fujian Agriculture and Forestry University for helping us test the weight of *E. vitis*.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Cai, X.; Luo, Z.; Meng, Z.; Liu, Y.; Chu, B.; Bian, L.; Li, Z.; Xin, Z.; Chen, Z. Primary screening and application of repellent plant volatiles to control tea leafhopper, *Empoasca onukii* Matsuda. *Pest Manag. Sci.* **2020**, *76*, 1304–1312. [CrossRef] [PubMed]
2. Li, J.G.; Li, B.; Zhang, W.Q. Modern Physics Prevention for Diseases and Pests in Agriculture and Forestry New Development Trend of Green Plant Protection. *Agric. Eng.* **2012**, *2*, 5–7.
3. Bian, L.; Yang, P.X.; Yao, Y.J.; Luo, Z.X.; Cai, X.M.; Chen, Z.M. Effect of Trap Color, Height, and Orientation on the Capture of Yellow and Stick Tea Thrips (Thysanoptera: Thripidae) and Nontarget Insects in Tea Gardens. *J. Econ. Entomol.* **2016**, *109*, 1241–1248. [CrossRef] [PubMed]
4. De, G.L.I.; Frake, A.M.; Rinderer, T.E.; Arbogast, R.T. Effect of height and color on the efficiency of pole traps for *Aethina tumida* (Coleoptera: Nitidulidae). *J. Econ. Entomol.* **2011**, *104*, 26–31.
5. Marco, I.; Gunnar, B.; Carlo, D.M.; Stefano, S. Assessing the efficiency of UV LEDs as light sources for sampling the diversity of macro-moths (Lepidoptera). *Eur. J. Entomol.* **2017**, *114*, 25–33.
6. Salehi, S.S.; Rajabpour, A.; Rasekh, A.; Farkhari, M. Repellency and some biological effects of different ultrasonic waves on Mediterranean flour moth, *Ephestia kuehniella* (Zeller) (Lepidoptera: Pyralidae). *J. Stored Prod. Res.* **2016**, *69*, 14–21. [CrossRef]
7. Keller, M.D.; Leahy, D.J.; Norton, B.J.; Johanson, T.; Mullen, E.R.; Marvit, M.; Makagon, A. Laser induced mortality of *Anopheles stephensi* mosquitoes. *Sci. Rep.* **2016**, *6*, 20–27. [CrossRef] [PubMed]
8. Liao, D.Q.; Huang, S.C.; Wei, L.M.; Xiong, W.J. Control effect of *Empoasca vitis* (Gothe) by wind force insect-killing machine. *China Plant Prot.* **2009**, *29*, 29–31. (In Chinese)
9. Xiang, T.H.; Han, B.Y.; Zhou, X.G. A survey on the trapping effect of four types of coloured sticky plates on various species of insects in tea gardens. *J. Tea Sci.* **2007**, *27*, 253–258. (In Chinese)
10. Luo, X.M.; Li, S.H.; Ren, Q.; Luo, W.; Tang, Y. Applying frequency-vibrancy pest-killing lamp in tea gardens in hilly region. *Hunan Agric. Sci.* **2006**, *5*, 86–88. (In Chinese)
11. Mazzoni, V.; Berardo, A. Dynamic analyzes for the optimization of a pest control system based on vibrations. In Proceedings of the ICE 2022: XXVI International Congress of Entomology: Entomology for Our Planet, Helsinki, Finland, 17–22 July 2022; p. 510.
12. Wen, Z.Y.; Cao, L.P. Image recognition of navel orange diseases and insect pests based on compensatory fuzzy neural networks. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2012**, *28*, 152–157.
13. Wu, D.K.; Xie, C.Y.; Ma, C.W. The SVM classification leafminer-infected leaves based on fractal dimension. In Proceedings of the 2008 International Conference on Computational Intelligence and Security, Chengdu, China, 21–24 September 2008; pp. 147–151.
14. Wu, S.S.; Zhou, A.L.; Xie, N.F.; Liang, X.H.; Wang, H.J.; Li, X.Y.; Chen, G.P. Construction of visualization domain-specific knowledge graph of crops diseases and pests field based on deep learning technology. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2020**, *36*, 177–185.
15. Wen, Z.Y.; Cao, L.P. Citrus fruits diseases and insect pest recognition based on multifractal analysis of Fourier transform spectra. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2013**, *29*, 159–165.
16. Zhao, L.X.; Hou, F.D.; Lv, Z.C.; Zhu, H.C.; Ding, X.L. Image recognition of cotton leaf diseases and pests based on transfer learning. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2020**, *36*, 184–191.
17. Wang, X.F.; Zhang, C.L.; Zhang, S.W.; Zhu, Y.H. Forecasting of cotton diseases and pests based on adaptive discriminant deep belief network. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2018**, *34*, 157–164.
18. Zhao, Q.Z.; Jin, G.C.; Zhou, W.J.; Wang, C.J.; Dai, J.G. Information collection system for diseases and pests in cotton field based on mobile GIS. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2015**, *31*, 183–190.
19. Zhou, B.; Dai, Y.T.; Li, C.; Wang, J. Electronic nose for detection of cotton pests at the flowering stage. *Trans. Chin. Soc. Agric. Eng.* **2020**, *36*, 194–200.
20. Yao, Q.; Zhang, C.; Wang, Z.; Yang, B.J.; Tang, J. Design and experiment of agricultural diseases and pest image collection and diagnosis system with distributed and mobile device. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2017**, *33*, 184–191.
21. Hadipour-Rokni, R.; Asli-Ardeh, E.A.; Jahanbakhshi, A.; Sabzi, S. Intelligent detection of citrus fruit pests using machine vision system and convolutional neural network through transfer learning technique. *Comput. Biol. Med.* **2023**, *155*, 106611. [CrossRef]
22. Wang, W.M.; Song, Z.Y.; Xiao, H.R.; Han, Y.; Mei, S.; Ye, T.S. Flow field simulation and parameter optimization of suction cylinder of physical insecticidal machine for tea garden. *J. Chin. Agric. Mech.* **2022**, *41*, 24–29. [CrossRef]
23. Chen, L.L.; Yuan, P.; Pozsgai, G.; Chen, P.; Zhu, H.; You, M.S. The impact of cover crops on the predatory mite *Anystis baccarum* (Acari, Anystidae) and the leafhopper pest *Empoasca onukii* (Hemiptera, Cicadellidae) in a tea plantation. *Pest Manag. Sci.* **2019**, *75*, 3371–3380. [CrossRef] [PubMed]
24. Chen, L.L.; Yuan, P.; You, M.S.; Pozsgai, G.; Ma, X.; Zhu, H.; Yang, G. Cover crops enhance natural enemies while help suppressing pests in a tea plantation. *Ann. Entomol. Soc. Am.* **2019**, *112*, 348–355. [CrossRef]

25. Xu, Z.; Peng, P.; Hou, Y.J.; Hu, X. Field efficacy trials of prevention and cure of 3% Acetamiprid on *Empoasca vitis* (Gothe). *Plant Dr.* **2005**, *18*, 19–20. (In Chinese)
26. Zhan, M.; He, L.; Chen, M.; Wang, B.; Li, Z. Screening for a highly virulent entomogenous fungal strain to Empoasca vitis (Homoptera: Cicadellidae) and its field efficacy. *Chin. J. Biol. Control.* **2012**, *28*, 41–46. (In Chinese)