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Seismic sensor-based management of the red palm weevil *Rhynchophorus ferrugineus* in date palm plantations

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Abstract

BACKGROUND: The red palm weevil (RPW), *Rhynchophorus ferrugineus*, is one of the gravest threats to palm trees. The challenge in monitoring RPW primarily arises from the inconspicuous presence of larvae within the stem, which is often devoid of noticeable symptoms. This study looks at the use of seismic sensors in RPW management in commercial date palm plantations. It explores whether the data garnered from the sensor domain, and its translation into the health status of date palms, can reliably inform precise decision-making.

RESULTS: Sensor and damage index values, as gauged by the Agrint IoTree seismic sensor, vividly mirrored RPW colonization activity. They also accurately portrayed the impact of three distinct insecticides: imidacloprid, phosphine, and entomopathogenic nematodes. The seismic values and damage index of healthy untreated palms strongly supported the decision to pursue tree recovery. Furthermore, this facilitated the computation of recovery pace discrepancies across the tested treatments, measured as the number of days required for tree restoration.

CONCLUSIONS: Our findings underscore the practicality of employing seismic sensors, as exemplified by the IoTree system and its network services, to both monitor and assess palm tree health. Furthermore, it validates their efficacy in evaluating the efficiency of management strategies adopted against RPW, all grounded in a wealth of sensor-derived data.

Keywords: seismic sensor; woodborer; monitoring; chemical control; microbial control

1 INTRODUCTION

Insect woodborers accidentally introduced into new areas often become invasive and destructive pests. Quite a few of these species successfully attack live trees with dramatic economic and ecological impacts on agricultural and forest areas.[1–5] Among the invasive woodboring weevils, there is little doubt that the red palm weevil (RPW) *Rhynchophorus ferrugineus* (Olivier) (Dryophthorinae; Curculionidae) is one of the most severe pests threatening both palm plantations and palm ornamental habitats and is currently reported in 40 palm species worldwide.[6] RPW inflicts severe damage on *Phoenix dactylifera*, a major fruit tree of the dry warm areas of the Middle East,[7] as well as in coconut plantations[8] and in oil palm plantations[9] in Southeast Asia. In the Mediterranean region, RPW also causes extensive mortality of Canary Island date palm *Phoenix canariensis*, a backbone ornamental tree in this area.[10]

RPW is a typical endophagous pest; the female lay eggs in cracks and crevices on soft palm tissue and the hatching larvae feed while penetrating the palm stem tissue where they are well protected from predation and adverse physical conditions.[10] In their native areas, these weevils are attracted to physiologically weakened or injured palms.[11] Susceptible palm species, particularly in RPW-invasive areas, are successfully colonized and succumb to the attack. This is intensified because volatiles released from fresh wounds on the palm attract RPW adult females.[12]

Development of RPW inside the stem is difficult to detect. Until now, detection of this severe pest to facilitate its management has focused on: (i) visual observation of external damage; (ii) acoustic and vibrational detection (insertion of a microphone into the soft stem tissue of the palm); (iii) olfactory sensing (detection of chemical signatures using sniffer dogs); and (iv) thermal remote sensing.[10,13–15] Jaques[16] presented guidelines on visual inspection for the early detection of RPW infestation in Canary Island date palms. However, there is no doubt that acoustic and vibrational sensors comprise the main scientific efforts to detect early RPW infestation.[17–26] This is also true for other notorious

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invasive woodboring beetles[27,28] or boring insects in wooden constructions.[29,30]

The challenge of monitoring woodborers is derived in part from the illusiveness of the adult during the short period of egg laying. In addition, the eggs are usually hidden in the outer layers of the bark, and hatching larvae penetrate the cortex, often without any conspicuous symptoms.[31] Therefore, prevention is usually the best strategy to avoid tree colonization. The application of contact insecticides against adults to prevent borer colonization involves excessive use of long-residue insecticides.[32,33] Several systemic compounds are frequently applied as preventive and curative measures.[10] Curative treatments are considered when monitoring colonization by the larvae is feasible. Once infestation occurs, the more promising approach to control borer immature stages in the phloem or xylem consists of injecting insecticides into the sapwood of the trunk. The insecticides are then distributed with the sap throughout the infested tissues. This has minimal non-target impact[34,35] while concentrating on only infested trees. The most widely used systemic insecticides are neonicotinoids and abamectins, which are delivered by injection into the stem against immature stages of RPW.[10,36,37] Entomopathogenic fungi and nematodes have been tested in several studies as both preventive and curative measures against RPW.[10,38–41]

The current study aims to examine the integration of a seismic sensor into RPW management in commercial date palm plantations. The question is whether the data supplied by the sensor measurements and interpretation of that data in relation to a palm damage index provide reliable information for the initiation of control measures against RPW.

2 MATERIALS AND METHODS

2.1 Early testing of the sensors

Early testing of the relationship between Agrint IoT (Internet of Things) seismic senspr (IoTree, Agrint Rockville, MD, USA) (Fig. 1) data and actual stem colonization by RPW larvae was conducted in four independent observations. The sensing device is a micro electro-mechanical system (Agrint Ltd, Hod Hasharon, Israel), a variation of the seismic intrusion sensor. Verification of the sensor (described below) was performed on date palms in Saudi Arabia,[42] Abu Dhabi[43] and Israel,[39] and on Canary Island date palm in Israel.[44] In each of the observations, the internal tissue of the palm stem in the experiment was exposed by slicing and, when needed, disintegration of the stem tissue. In this way, the presence of weevil larvae and their typical excavations were observed and recorded. Early testing by Agrint (unpublished data) in Saudi Arabia[42] included monitoring infestation after artificial implanting of RPW larvae inside a palm tree stem. In all cases, the detection accuracy of the sensor was about 95% when RPW larvae were present in infested palm stems compared with healthy 'control' palms. In these early observations, the detection frequencies were set and a detection range of 130 cm from the sensor along the palm stem was determined. Applications, including the sensing ranges, were measured by artificially colonizing first-instar larvae in trees in date plantations at ages susceptible to infestation by the pest. It should be emphasized that the sensor is seismic and not acoustic. The detection range of 130 cm refers to a date palm stem and was empirically determined by the sensor's manufacturer.

Figure 1. Agrint IoTree seismic sensor installed in a date palm in Ein Yahav, Israel.

2.2 Study plots, sampling of the tested trees and RPW treatments

Information about the four date palm plots used in this study and the number of tested palms in each plot is presented in Table 1. Trees were about 6–8 years old (Table 1), with a diameter of about 45 cm. The tested palm trees were divided into those that were not treated and were considered healthy, and others that were infested and treated against the weevil during the sampling procedure. The treated group of trees in the Idan (Israel) study plot included, in addition to successfully treated trees, trees whose treatment was considered unsuccessful. The latter remained infested following treatment. In the Ein Yahav and Patza'el (Israel) plantations, imidacloprid, a systemic insecticide of the class of chloronicotinyl neonicotinoids and produced under different trade names, was applied to RPW-infested palms. Treatment was based on recommendations given to growers in Israel. The suggested imidacloprid dose was 10 ml per tree into the roots, in the second and third irrigation cycles through the irrigation system in a concentrated manner to all trees in the plot.[45,46] In sensor-based management, only trees initially manifested as infested by the sensor are treated. In this case, one treatment is manually applied; in a few cases, a double treatment is performed. In Ein Yahav and Patza'el, and in Marai el Ein (Abu Dhabi, see below) control activity was conducted in the early hours of the morning. In Idan, infested palms were managed with entomopathogenic nematodes (EPNs), *Steinernema carpocapsae* strain All (Nemastar® e-nema, Gesellschaft für Biotechnologie und biologischen Pflanzenschutz, Schwentinental, Germany). The application was carried out by spraying the trunk and its nodes to a height of 2 m until runoff. Spraying was done twice with a second application 2 weeks after the first. A volume of 20–30 L, containing a total of 25 million nematodes, was used per tree. The nematode treatment was applied in the very early morning or late afternoon when the ambient temperature is more moderate. In the Marai el Ein plantation, infested trees as indicated by the sensor were treated with phosphine formulated in a procedure similar to that suggested by Ballaa and Faleiro[47] and Sutanto *et al.*[40] Three-gram aluminum phosphide tablets (Celphos, Lahore, Pakistan) were inserted into five or six holes drilled to a depth of about 10 cm in the trunk. The treated trunk was covered with a plastic sheet and tightly wrapped; the plastic sheet was removed about a week later.

Table 1. General information about the study areas and tested palm trees

Country	Location	Coordinates	Date palm variety	Planting year	Palms considered as infested by the sensors 2 weeks after installation (%)	Number of tested trees: Healthy untreated	Number of tested trees: Treated, and compound
Israel	Ein Yahav	35°21′65″03‴N 30°63′90″19‴E	Medjool	2015	0.5	5	5, Neonicotinoids
	Patza'el	35°48′61″4 5‴N 31°90′84″94‴E	Medjool	2016	3.0	7	7, Neonicotinoids
	Idan	35°27′53″29‴N 30°82′42″16‴E	Medjool	2014	2.0	10	15 (3[a]), Nematodes
Abu Dhabi	Marai Al Ein	55°78′85″84‴N 24°41′96″70‴E	Khalas	2015	9.5	5	4, Phosphine

[a] Unsuccessfully treated.

2.3 Measurement of sensor values

Measurement of the sensor values and calculation of the palm damage index (see below) for each studied palm tree were conducted at 2-week intervals for a total duration of 12–18 weeks. Measurements were further divided into three time stages: (i) 'pre-treatment', before or during the very early stages of RPW infestation; (ii) 'during treatment', beginning when the palm first was considered colonized and ending when treatment against larvae commenced; and (iii) 'post-treatment', after the presumed death of the larvae, usually the last two or three measurement periods for each treated tree. For each measurement period for each tree, two parameters were considered: magnitude of the seismic sensor vibration and palm damage index, both of which are elaborated upon further in the following sections.

2.4 Mode of operation and calculation of the sensor values

The seismic vibrations generated by the larvae are an indication of weevil activity in the palm stem and are the basis of palm health decision-making. The sensor's mode of operation has seven stages. (i) Receiving a vibrational signal from inside the tree via a metal screw inserted about 12 cm deep in the palm stem; the number of sampling intervals depends on the infestation activity. Typical sampling interval durations range between 1 and 24 h and are induced by the number of impulse bursts per sampling. If the standard sampling interval is set at 24 h, a positive reading event triggers a shortened interval of 2 h. If this next sample also yields a positive reading, the subsequent intervals remain short. However, if the next sample does not result in a positive reading event, the subsequent interval returns to 24 h. A timer for operational savings sets the sampling intervals. (ii) The sensor reads the seismic vibrations in intervals (interval = reading event) and converts them into electronic signals. The number of positive reading events (PRE) characterizes the level of infestation. The reading intensity defines the sensor measured value, which is the sum of the PREs divided by the total reading events (TRE), *viz* the number of above-threshold seismic impulse bursts per sampling interval. The resulting value is multiplied by 100 to give percent expression.

$$\text{Sensor value}(\%) = 100\times\text{PRE}(\text{in the last 12 days})/\text{the TRE in the last 12 days}$$

The sensor stores the signals until they are transmitted. We measured the rate of insect-produced signals as a proxy for damage, interpreted as RPW activity and damage. The palm damage index is based on previously published studies,[42,43] and unpublished Agrint Ltd data. (iii) Filtering is conducted in two steps, in the sensor and in the Microsoft Azure Cloud (Redmond, WA, USA). Signal filtering is based on receiving and processing both endogenous and exogenous signals, and algorithm software noise attenuation analyzes the environmental background noise. (iv) Bluetooth maintains one-way continuous communication between several sensors in the study plot and the gateway; cellular communication between the gateway and Microsoft Azure Cloud operates periodically, at least once a day. (v) Microsoft Azure Cloud processing units are established on the decision-making system based on machine learning methods. The description of the specific machine learning algorithm uses a hidden Markov model, which includes two main components: underlying states that cannot be directly observed and data points that are visible and can be measured or observed.[48] (vi) Decision control and surveillance monitoring is done by the machine learning algorithm with continuous upgrading by Agrint analyst personnel. The enhancement process encompasses both statistical analysis and machine learning techniques. Illustrative system upgrades include refining touch-based notifications for optimal responsiveness, mitigating noise interference from diverse installations, and reducing the duration of the 'suspicious' status. These enhancements derive from a synthesis of statistical analysis and machine learning, functioning independently of user feedback. Instead, they stem from an extensive sequence of empirical experiments. This system, although not reliant on user input, thrives on aggregating affirmative feedback from clients concerning larval detections. Instances in which users promptly report the presence of larvae and the system subsequently alerts about infestations have a pivotal role in enhancing its effectiveness. This symbiotic relationship between user input and system performance fosters ongoing improvements. Post-feedback integration, the incorporation of newly amassed features, transpires through the application of machine learning models. Although there is no fixed model in place, the selection of a methodology aligns with the specific problem under consideration. The chosen approach undergoes validation by an Agrint expert, who simulates historical samples to assess the impact of the envisaged modification. Following this, post-model implementation, a vigilant monitoring and tracking mechanism ensures the effective integration of the novel changes. (vii) Communication between Microsoft Azure Cloud and the end user (the grower in most cases) is based on Internet of Things (IoT) by different modes of transmission (e.g., web browser, smartphone application).

2.5 Palm damage index

The palm damage index is based on alterations in sensor data and their directional changes. These determinations draw from a collective knowledge gathered through the examination and summarization of thousands of cases, meticulously documented in internal reports.[39,42,43] The 'suspected' category is ascribed to conditions occurring before the 'infested' designation, although it may subsequently shift, often marking the inception of an unsuccessful infestation by weevil larvae that later reverts to 'healthy' status. The 'suspected' category serves as an early indication preceding the 'infested' category. Meanwhile, the 'declining' category signifies a marked regression in sensor readings from the 'infested' classification, typically stemming from a treatment intervention, which usually leads to 'healthy' classification.

The palm damage index has five levels: healthy, susceptible (as infested), reducing infestation (relevant to the declining activity of the larvae after the treatment), moderate infestation and high infestation. In healthy palm trees, the sensor value is in the range of 0–20. This is due to the limitation of filtering out low-level background vibrations. The threshold was determined through a two-step process: it was initially calculated by the sensor manufacturer using artificial colonization experiments involving young weevil larvae and date palm trees. Subsequently, it underwent further refinement through meticulous analysis of cumulative data from thousands of samples, collected and curated by the manufacturer. The threshold of the sensor value was determined to be 25–30 units for shifting from the healthy to infested condition. The algorithm for this decision is not explicated because it is the intellectual property of the sensor manufacturer. Above this threshold, the palm is considered to be infested by RPW. An increase of 10 units or more above the data average of previous samples, between two sampling periods, denotes the palm is suspected of RPW infestation. In the case that the threshold is crossed with an increase of 10 units or more, the palm is considered infested. High infestation likelihood is assessed when the sensor scores exceed 70 units during more than one period. The palm damage index for low levels of infestation is determined when the sensor values decrease by at least 10 units near the threshold. As such, the complete list of index damage levels are: 0 = 'healthy' non-infested palm; 1 = 'suspected infestation'; 2 = 'declining infestation'; 3 = 'moderate infestation'; 4 = 'high infestation'; and 5 = 'very high infestation' (rarely observed in this study).

2.6 Measuring sensor values and palm damage index levels with respect to palm condition and the effect of the tested insecticides

All statistical analyses were performed with JMP 16 and statistical significance was set at 0.05. Treated palm trees were

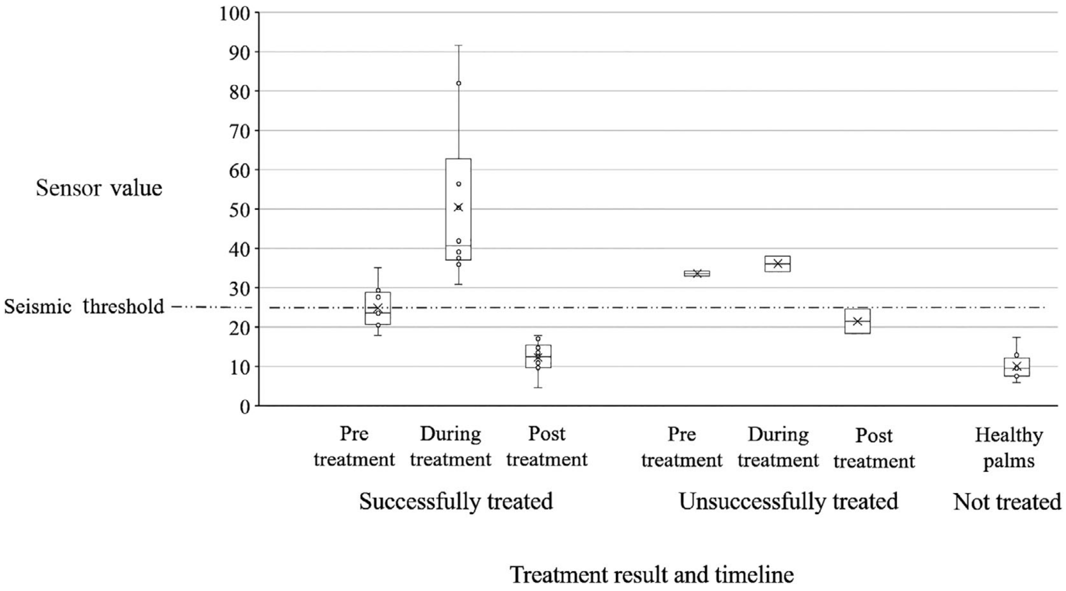

Figure 2. Change in sensor value related to the timeline of treated palm trees and compared with untreated healthy palm trees.

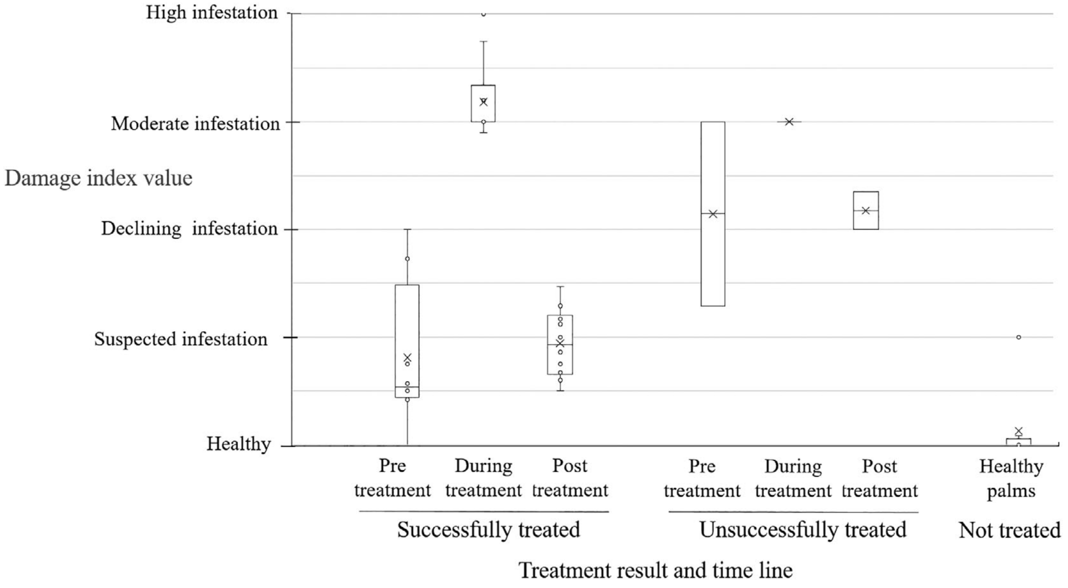

Figure 3. Change in damage index related to the timeline of treated palm trees and compared with untreated healthy palm trees.

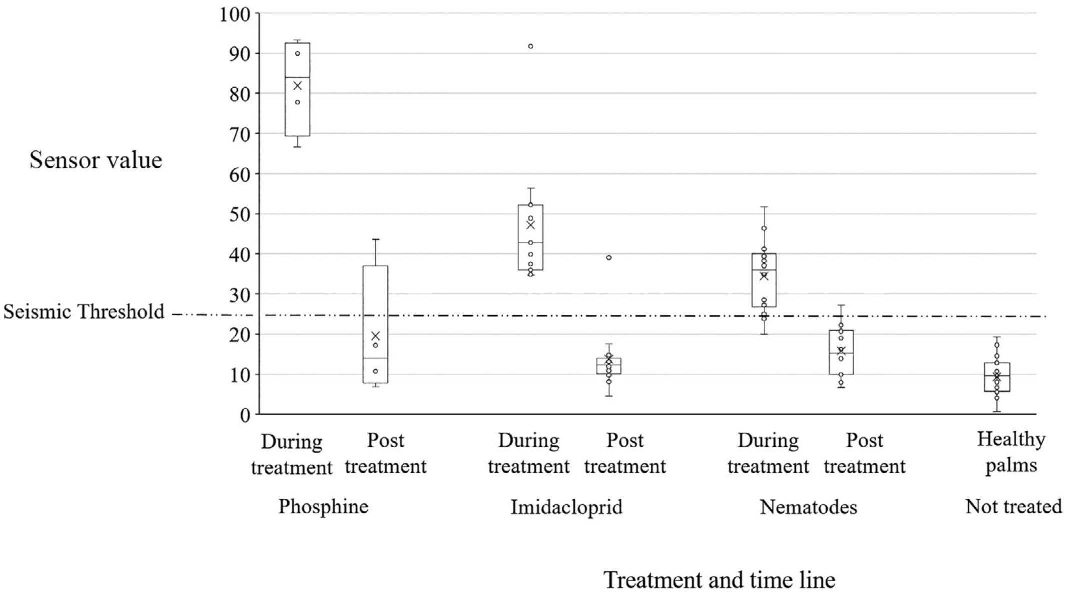

Figure 4. Change in sensor value related to the timeline of palm trees treated with three kinds of insecticides and compared with untreated healthy palm trees.

compared with untreated healthy palm trees with regard to mean seismic scores and palm damage index values, calculated after treatment for each tree in the former group and for the whole observation period in the latter group. The comparison included three types of trees (Figs 2 and 3): successfully treated palms from all studied plantations ($n = 27$), unsuccessfully treated palm from Idan ($n = 3$) and untreated healthy palms ($n = 27$).

Changes in mean sensor values and mean damage index levels from 'during treatment' to 'post-treatment' for the three groups of trees, each treated with a different insecticide (Figs 4 and 5), were also calculated. The number of trees in each treatment was as follows: phosphine ($n = 4$), imidacloprid ($n = 12$) EPNs ($n = 14$), and untreated healthy palms ($n = 27$).

Mean sensor value and mean damage index are assumed to have a normal distribution by the central limit theorem (the standardized sample mean tends toward the standard normal distribution even if the original variables themselves are not normally distributed[49]). For both Marai el Ein and Ein Yahav plantations, where the data were collected for a single sampling interval, the differences between the four groups 'pre-treatment' ($n = 0,\ 5$) 'during treatment' ($n = 4,\ 5$), 'post-treatment' ($n = 4,\ 5$) and untreated healthy trees ($n = 5$,) for each plantation separately were tested by an analysis of variance (ANOVA) model with group as a fixed factor and tree nested within treatment (yes/no) as a random factor. Pairwise comparisons of means were performed using the Tukey–Kramer HSD test. For both Idan and Patza'el plantations where data were collected during several different sampling intervals, the ANOVA model included group as a fixed effect, and the random effects were sampling interval and tree nested within sampling interval and treatment (yes/no). Pairwise comparisons of means were performed using the Tukey–Kramer HSD test.

One-way ANOVA was used to compare the effectiveness of the three tested insecticides in eliminating RPW infestation separately for 'during treatment', 'post-treatment', and the delta (differences) between these measurement times. Pairs of insecticides were compared using the Tukey–Kramer HSD test.

The four groups were also compared with regard to variations in the sensor values and the palm damage index. For each tree, the standard deviation (SD) between measurements was calculated for each of the three periods—'pre-treatment', 'during treatment' and 'post-treatment'—for treated trees and over the whole measurement period for healthy untreated trees. The data are presented in Fig. 6. SD values were compared in the same way between groups for each plantation, as were the means with the mixed model ANOVA described above.

One-way ANOVA was used to compare the insecticides with regard to the difference between sensor values during treatment *versus* post-treatment and the difference between palm damage index level during treatment *versus* post-treatment. Comparisons for three pairs (phosphine *versus* imidacloprid, phosphine *versus* nematodes and imidacloprid *versus* nematodes) were conducted using Tukey–Kramer HSD. Data are presented as mean ± SD.

2.7 Calculation of insecticide treatments time to recovery

Time to recovery was calculated for each tree in the successful treatment category. Two values were calculated as follows: (i) between the time when the maximum sensor value was recorded and the time when the sensor value became less than or equal to the maximum of the average value of the sensor among the relevant healthy trees; and (ii) between the time of the maximum recorded damage index and the time when the 'healthy tree' score was obtained.

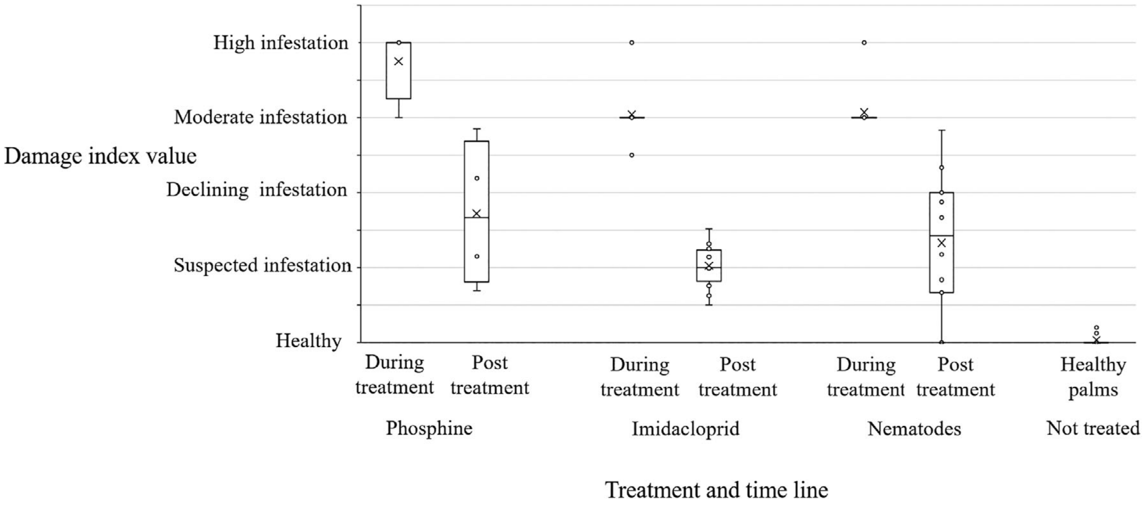

Figure 5. Change in damage index related to the timeline of palm trees treated with three kinds of insecticides and compared with untreated healthy palm trees.

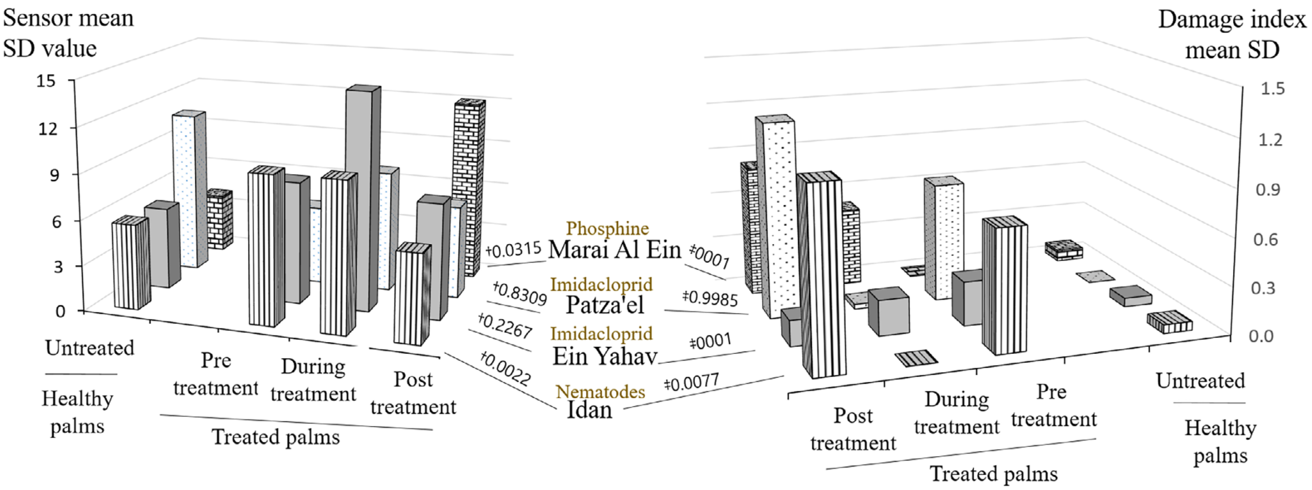

Figure 6. Variance analysis standard deviation in sensor value (left) and damage index (right) related to the timeline of treated palm trees and compared with untreated healthy palm trees in four studied plantation areas *P* values for the differences between treatment stages and untreated healthy palms are indicated by † for sensor values and by ‡ for the damage index.

Because duration variables typically show non-normal distribution, a comparison of the insecticides with regard to time to recovery for each of the above definitions was performed using the Kruskal–Wallis test. Non-parametric comparisons for all pairs were carried out using the Steel–Dwass method. The graphical description of the relationship between the two settings of time to recovery was based on 19 successfully treated trees, imidacloprid ($n = 12$), nematodes ($n = 5$) and phosphine ($n = 4$).

3 RESULTS

3.1 Change in sensor value and damage index along the timeline for treated palm trees

Figure 2 presents the change in sensor value related to the timeline of treated palm trees, regardless of the specifically applied compound and the sensor value of untreated palms. The mean (± SD) sensor value of untreated healthy palm trees was 10.0 ± 3.6. During early indications of RPW infestation, as noticed in the pre-treatment periods, the mean sensor value changed to 25.8 ± 5.2, whereas at the time of treatment application it increased 51.7 ± 21.4. In the case of successful treatments (most of the examined palms), the mean sensor value was reduced to an average of 12.6 ± 4.0, similar to that obtained for untreated healthy palms. In the case of unsuccessfully treated palm trees (studied only in the Idan plot), the sensor value during the pre-treatment period was 33.6 ± 0.9, already above the defined threshold. This value did not change much during treatment (−36.1 ± 2.8), with a significant ($P < 0.0001$) reduction in the recorded value after treatment (−21.5 ± 4.4). However, the latter value was significantly ($P < 0.0003$) higher than the mean value for untreated healthy palms (−10.1 ± 4.2) in the Idan plot.

Figure 3 presents the change in the damage index along the timeline of successfully and unsuccessfully untreated palm trees and compared with untreated healthy palm trees. Successfully treated palms during the pre-treatment periods were defined as 'healthy' and 'declining infestation' (0.81 ± 0.69). The damage index during treatment ranged between 'moderate' and 'high infestation' (3.18 ± 0.38) and later changed to 'susceptible' (0.94 ± 0.32). 'Health' was the determined index for the untreated healthy palms (0.02 ± 0.03). In the case of unsuccessfully treated palm trees (Idan plot), the damage index in the pre-treatment period ranged between 'susceptible' and 'moderate' (2.14 ± 1.21), changing to 'moderate' (3.00 ± 0.03) in the treatment periods and 'declining' significantly ($P < 0.0003$) in the post-treatment periods to 'declining infestation' (2.17 ± 1.25).

The correlation coefficient between sensor values and the damage index suggested a strong relationship between both parameters measured during summer (May to October, Spearman $\rho = 0.6817$, $P < 0.0001$) and winter (November–February, Spearman $\rho = 0.6825$, $P < 0.0001$).

3.2 Comparing the effect of the three insecticide treatments as reflected by sensor value and damage index

The effect of treatment was conspicuous for all three applied insecticides (Figs 4 and 5). The sensor value measured during treatment decreased significantly (Fig. 4; Table 2) 'post-treatment': from 81.9 ± 12.2 to 19.6 ± 16.6 for phosphine, from 46.5 ± 15.8 to 11.6 ± 3.3 for imidacloprid and from 34.5 ± 9.1 to 15.8 ± 6.3 for EPNs. The sensor values differed significantly between the applied insecticides during treatment ($P < 0.0001$) but not 'post-treatment' ($P = 0.1371$). 'Post-treatment' sensor values did not differ significantly from those for healthy untreated palms in any of the four studied plantations (Table 2). The delta of the sensor values 'during' and 'post-treatment' differed significantly ($P < 0.0001$) between all three applied insecticides. The sensor value measured during treatment decreased significantly (Fig. 5; Table 2) in the relevant post-treatment periods. The mean damage index for phosphine changed from 'high infestation' (3.7 ± 0.5) to between 'declining infestation' and 'susceptible' (1.7 ± 1.0); the change for imidacloprid was from 'moderate infestation' (3.0 ± 0.3) to 'susceptible' (1.0 ± 0.3); and a similar change was calculated for the EPN treatment (3.1 ± 0.3 to 1.3 ± 0.9). The 'post-treatment' damage score did not differ significantly from the values for healthy untreated palms in plantations managed using imidacloprid, whereas the values differed significantly in plantations treated with phosphine or EPNs (Table 2). The delta values of the damage index by treatment between the measurement times 'during' and 'post-treatment' did not differ significantly between all three applied insecticides. The delta values between the measurement times were compared using

Table 2. Comparison of seismic and health parameters of date palm (mean ± SD) under curative treatments against the red palm weevil

			Treatment and timing				
				Treatment stages			
Treatment	Location and treatment result	Health parameter	Nontreated healthy	Pre-treatment	During treatment	Post-treatment	ANOVA Probability > F
Phosphine	Marai Al Ein[a]	Sensor value	7.5 ± 7.0 B	–	81.9 ± 12.2 A	17.8 ± 14.4 B	<0.0001
	Successful.	Damage index	0.03 ± 0.07 C	–	3.75 ± 0.5 A	1.47 ± 0.83 B	<0.0001
Imidacloprid	Ein Yahav	Sensor value	9.6 ± 3.3 C	21.2 ± 3.9 B	39.4 ± 10.5 A	12.5 ± 3.6 BC	<0.0001
	Successful	Damage index	0.03 ± 0.06 D	2.90 ± 0.28 A	0.57 ± 0.22 C	1.12 ± 0.16 B	<0.0001
	Patza'el	Sensor value	12.9 ± 8.7 B	25.2 ± 6.9 B	51.3 ± 19.5 A	11.0 ± 3.3 B	<0.0001
	Successful	Damage index	0.00 + 0.00 C	0.75 ± 0.82 B	3.14 ± 0.38 A	0.87 ± 0.32 B	<0.0001
Nematodes	Idan	Sensor value	10.1 ± 4.2 B	26.0 ± 6.0 A	32.7 ± 10.0 A	12.4 ± 5.0 B	<0.0001
	Successful	Damage index	0.08 ± 0.11 C	1.24 ± 0.85 B	3.13 ± 0.35 A	0.70 ± 0.54 BC	<0.0001
	Idan	Sensor value		33.4 ± 4.9	36.7 ± 8.0	20.4 ± 4.7	
	Unsuccessful	Damage index		1.86 ± 0.99	3.00 ± 0.00	2.12 ± 0.41	

[a] Abu Dhabi, all other locations are in Israel.

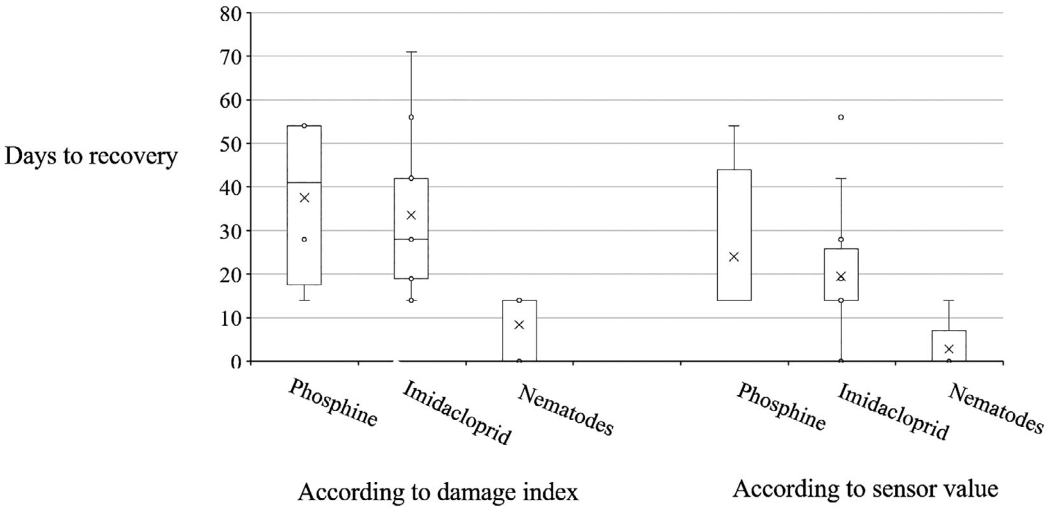

Figure 7. Calculation of number of days elapsed between treatment of red palm weevil-infested palms and their recovery related to the applied compound according to damage index and the sensor value.

one-way ANOVA. The mean ± SD (confidence intervals) values were: 2.01 ± 0.72 (0.87–3.19) for phosphine, 2.02 ± 0.44 (1.73–2.30) for imidacloprid and 1.74 ± 0.87 (1.24–2.25) for nematodes. Pairwise comparisons using the Tukey–Kramer HSD did not show significant differences: phosphine *versus* nematodes, $P = 0.76$; phosphine *versus* imidacloprid, $P = 1.0000$; and imidacloprid *versus* nematodes, $P = 0.59$.

3.3 Variance in sensor value and damage index as a reflection of the difference between trees as related to treatment and condition with respect to RPW infestation

Sensor SD values and damage SD index values were compared between the tested palm trees along the timeline of treated palm trees; these values were compared with untreated healthy palm trees for each of the four studied plantations (Fig. 6). No uniform patterns were observed. For both parameters, in most cases, the SD mean for healthy palms was rather low, increased during the 'pre-treatment' and treatment periods and remained relatively high in most cases (Fig. 6). In Idan (nematode treatment) and Marai Al Ein (phosphine treatment), both sensor SD values and damage SD index values differed significantly between the palm treatments.

3.4 Comparison of the time required for palm recovery between the different treatments

The average time taken by palms to recover from RPW infestation after insecticide application, as determined by sensor and damage index values, was calculated with respect to the threshold, defined as the maximum mean sensor value of healthy untreated palms (Fig. 7). According to sensors values, time to recovery was 24.0 ± 20.0 days for phosphine application, 19.5 ± 16.0 days for imidacloprid and 2.8 ± 6.3 days for EPN. The nematode treatment tended to differ significantly from both the phosphine and imidacloprid treatments ($P = 0.0807$, $P = 0.0535$, respectively), which did not differ significantly ($P = 1.0$) from each other. According to damage index, time to recovery was 37.5 ± 19.9 days in the phosphine application, 33.6 ± 17.6 days for imidacloprid and 8.4 ± 7.7 days for EPN. The nematode treatment differed significantly ($P = 0.0123$) from phosphine, whereas the imidacloprid treatment did not differ significantly from either phosphine or EPN ($P = 0.9671$ and $P = 0.0971$, respectively).

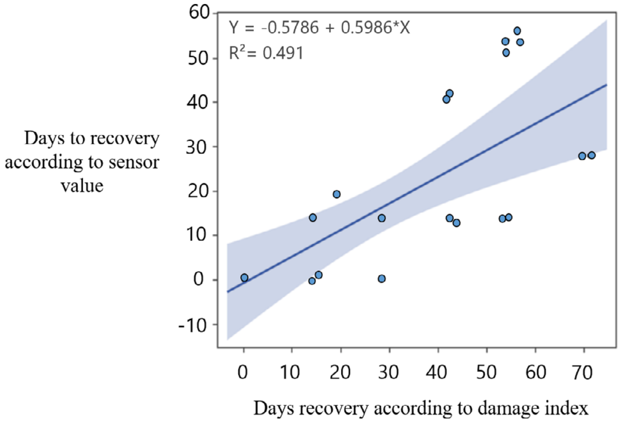

Figure 8. Correlation between numbers of days needed for the palm to recovery after red palm weevil control treatment as determined by sensor value *versus* resolved by damage index.

Figure 8 is a graphical representation, based on 19 successfully treated trees, of the number of days needed for the palm to recover after RPW control treatment as determined by sensor value *versus* resolved by damage index. The correlation $R^2 = 0.491$ ($F = 18.36$, $P < 0.0004$) suggests rather strong relationships between time to recovery for the two settings.

4 DISCUSSION

The main challenge underlying the management of RPW is the need for early identification of an infestation to enable the rapid application of control measures before significant damage occurs. Because of the magnitude of the damage caused by RPW in coconut palm, oil palm and ornamental palm species, the scientific literature is rich with published studies on approaches to early detection and prototype tools. Most of these studies have concentrated on the use of potential acoustic sensors[9,19,50–53] (and literature cited therein). The leitmotif of these studies has been to develop a technology to detect the early stage of RPW infestation with the idea that by the time external symptoms of conspicuous injury are manifested, the prospects of effective management and recovery are slim. So far, and to the best of our knowledge, the Agrint IoTree seismic sensor alone routinely serves to monitor RPW infestation in commercial date palm plantations as well as public settings with ornamental palms. Extensive use of this sensor and the accumulated information provides an opportunity to study colonization and recovery patterns in date palm with respect to RPW and the adopted reactive management. It is suggested that a reliable sensor may help to overcome a fundamental bottleneck in studying this system; that is, the sensor may serve as a worthy replacement for the destructive dismantling of palm tissue to directly observe RPW immature stages and evaluate their activity and vitality. Dismantling the stem is not economically realistic when destroying quite a few trees is required. In date palms, approximately 70% of the infestation was detected from the ground up to a height of 1–1.5 m, whereas in Canary Island date palms, 80%–90% of the infestation was localized in the tree's apical portion.[54] The results collected thus far indicate that applying sensors to the apical portion of a Canary Island date palm has similar benefits to installing sensors on the stem of the date palm at a height of 1 m above ground (authors' unpublished data).

Management practices in each of the four plantations were well recognized as effective curative treatments against RPW. Imidacloprid is effective in controlling various stages of RPW and larval mortality is increased with exposure time and dose.[55] Phosphine is a powerful insecticide and has been proven to eliminate larval activity within the palm 10 days after application.[40,54] It is likely that most of these treatment effects coincide with how rapidly the active ingredients reach the larvae. One cannot rule out the possibility of RPW resistance against both the above-mentioned compounds that could be acquired over a period of years. For example, it has been found in Pakistan that all studied populations displayed high levels of resistance to phosphine and other organophosphates,[56] probably due to the long-time application of such compounds. However, concerning all three plantations, the applied insecticides were initiated in recent years and therefore we may assume that effective resistance may not yet have developed. Several aspects of EPN application (such as delivery to farms and storage until use) against RPW infestation remain challenging. However, there is evidence of the usefulness of field application of *S. carpocapsae*, especially against RPW larvae.[39–41,57] The importance of replacing chemical pesticide-based management with an environmentally friendly method, such as the use of entomopathogenic microorganisms, is increasing over time.[40,58] Therefore, in the research much attention was given to examining the effect of the application of *S. carpocapsae* compared with the above-mentioned synthetic insecticides, according to the sensor indication.

Our findings confirm that seismic measurements correlate with the magnitude of RPW feeding activity in the studied date palms. Analyses of the sensor (Fig. 2) data indicate that values obtained by the sensor correlate with changes in the activity of RPW larvae after treatment. Although the tested palms represent different conditions and areas, the pre-treatment situation points to activity above the empirically defined threshold. This information was acquired through numerous early accumulated observations, indicating that sensor values at this level effectively represent the threshold for taking action. The sensor values and calculated damage index values indicated significantly higher activity during insecticide application, justified the treatment and led to the recovery of palms. The recovery decision was well supported by the sensor values from healthy untreated palms. The rate and pattern of RPW impulse bursts differ from those of typical background seismic variations. Unsuccessfully treated palms, three in total, in the organic farm at Idan were characterized by advanced levels of infestation during the pre-treatment period and sensor values higher than the seismic threshold post-treatment. Although these three palm trees showed renewed RPW activity during the first 10 weeks after the treatment, all 28 successfully treated palms remained healthy during this period (data not shown). Analysis of changes in the damage index (Fig. 2), the information provided to growers by the sensor network, displayed clearer and more conspicuous differences in palm health based on several characteristics, but still coincided with the sensor value (Spearman $\rho = 0.682$).

Comparing the change in RPW activity according to mean values of the treatment showed clearly that the sensor values during treatment in Marai Al Ein (phosphine) were much higher than those in the other plots. The palms in this plot were already in the advanced stages of RPW infestation when the sensors were installed; this was probably why phosphine was preferred. Both sensor and damage index values suggested that recovery was not as good for the phosphine-treated palm compared with the other treatments, probably because of the belated time of intervention in this case. However, the success of the applied measures is supported by the change in damage index values after treatment, which did not differ significantly between the three applied insecticides. Thus, we may safely assume that the inferior performance of phosphine is related to the advanced initial level of RPW infestation.

Rates of recovery for each of the tested treatments, based on the calculation of differences among sensor and palm damage index values, were significantly lower after nematode treatment compared with the other insecticides. This can be explained by the management design in each case. EPNs, in particular *S. carpocapsae*, can quickly reach and infect both RPW adults and immatures in the tree cavity in tubes filled with moist coconut pith[59]; EPNs were detected in different internal sections of the date palm trunk and in RPW cadavers.[41] We may assume that the effect of imidacloprid added to soil water will be slower than that of the nematode application and compared with the time needed to kill the relatively advanced developed RPW larvae exposed to phosphine. Also, the decision-making in Idan relied on an immediate response by application of nematodes following the change in the palm tree health status.

Sound production by insects can be divided into two types: deliberate, mainly for communication, and that produced incidentally by activities such as flying and eating.[60] For example, a seismic component has been documented in the sexual advertisement calls of prairie mole cricket *Gryllotalpa major* (Orthoptera; Gryllotalpidae).[61] Mankin and Benshemesh[62] used a geophone system to monitor the activity of subterranean termites and ants in a desert environment. Woodboring beetles are a cause of significant economic and environmental costs globally, particularly as invasive species. Successful detection of the activity of woodboring larvae in live trees, timber or wood products, is first based on the sound or seismic vibrations caused by a combination of larval feeding activity and the feeding substrate.[29] Efforts to develop automated detection of the feeding activity of woodboring larvae have mainly relied on systems that extract a specific acoustic signature from the total background noise. Recently, Sutanto *et al*.[40] used vibrations monitored with a TreeVibes acoustic detection device, to demonstrate the efficacy of injecting entomopathogenic fungi isolates into RPW colonized date palms, which resulted in no larval activity 42 or 52 days after the application of *Metarhizium anisopliae* and *Beauveria bassiana*, respectively. Similarly, in recent years, we have evaluated the efficacy of entomopathogenic fungi as a preventive measure. Prevention was accomplished by applying fungi to the trunk of healthy date palms and in the soil around the palm because that is the main site from which the female weevils attack. Prevention results from inoculating adult weevils with fungal conidia (the infection unit) and its transmission to early instars.[39,63]

There are several aspects to innovations involved in the field of IoT in agriculture. Among them is improved pest management.[64] The most frequently employed monitoring procedure is visual detection, usually through ground surveys.[65] The challenge posed by invasive woodboring beetles such as RPW is here to stay. Early detection of invasive pests, as a part of post-introduction activities, as well as a rapid warning of host tree colonization, enables faster management responses, leading to more successful outcomes.[66] Although early detection of a new invasive pest may be derived from various sources,[67] management is often challenging. For example, ineffective detection methods for the emerald ash borer *Agrilus planipennis* have hampered attempts at early management interventions.[68] At the plantation or stand level, woodborer early colonization is usually ignored until the tree displays symptoms of stress or even dies. There are direct relationships between the degree of success of borer population restraint and the time elapsed between discovery and response, either with biological or synthetic insecticides.

5 CONCLUSIONS

Our analyzed data concentrated on the early detection of RPW in date palm, and suggests that this is key to an efficient response to eliminate RPW infestation. This study did not aim to compare the effectiveness of the three types of applied control measures against the immature stages of RPW, but points to the usefulness of sensors such as IoTree in evaluating the effectiveness of management used against the weevil.

AUTHOR CONTRIBUTIONS

ZM conceived and designed research, contributed to the analytical tools, analyzed the data and wrote the manuscript. HV shared the analysis of the manuscript and was responsible for the statistical analysis. NM conducted part of the experiments and contributed to the analytical tools. RN conducted part of the experiments. DM was involved in conceiving and designing research and conducted part of the field experiments.

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CONFLICTS OF INTEREST

The authors have no relevant financial or nonfinancial interests to disclose.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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