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Article

Acoustic sensor-based field efficacy evaluation of three different insecticides—Trunk injections against the red palm weevil, *Rhynchophorus ferrugineus*

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Abstract: Red palm weevil (RPW) is one of the major pests that has caused significant losses in date palm production worldwide in recent years. Effective management of RPW is important to minimizing its impact on date palm yields. Conventional techniques utilized to manage RPW have shown minimal effectiveness. The study aimed to evaluate the efficacy of the insecticides Fipronil, Imidacloprid, and Thiamethoxam against RPW by applying a trunk injection technique in naturally infested date palm fields. Additionally, the study monitored the efficacy of the insecticides for ten months post-treatment using an acoustic sensor. After treatment with Fipronil, Imidacloprid, and Thiamethoxam, the mean burst rate impulses from RPW sound activities inside the date palm trunk was reduced, confirming the gradually mortality of RPW. The RPW impulse burst rate was decreased within 1–2 months post-treatment with these insecticides, while it increased in the control treatment. The results reveal that Fipronil reduced the RPW impulse burst rate from 0.50/s on day 0 to 0.07/s after 50 days post-treatment. In comparison, Imidacloprid reduced the RPW impulse burst rate to 0.07/s after 70 days post-treatment, which indicates a low level of infestation. Similarly, Thiamethoxam reduced the impulse burst rate from 0.97/s on day 0 to 0.08/s after 70 days of treatment. After 4 months of insecticide treatments, the RPW impulse burst rate dropped to zero which indicates the complete cessation of the RPW sound activities. The results suggest that a balloon injector may aid in delivering insecticides directly into the date palm trees, reaching the target more effectively. Furthermore, the acoustic sensor proved to be an effective tool for detecting and monitoring RPW activities in date palms.

Keywords: detection; insecticides; acoustic sensor; RPW sound signal; Thiamethoxam; Imidacloprid; Fipronil; palm

1. Introduction

Red palm weevil (RPW), *Rhynchophorus ferrugineus* (Coleoptera: Dryophthoridae), is an exotic and serious pest of coconut palm (*Cocos nucifera* L.). In the countries it invades, this species shows preference for *Phoenix* spp [1]. RPW was first recorded in Saudi Arabia in 1987 in the Al-Qatif region as a pest attacking date palm trees. Since then, it has continued to spread to many regions that cultivate date palms in Saudi Arabia [2]. To date, RPW has been detected in 53 countries, including the United States, the Netherlands, the Antilles, and regions across Asia, Africa, and Europe [3]. In some countries, the presence of RPW have been confirmed through surveys, while in others, there is no information regarding its global distribution [4]. According to reports, RPW attacks 37 species of palm, with date palm, coconut palm, and canary palm being the most common hosts [5]. Date palm trees weaken under heavy infestation, often resulting in unexpected losses, typically preceded by a pronounced tilt of the canopy. RPW are cryptic insects, remaining hidden within the palm tissues [6]. Current management approaches for RPW rely heavily on integrated pest management (IPM) tactics, such as phytosanitation, the use of conventional insecticides, pheromone traps, and bio-control agents. Pesticide application is one of the primary methods for controlling RPW [7]. Many insecticides, including Imidacloprid, Fipronil, Emamectin benzoate, and Deltamethrin, have been tested and evaluated for their efficacy against RPW in both laboratory and field settings [8,9]. For example, Emamectin benzoate has shown a significant difference between control and treatment groups for the larval and pupal stages when observed in the field after cutting the trees, resulting in 86%–100% mortality after 2 months [10]. In a field study, Imidacloprid demonstrated to be an effective insecticide at a concentration of 20 ml/4 L of water per tree applied using soil drench irrigation around the tree trunk, resulting in mortality rates of 61.9% for larvae and 42.6% for adults, after 25 days post-treatment [11]. Various methods can be used to apply insecticides to date palm trees, with trunk injection being one of the alternative methods for delivering insecticides directly into the trunks [12].

As previously reported, using an acoustic sensor to detect insect borers, as well as RPW inside the trunk through natural infestation, has been investigated and monitored acoustically in the field [13–18]. For example, the efficacy of fungi against RPW can be determined by monitoring the RPW sound spectral profile pattern of impulses burst rate, and frequency level [14]. The acoustic sensor used to detect large RPW feeding or movement activity with a specific pattern is produced up of groups of sounds (burst impulses) produced by the larvae, with separated intervals of less than 25 ms (< 25 ms) depicted inside the date palm trunk, as reported [19–21]. The detection of RPW larval activity using an acoustic sensor is very substantial because the size of the larvae, the position of larval activity inside the date palm trunk, and the size of the tree all affect the distinctive spectral profile produced by RPW activities [22]. This study aimed to evaluate the field efficacy of Thiamethoxam, Imidacloprid, and Fipronil insecticides against RPW when applied through trunk injection, in order to determine the most effective insecticide. The most challenging aspect of the present study was evaluating the effectiveness of the insecticides after they were applied to the infested palm trees, as most previous studies assessed effectiveness by cutting down the palm trees. However, in the present study, alternative tools, such as the acoustic sensor TreeVibes, were used to evaluate insecticides under field conditions to avoid cutting trees.

2. Materials and methods

2.1. Date palm orchards and tree selection

The experiment was carried out on RPW-naturally infested date palms in the Huraymila region (25°07'28.4" N 46°07'02.1" E) in Northwest Riyadh, Kingdom of Saudi Arabia. Twelve date palm orchards were scanned using an acoustic sensor (TreeVibes, Chania, GR-73100, Crete, Greece) to detect RPW sound signals (feeding and movement) inside the date palm trees. The infested date palm trees used in this experiment were located in 6 different orchards within an area range of 10 km^2. The infested date palm trees were selected with similar ages (approximately 4–8 years), and medium sizes (height 1–5 meters). In total, 35 infested date palm trees were used in the present study, and the distribution of the selected date palm varieties was as follows: Selaj (1 tree), Fahal (2 trees), Meskani (1 tree), Naboot saif (1 tree) Nebtah (2 trees), Khalas (7 trees), Burhi (9 trees), Munifi (6 trees), Sukari (3 trees), and Halwa (1 tree). For the treatment, we randomly distributed all the varieties. Before beginning the experiment, we gathered information on any past use of chemicals for pest management, and any orchard where chemicals had previously been used was excluded orchard the study. Irrigation techniques and planting density were nearly identical across the orchards where experimental trials were conducted. All the treatments were randomly assigned to palms, taking into account palm height, location, and estimated infestation levels.

Chemical insecticides

The experiment was conducted on three insecticides (Fipronil, Imidacloprid, and Thiamethoxam) commonly used to control RPW. Fiprol (Fipronil) (Delta, Saudi Arabia) is a cyclodiene insecticide that belongs to the phenylpyrazole group, with Fipronil 5% (SC) as the active ingredient: 5-Amino-1-[2,6-dichloro-4-(trifluoromethyl) phenyl]-4-[(trifluoromethyl) sulfinyl]-1H-pyrazole-3-carbonitrile [23]. Confidor (Imidacloprid) (Bayer, Germany) is a systemic insecticide belonging to the neonicotinoid insecticide group. The active ingredient is Imidacloprid 35% (SC): 1-(6-chloro-3-pyridylmethyl)-N-nitroimidazolidin-2-ylideneamine. Actara (Thiamethoxam) (Syngenta, Greensboro, NC, USA) is a systemic insecticide that belongs to the neonicotinoid group, with Thiamethoxam 25% (WG) as the active ingredient: 3-(2-Chloro-thiazol-5-ylmethyl)-5-methyl-(1,3,5) oxadiazinan-4-yldene-N-nitroamine [24].

2.2. Chemical insecticides solution preparation

The doses of insecticides were as follows: Thiamethoxam at 10 g/tree, Fipronil at 11 ml/tree, and Imidacloprid at 20 ml/tree. Each insecticide solution—Thiamethoxam, Fipronil, and Imidacloprid—was prepared by diluting 100 g of Thiamethoxam, 110 ml of Fipronil, and 200 ml of Imidacloprid in 4 liters of distilled water, ensuring thorough mixing as described in references [11,25]. Additionally, distilled water was used as the control treatment. All treatments were stored in plastic containers. To fill each balloon injector (Inject, Cordoba, Spain) with 100 ml insecticide solution, a 20 ml syringe (Henke-Sass, Wolf GmBH, Tuttlingen, Germany) was used, requiring five syringe fills per balloon.

2.3. Application of chemical insecticides

The experiment involved field application and layout of three insecticides, all administered through trunk injection. All treatments were applied through trunk injection. Each treatment included ten replicates, while the control treatment involved five replicates of infested date palm trees, with each tree serving as a replicate. Holes were drilled at a 30-degree angle using an 8 mm diameter drill bit. The drilling followed a spiral pattern around the trunk at 25, 50, 75, and 100 cm above ground level. After drilling, the insecticide solution was injected using a balloon injector (**Figure 1**). Each selected tree received four injections (400 mL/tree), with each injector containing 100 mL of insecticide solution. In contrast, the control treatment was injected with distilled water. All selected date palm trees were injected on the same day.

Figure 1. Depiction of insecticide application on date palm trunks using a special balloon injector.

2.4. Assessment of acoustic sensor: TreeVibes

An acoustic sensor (SN.867584031577203), developed by Insectronics, (Insect Surveillance Technology, GR-73100, Crete, Greece), was used to detect the RPW activity inside the date palm trees. This sensor is designed specifically for the detecting wood-boring insects in tree hosts. Detection relies on vibrations produced inside date palm trees. The sensor is equipped with an SD card, USB port, antenna, and a waveguide adaptor (6 mm × 30.5 cm). It operates on batteries and is also connected to a solar panel for power [26].

2.5. Data collection and acoustic recording

The detection of infested date palm trees was conducted prior to injection using the acoustic sensor TreeVibes at the beginning of the experiment. The mark point for obtaining readings on each date palm tree varied with height. A single hole was drilled into the trunk one meter above the ground, from the base of the tree trunk, and the acoustic sensor was inserted into the hole to capture sound reading data for the entire tree. The 35 cm-long acoustic sensor probe, equipped with an earphone, was inserted into the previously drilled hole. The acoustic sensor was connected to a headphone and used to evaluate the sound signals of RPW activities. The detected sound signals were compared to the typical sounds produced by RPW larvae, specifically the group train 7-199, characterized by 3–30 ms intervals between impulses and < 0.25 s per impulse [19]. Many impulses (vertical spectral lines or "click sound") within and between bursts were likely caused by larvae sliding, scraping, snapping, and their feeding activity on wood fibers inside the tunnel [18,27]. The sound of insects and background noise were analyzed using the Davis program, which revealed distinct spectral profiles between background noise and insect sounds [19]. The sensor can either store data on an SD card or send it directly to the server. The efficacy of the insecticides was monitored daily using the TreeVibes acoustic sensor, recording the sound of RPW and their vibrational activities during feeding and moving inside the trunk. The sensor is capable of detecting RPW sound signals within a range of 2–4 m inside a date palm tree. In this experiment, a 5 m repeating period and a 20 s recording duration were set up [26]. The acoustic sensor was installed in the trunk of each palm tree to capture sound data (**Figure 2**). The sound files were saved in a specific format such as, "F_20210312193118_1.wav," and the recording time for each file was provided. The data was downloaded from an online platform and stored on PC. The Audacity program was then used to convert the sound files from mp3 format into a wave file. The wave files were then analyzed using the Davis program. The same data was transferred to the Davis program for analyzing wave files. The frequency and impulse range of the signal were categorized using DAVIS software, determining if the signal closely matched the known RPW spectral profile. The treated tree eventually recovers and became healthy, demonstrating the sensor's accuracy while eliminating the need to cut down the trees to confirm the results.

Figure 2. The recording of red palm weevil sounds using an acoustic sensor installed inside a date palm tree.

2.6. Signal processing

In order to identify the sound signals caused by RPW activities, the sound files from each recording were analyzed using Raven Pro.1.5, an interactive sound analysis software. Oscillograms and spectrograms were generated, allowing observation of the spectral waveform and impulse burst rate over time. For analysis, the sound waves had to be formatted as waveform audio files (WAV) with 16 pulse code modulation (PCM) and 8 kHz sound rate in Audacity [28]. The Davis program was then used to analyze the sound data. The sound signals produced by RPW larvae inside date palm trees were confirmed through this analysis. By analyzing these insect signals, the Davis program was able to generate precise RPW larval profiles [19].

2.7. Statistical analysis

In this experiment, insecticides (Imidacloprid, Thiamethoxam, and Fipronil) were used as one of the factors. The experiment was carried out using a complete randomized block design (CRBD). Impulse burst rates, rs, were analyzed using SAS software version 9.1. An analysis of variance (ANOVA) was used to determine differences between treatments, and Duncan's multiple range test at $p < 0.05$ was employed to distinguish among the means [29]. The initial infection level for each tree at the start of the infestation was unknown, and additional infestation by RPW may have occurred after treatment. To monitor the success of the treatment, a one-year observation period is necessary, with daily sound recordings for the first three months and monthly recording for the following seven months. This extended monitoring period accounts for the possibility of re-infestation by RPW, even after the tree has shown signs of recovery.

3. Results

Impulse burst rate (rs) of RPW activities within date palm trees after treatment

The results of the impulse burst rate for all treatments are presented for a four-month period, until no burst impulses were recorded across all treatments. Three days post-treatment showed a significant reduction in the mean impulse burst rate of RPW activities in the insecticide-treated date palm trees. Among the three tested insecticides, Imidacloprid was the most effective on day 3 post-treatment, decreasing the mean impulse burst rate from 0.97 to 0.26 (rs). Conversely, Fipronil was the least effective insecticide on day 3 post-treatment, with the mean impulse burst decreasing from 0.50 to 0.21(rs) (**Table 1**). In contrast, the burst rate in the control treatment date palm trees continued to increase up to 7 days (**Table 1**).

For all studied insecticides, the impulse rate consistently decreased until 50 days after treatment. By day 70, the burst impulse rate for all treatments reached its lowest point, confirming the death of RPW within the treated date palm trees. However, the impulse burst rate decreased only slightly in the control treatment, which could be associated with larval growth transitioning into the next (pupal) stage. By day 90 post-treatment, the reported impulse burst rate for all insecticides was zero (**Table 2**). Surprisingly, the impulse rate in the control treatment was also zero, indicating that the larvae had developed into adults and migrated to infest the new trees. Moreover, it is noteworthy that in the control treatment, two date palm trees were dead within the three-month period following the treatment.

Figure 3 depicts the overall outcomes for all insecticide treatments, including the control treatment, for each month throughout a seven-month period. The data in the figure is only for four months, because after four months, the impulse rate was zero in all treatments, including the control (**Figure 3**).

Table 1. Impulse burst rate of RPW sound activities inside infested date palm trees for insecticide treatments Fipronil, Thiamethoxam, Imidacloprid, and control during 25 days.

Treatment	Day 0	Day 3	Day 7	Day 12	Day 25	ANOVA Parameter *F*, Df, *P*
Imidacloprid	0.97 ± 0.11 Aa	0.26 ± 0.05Ab	0.20 ± 0.04 Bb	0.17 ± 0.03 ABb	0.15 ± 0.03 Bb	$F = 21.4$; 4; < 0.0001
Thiamethoxam	0.54 ± 0.11 ABa	0.34 ± 0.05 Aa	0.22 ± 0.08 Ba	0.16 ± 0.05 ABa	0.34 ± 0.04 Aa	$F = 2.44$; 4; < 0.0758
Fipronil	0.50 ± 0.11 Ba	0.21 ± 0.05 Ab	0.23 ± 0.05 Bab	0.12 ± 0.04 Bb	0.12 ± 0.03 Bb	$F = 4.82$; 4; < 0.0034
Control (H_2O)	0.22 ± 0.15 Ba	0.29 ± 0.07 Aa	0.43 ± 0.06 Aa	0.34 ± 0.05 Aa	0.34 ± 0.04 Aa	$F = 1.90$; 4; < 0.1494
ANOVA Parameter *F*, Df, *P*	$F = 5.86$; 3; < 0.0027	$F = 1.09$; 3; < 0.3699	$F = 2.74$; 3; < 0.0678	$F = 4.20$; 3; < 0.0195	$F = 9.75$; 3; < 0.0004	

Means followed by the same letters (small) in the same row or with the same letters (capital) in the same column are not significantly different at $p < 0.05$.

Table 2. Impulse burst rate of RPW sound activities inside infested date palm trees for insecticide treatments Fipronil, Thiamethoxam, Imidacloprid, and control during 90 days.

Treatment	Day 35	Day 50	Day 70	Day 90	ANOVA Parameter *F*, Df, *P*
Imidacloprid	0.13 ± 0.04 Aa	0.14 ± 0.03 ABa	0.07 ± 0.04 Bab	0.0 ± 0.0 Ac	$F = 6.39$; 3; < 0.0016
Thiamethoxam	0.34 ± 0.06 Aa	0.28 ± 0.04 Aa	0.08 ± 0.04 Bb	0.0 ± 0.0 Ac	$F = 11.5$; 3; < 0.0001
Fipronil	0.11 ± 0.07 Aa	0.07 ± 0.05 Bb	0.06 ± 0.04 Bb	0.0 ± 0.0 Ac	$F = 2.73$; 3; < 0.0068
Control (H_2O)	0.34 ± 0.07 Aa	0.21 ± 0.04 ABab	0.35 ± 0.06 Aa	0.0 ± 0.0 Ac	$F = 6.35$; 3; < 0.0049
ANOVA Parameter *F*, Df, *P*	$F = 3.93$; 3; < 0.0244	$F = 3.92$; 3; < 0.0283	$F = 5.35$; 3; < 0.0043	*F* = -; 3; < -	

Means followed by the same letters (small) in the same row or with the same letters (capital) in the same column are not significantly different at $p < 0.05$.

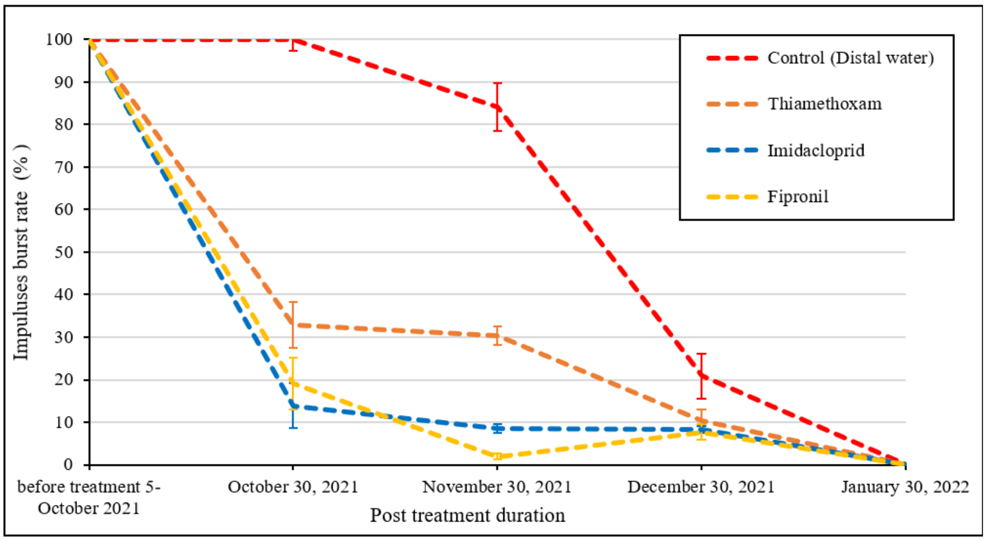

Figure 3. The average number of impulse bursts in date palm trees that are infested with RPW as a proportion of the highest mean rate seen after a certain chemical treatment, measured over time starting at the treatment time (0) and continuing at monthly intervals.

4. Discussion

In the present study, the acoustic sensor used to record the feeding activity of RPW proved to be very successful and beneficial. Without this device, validating the results of insecticides on RPW would have required dissecting the date palm trees, which would have resulted in significant loss. In contrast, this device allowed us to save the infested trees by injecting the insecticides. Several studies have also utilized this device in different experiments and reported satisfactory results, which are in line with and strengthen our methodology. The acoustic sensor can measure and differentiate RPW hidden larvae feeding and movement activity from background noise by comparing the frequency spectra and timing of sound impulse bursts. This capability has been confirmed through experimentation measurements of the larvae [17]. Previous research supports this study, indicating that small instar larvae may be detected at distances 0.5 and 1 meter, whereas late instar larvae can be detected at distances of 1–4 m [18]. Most studies on the acoustic detection of RPW have been conducted in enclosed conditions. Moreover, a current study that aim to detect RPW in both enclosed and exposed conditions observed no significant difference in the larval burst rate. It indicated that late instar larvae could be detected without the need for enclosed conditions [19]. The sensitivity of the acoustic sensor to detect RPW sound activities was supported by a similarly conducted study on another insect borer pest. the rice weevil *Sitophilus Oryza*, using the TreeVibes sensor [30]. The current study employed an acoustic sensor to evaluate the efficacy of insecticides following trunk injection. A similar study was conducted to evaluate the efficacy of the entomopathogenic fungi *Beauveria bassiana* and *Metarhizium anisopliae* under field conditions using the acoustic sensor TreeVibes. The results show that after two months of fungi injection, the RPW sound activity declined and the mean rates of RPW impulse bursts became zero, following the injection of fungi into the infested tree [31]. In contrast, a previous study utilized an acoustic sensor to determine the presence of RPW and termite activity in Malaysian oil palm trees, although the spectrum profiles produced by termite and RPW activity were different [16]. The spectral profile of insect borers revealed distinct impulse trains, showing varied spectral profiles and frequency variations in infested trees, however, the spectral profile was flattened in non-infested trees [26]. Additionally, another study was conducted to monitor the RPW in naturally infested date palm trees and evaluate the efficacy of several treatments, such as entomopathogenic fungi, nematodes, and insecticides, using trunk injection, spraying, and fumigation methods. These treatments were applied to the date palm trunk while monitoring with an acoustic sensor [32]. Previous investigations have established that RPW activities inside date palm trees produce sound signals, and the sound signals detected in our study are consistent with those findings [16,18,19,21,33]. Furthermore, such sensors have been utilized to investigate acoustic characteristics and classify stored product insects [34,35].

The comparative efficacy of three insecticides was evaluated in this study by recording RPW sound activity inside infested date palm trees using Tree Vibe acoustic sensor. Moreover, an investigation was conducted to evaluate the small infected offshoots treated with fungus, as well as untreated trees, by recording the sound signals of RPW larval activity using an acoustic sensor [14]. In contrast, the impulse bursts from other treatments decreased to zero after three months. Several studies have used the trunk injection method of insecticides, administered via a drilling, as a curative treatment for infested palm trees [8,36–38]. The date palm trees used in the present study were naturally infested; however, the exact number of RPW larvae inside the date palm trunks was unknown. The acoustic sensor could not determine the precise number RPW larvae within the tree trunk; it is possible that multiple generations were present, as indicated by dead trees in the control treatment. This study indicated that an acoustic sensor cannot be used to determine the age of RPW larvae because different behavior produces different sound rates, and the distance between the larva and the acoustic sensor significantly impacts the ability to detect acoustic signals [15]. Although other insects' activities were not recorded in this study, the sound signals produced by RPW activity inside date palm trees were clearly evident in the spectral profile and could be differentiated from other types of background noise.

The use of a balloon injector for delivering insecticides into tree trunks proved to be more effective for reaching the target area. According to the findings of this study, insecticides (Imidacloprid, Thiamethoxam, and Fipronil) applied through trunk injection using a balloon injector had a significant impact on RPW in the field. However, a study found that Imidacloprid, applied through drench irrigation, was effective against RPW 25 days after treatment [11]. Furthermore, previous studies on the application of Emamectin benzoate through trunk microinjection in Saudi Arabia showed a significant difference in mortality rates between the control and treatment groups for the larval and pupal stages, with 86–100% mortality after 2 months. Additionally, after 6 and 12 months of treatment, the mortality reached 100% [10].

As the lifecycle of RPW insects progresses through different stages, the larval stage is the most critical. Four months post-treatment, in the control treatment, the larvae developed into the adult's stage and migrated to infest new trees. This may explain the absence of recorded RPW sound activity, and the reduction of impulse burst rate to zero in the control treatment. Furthermore, two of the five replicates of the control group died two months after treatment, which was used to determine the decrease of impulse burst rate in control treatments.

The results showed the effectiveness of the injection method using a balloon injector to deliver insecticides into the trunks of date palm trees under field conditions, and the impact of the insecticides was detectable with an acoustic sensor. The injection method is favorable for delivering insecticides inside infested trunks, and the use of an acoustic sensor could be valuable for detecting RPW inside date palm trees. The findings of the current study can be useful for further field experiments that are necessary to determine the optimal timing for injecting insecticides into infested trees. Furthermore, researchers can benefit from this study when evaluating several treatments aimed at controlling RPW in the field. In addition, it is recommended to conduct an artificial experiment using an acoustic sensor to estimate the number of larvae within a tree trunk. Farmers are also advised to use trunk injection to deliver insecticides directly into tree trunks to control RPW without harming the trees and utilizing an acoustic sensor for early detection of RPW.

5. Conclusion

The treatments can effectively reduce the immediate infestation and the spread of RPW in treated date palm trees for a period. The injection of insecticides such as Fipronil, Thiamethoxam, and Imidacloprid using a balloon injector showed promising results against RPW in the field. The acoustic sensor can be exploited and utilized to monitor infestations of this destructive pest within the date palm trees.

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