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Recent Methods and Technologies for an Early Detection of Red Palm Weevil Infestation: A Review

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The red palm weevil (*RPW*) (Rhynchophorus ferrugineus) *is one of the world's most destructive pest of oil palm plantation as it can damage the entire palm and incur a total loss to the planters. Early detection of the RPW is difficult, and when the symptoms of infestation are discovered, usually the plant is not salvageable. The adult RPW lays the eggs inside the tree trunk and starts feeding on the tissue of the plant and remains inside until the tree dies. Intensive efforts have been explored to enhance the early detection process of RPW in the field. There are numerous detection methods for discovering the infected trees, such as manual visual inspection, acoustic detection, chemical odour/signal detection, canine detection, thermal sensing, remote sensing, Geographic Information System mapping (GIS), Internet of Things (IoT), cloud platform and data mining-based technology. In this article, the current methods and technologies used for the early detection of RPW are explored and discussed.*

Keywords: *Red palm weevil, acoustic detection, canine detection, thermal sensing, early detection, IoT.*

The red palm weevil (RPW) *Rhynchophorus ferrugineus* (Olivier) is one of the most destructive pests that affects palm tree species worldwide (FAO, 2019). Currently, in Malaysia palm plantations, especially coconut, are facing threats and damage from RPW. Furthermore, there were reports on the presence of RPW population in oil palm plantations, though infestation was not observed (Idris *et al.,* 2014; Wahizatul *et al.,* 2017). RPW is a major stem borer with a broad host range restricted to palm tree species and attacks mostly young trees less than 20 years old (Hoddle *et al.*, 2015). It was claimed that RPW originated from South and Southeast Asia and Melanesia, where it was considered one of the most destructive pests of coconut, *Cocos nucifera* L. (Faleiro, 2006).

Currently, RPW has been reported to have infested 24 palm species (Faleiro, 2006; Soroker & Colazza, 2017). Infestation of RPW on date palm plantation was first detected in the mid-1980s in the Arabian Gulf region and since then had caused production losses of up to 30 per cent (Kurdi *et al.,* 2021). To control the damage by RPW, the farmers opted to burn the infested palms thus minimising the spread of the RPW. This approach was taken due to difficulty in detecting the early sign of the RPW infestation. Early detection of RPW infestation is crucial for more effective control of pest damage. However, as the RPW larva resides within the palm stem, the detection process becomes a challenge hindering early discovery of the infestation (Nazmi *et al.,* 2020). Therefore, compilations of various viable and

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relevant methods which consist of different approaches, advantages, pitfalls and potential future implementation for early detection of RPW are discussed in this article; with the hope that early detection methods, preventative and curative measures can be carried out effectively to control RPW in Malaysia.

HOST PALM OF RED PALM WEEVIL

RPW is a major economic invasive tissue borer for a broad range of palm trees worldwide. Among its host of palm trees are coconut, date palm, Pindo palm, Sago palm, Washington palm, Silver Date palm, Canary Island Date palm, and many more. Detailed information on the RPW infestation in palm species in different countries are summarised in *Table 1*.

LIFE CYCLE OF RED PALM WEEVIL

Currently, there is still no single effective technique to detect RPW infestation at an early stage. This is due to the fact that the infestation is not visible at an early stage. According to the Department of Agriculture (DOA) Malaysia and as stipulated in the Standard Operating Procedure (SOP) Malaysia (2013) (DOA, 2013), the lifecycle of RPW is 2-5 days of egg stage, 25-105 days larval stage, 14-21 days pupal stage and 60-105 days adult life span. It means that it takes about 3.5 months for RPW to complete its life cycle i.e. from the egg to the adult. The different biological parameters established by previous researchers for each of the developmental stages of RPW are listed in *Table 2*.

SEVERITY LEVEL OF RPW INFESTATION

According to Faleiro (2006), the symptomatology of a palm tree infested by RPW varies depending on the species of the palm tree, infestation level and attack area. In order to identify those symptoms, the lifecycle of RPW, especially in the early stage of infestation (i.e. from egg to larva, pupae, and adult stages) needs to be confirmed. The different stages of severity for RPW infestation as outlined by Soroker *et al.* (2013) are summarised in *Figure 1.*

RECENT METHODS FOR EARLY DETECTION OF RED PALM WEEVIL

Recently, several breakthroughs have been made to improve the management of RPW infestation in palm plantations. Several methods have been implemented, including Integrated Pest Management (IPM). These include controlling and monitoring the ecology (e.g. insects and surroundings), biology (lifecycle), semiochemicals (pheromone trap) and chemical (e.g. pesticide and trunk injection). Apart from that, several advanced early detection methods have also been proposed to overcome the lack of effectiveness of visual inspection and pheromone trapping by adopting and integrating modern and smart technologies. Some examples are thermal imaging techniques, acoustic sensor technologies, canine detection, Geographic Information System (GIS) mapping of palm trees stress and using Internet of Things (IoT) with the cloud platform and data mining which may enhance effectiveness in detecting the infestation of RPW. The possibilities and limitations of the latest breakthroughs are discussed in this paper.

Visual inspection and pheromone traps

Currently surveillance of RPW in the palm plantation can be done by either individual tree

TABLE 1
HOST PLANT SPECIES OF RPW IN MALAYSIA AND WORLDWIDE

Host species	*Common name*	*Native range of plant*	*Country of records*	*References*
Areca catechu (Linn.)	Betel nut palm	Malaysia and Indonesia	Philippines, Malaysia	Wattanapongsiri (1966)
Arenga pinnata (Wurmb.)	Kaong,Yomuti palm or Aren palm	India and Southeast Asia	Indonesia, Philippines	Wattanapongsiri (1966)
Arenga saccharifera (Labill.)*	Kabong or Sugar palm	India and Southeast Asia	India, Southeast Asia	Wattanapongsiri (1966)
Borassus flabellifer (Linn.)	Toddy palm	India and Malaysia	India, Indonesia	Wattanapongsiri (1966)
Corypha gebanga (Mart.)	Gebong	India, Vietnam, Laos, Malaysia, Philippines, Indonesia, Papua New Guinea and Australia	Indonesia	Wattanapongsiri (1966)
Corypha elata (Roxb.)	Buri palm	India, Vietnam, Laos, Malaysia, Philippines, Indonesia, Papua New Guinea and Australia	Philippines	Wattanapongsiri (1966)
Caryota maxima (Blum.)	Pugahan	Malaysia and Indonesia	Philippines	Wattanapongsiri (1966)
Cocos nucifera (Linn.)	Coconut palm	Western Pacific	India, Indonesia, Philippines, Malaysia	Wattanapongsiri (1966)
Elaeis guineensis (Jacq.)	Oil palm	West Africa	Indonesia, Philippines, Kerala, India	Dhileepan (1991;1992)
Metroxylon sagu (Rottb.)	Sago palm	Papua New Guinea and Maluku	Indonesia	Dhileepan (1991;1992)
Oncosperma tigillarium (Jack) Ridley	Nibong			Kalshoven, *et al.* (1981); Lever (1979)
Oreodoxa regia (HBK.)	Royal palm			Abraham *et al.* (1998)
Phoenix dactylifera (Linn.)	Date palm		India, Australia, the United Arab Emirates, Kingdom of Bahrain, Qatar, Kingdom of Saudi Arabia (KSA), Iran, Egypt, Sultanate of Oman, Kuwait, Jordan, Palestinian Authority Territories, Israel, Turkey, Greece, Cyprus, France, Republic of Georgia, Lebanon	Ferry and Gomez (2002); Ajlan and Abdul Salam (2000); Faghih (1996); Kehat (1999); Azam *et al.* (2001); Zaid *et al.* (2002) Kontodimas *et al.* (2006)
Phoenix canariensis	Canary Island date palm		Canary Islands, Italy, Greece, Cyprus, Portugal, USA, Morocco	Kontodimas *et al.* (2006)
Washingtonia filifera	California palm		Greece, Cyprus, Republic of Georgia	Kontodimas *et al.* (2006)

Source: El-Mergawy and Al-Ajlan (2011)

TABLE 2
THE DEVELOPMENT PERIOD OF *R. FERRUGINEUS*

Development period (days)			*Total days (egg to adult)*	*Host plant*	*Previous researches*
Egg	*Larva*	*Pupae*			
3-5	33-46	20-36	-	Date palm	El-Shafie *et al.* (2013)
3-4	30-67	23-36	-	Washington palm, Canary Island date palm, Chusan palm, Pindo palm and Silver date palm	Ju *et al.* (2011)
5	69	16-29	90-93	Date palm	Salama, *et al.* (2009)
1-6	41-78	15-27	-	Palm lumps	Faghih (1996)
-	44-210	-	105-210	Sago palm pith	Kalshoven *et al.* (1981)
3-4	84-86	18-21	119-124	Palm leafbase and palm heart lumps	Kakeh (2005)

Source: Ávalos *et al.*, (2014)

Stage 1: Two differences – frond in V shape or in a zigzag position

Stage 2: Some leaves of date palm collapsed due to asymmetric inner leaf growth

Stage 3: Crown partially collapsed; no new inner leaves of coconut palm observed

Stage 4: All crown leaves of coconut palm collapsed into "umbrella" shape, the tree cannot be rehabilitated and need to be chopped down

Figure 1 The stage of severity of red palm weevil infestation in palm trees (Soroker et al.*, 2013)* inspection or trapping adult weevils using baited pheromone traps. However, the early stage of detection for RPW infestation is the utmost crucial step in ensuring the successful RPW-detection programme (Faleiro, 2006). Manual visual inspection enables detection of infestation with visible symptoms in which the tree has already been severely damaged (CABI, 2017). In contrast, the pheromone trap is used to control the adult weevils, not the larvae, which is the main culprit of tree damage that forms at the early stage of infestation (Soroker *et al.*, 2016). The visual inspection method depends on the RPW activity of infestation, for example, like emerging tunnels on the trunk and the bases of frond's petiole, oozing of thick brown liquid, frass composed of chewed plant tissue with fermenting odour (Bannari *et al.*, 2016), remains of weevils and their pupae cocoons around the tree; and at the most severe cases of infestation such as breaking off the trunk or the topping. Still, early symptoms are very much likely dependent on the site of infestation, physiological age and status of the attacked palm, thus the type of palm species. For example, in the coconut palm, inner crown fronds tend to wilt when the RPW develops in the lower part of the trunk, where oozing wounds may be observed, but more often, symptoms remain hidden amid offshoots, leaf bases or stem fibres. The infected palm may look healthy until the damage to the trunk tissues exceed the limit and causes the tree to collapse. The RPW infestation symptoms in a palm tree and the associated degree of possibility to save the tree are depicted in *Figure 2*.

To increase efficiency for RPW detection of early symptoms, a 50-60 cm wide open cutting (window) into the palm from the base of the canopy up to the centre is advisable since the chewing symptoms of RPW in inner leaves is not easy to detect even from a close distance. The window cutting procedure must be conducted with precaution since volatiles released from the cutting wound might attract wandering weevils to the uninfected palm trees. However, the visual inspection method has its disadvantages, such as being very laborious, time-consuming, costly, not feasible on a large scale and yet inaccurate. Thus, it does not meet the spatiotemporal behaviour in understanding the fundamental space and time of the RPW infestation pattern, thus hinder the analytic and projection of the control management. This suggests that both practices of visual inspection and pheromone trapping are not yet effective for the early detection of RPW infestation and by the time, it will be too late to save the infested tree.

Satellite remote sensing detection

The remote sensing technique is an alternative as it can assist in detecting attacks by RPW using satellite imagery. The use of spectral vegetation indices (VI), calculated as a ratio or normalised difference from near-infrared (NIR, 750–1350 nm) and visible bands, has become one of the most common remote-sensing approaches to retrieve biophysical variables, including early stress detection of the tree over the past three decades (Sonobe *et al.*, 2018). Therefore, it is believed that different stages of palm tree stress-attack can be differentiated using the empirical data related to spectral bands. Such a study was performed by Faradina *et al.* (2020) to detect RPW infestation based on the coconut tree vegetation status and discriminate stress-attacks using different spectral vegetation of Sentinel 2A data for the year 2018. Sentinel 2A comes with a multispectral instrument (MSI) sensor with blue (band 2), green (band 3), red (band 4), and

Coconut palm

Tunnels on the trunk and the base of frond's petiole

Breaking trunk and topping

Date palm

Weevil and remaining pupae cocoons around the tree

Extensive chewing/cutting symptoms of V shape

Canary Island date palm

All the crown leaves collapsed into an "umbrella" shape

Figure 2 Visual symptoms of red palm weevil infestation on different host palm species near-infrared (band 8) at 10-meter spatial resolution (SUHET, 2013). Thus, suitable VI's can be identified based on the spectral bands. The result from the study performed by Faradina *et al.* (2020) indicated that VI such as Normalised Difference Vegetation Index (NDVI) and Green Vegetation Index (GVI) derived from Sentinel 2A multispectral imagery offer a potentially viable and important alternative for discerning the severity level of RPW stress-attack as shown in *Figure 3*. The data indicates the healthiness of tree stress to be between 0.308-0.673 range with 55 per cent to 91 per cent accuracy. Therefore, remote sensing technique using Sentinel 2A data could be a promising alternative for RPW detection based on VI and perhaps analyse with other parameters that might influence the RPW outbreak, especially on palm tree species.

Thermal imaging detection

Thermal remote sensing is one of the parts of remote sensing that deals with the acquisition, processing and interpretation of data acquired primarily in the thermal infrared (TIR) region of the electromagnetic (EM) spectrum. Thermal remote sensing measures the radiations 'emitted' from the surface of the target, as opposed to optical remote sensing, where the radiations 'reflected' by the target under consideration are measured. Since the visual inspection of the RPW infestation is challenging, other possible methods have been introduced in helping to detect the infestation in the early stage. The possibility of detecting physiological changes is very high, especially for the infested palms (Al-doski *et al.*, 2016). Intensive fermentation of plant tissues from pest feeding within the palm trunk can increase the total temperature inside the crown/trunk beyond the ambient level of average temperature of palm trees from 30ºC and above 45ºC (Ahmed *et al.*, 2019). So, there are several observations reported where there are temperature elevations at the infested trunk, which were detected by thermal infrared cameras. The furrowing activity of RPW demolishes the vascular system of the palm tree and therefore creates water stress condition. Indeed, the crop water status can be sensed and inspected using the thermal portion of the spectrum of reflected irradiation (Bannari *et al.*, 2017).

Thermal imaging and sensing are alternative methods that is viable for point measurements to detect the RPW infestation. Thus, it can be performed through aerial drones that can cover larger areas with higher accuracy. The canopy temperature of the palm tree can represent the stress condition either the tree faced water stress condition or pest and disease infestation. With the help of the Geographical Information System (GIS), thermal mapping can be created instantly from the thermal sensing information, which can help indicate and provide instant data of the palm tree conditions, including water stress or pest and disease infestation. According to Cohen *et al.* (2012), aerial thermal images have proven to be a promising tool to map the water status of date palms on a commercial scale. Similarly, a map for the potential infestation in palm trees in a homogeneous plantation on a wide area scale can be created, derived from the detection of canopy temperature based on aerial thermal images using semi-automated procedures (Soroker *et al.*, 2013). Thus, there are promising results in the laboratory and field research to detect the RPW infestation through thermal imaging and sensing techniques by identifying specific signature frequencies of RPW infestation in palm trees.

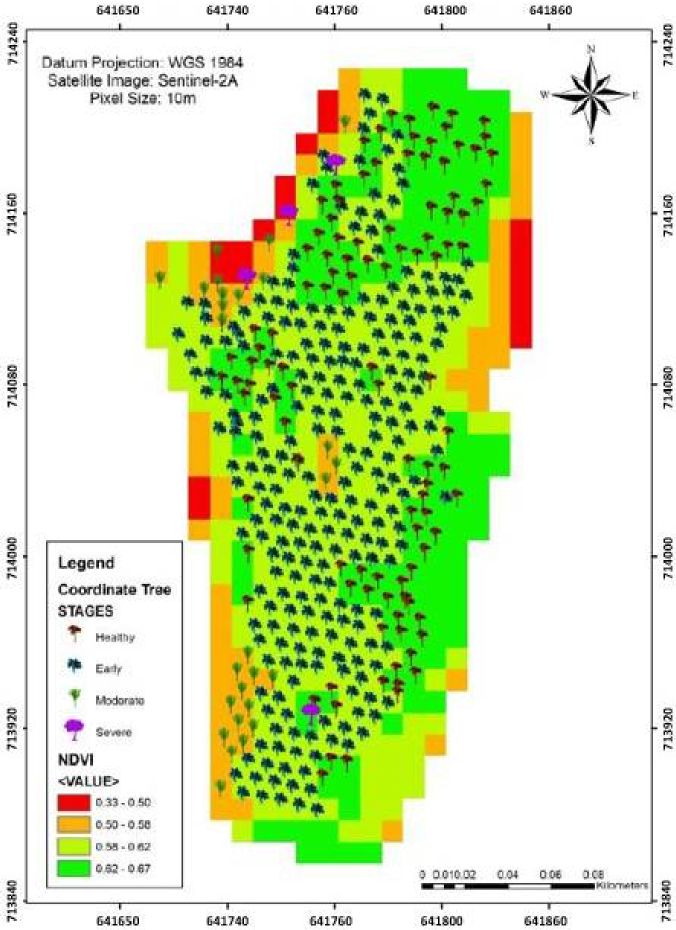

Figure 3 NDVI map of coconut tree stress from RPW infestation (Adapted from Faradina et al., *2020)*

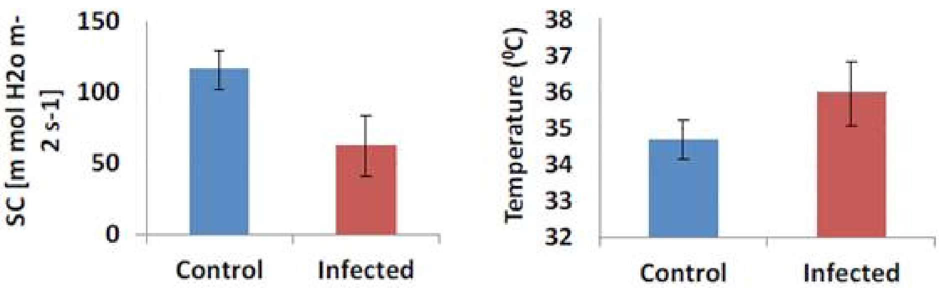

Figure 4 Canopy temperature (right) and stomatal conductance (left) of infected and not infected date palm seedlings. Bars represent confidence intervals of 95 per cent (Adapted from Soroker et al., *2013)*

High canopy temperature with lower stomatal conductance is observed for RPW infected palm seedlings compared to the healthy palm tree (Cohen *et al.*, 2012) as shown in *Figure 4*. High canopy temperature is much associated with the symptom of water stress. The infestation was detected based on the water stress after 25 days, roughly about 3 weeks before visual symptoms were observed.

Acoustic detection method

In pest-infected palm trees, there were distinct gnawing sounds produced from larvae chewing and moving inside the trunk. So, the theory of performing the acoustic detection of RPW originated from gnawing sounds. Using the acoustic method was successful in detecting the larvae in the offshoots from the gnawing sounds with the naked trained ear (Siriwardena *et al.*, 2012). However, the main problem is that the sound produced by young larvae is too low, hard to hear by the untrained naked ear and difficult to perceive from the surrounding or background sound. Apart from that, other problems related to acoustic detection are difficulty in recognising specific acoustic patterns associated with larvae activities, especially young larvae, and differentiating larvae sounds from physiological sounds emitted from host plants, and sound from other inhabitants like arthropods, rodents, birds, wind, and other ambient noise.

There are various studies suggesting a selection of bio-acoustics attributes of RPW gnawing sound based on the analysis of the unique frequency domain (Mankin *et al.*, 2011). Thus, several dominant frequencies that mark typical larval activities are successfully recognised and thus isolated for recognition. In the study by Hussein *et al.* (2010), 94 per cent of detection in the cut-infected trunk in the quarantine phase, with the absence of any other apparent inhabitants is possible. Moreover, fast detection of activities by young larvae of within 2 weeks of age by using the acoustic sensor in a controlled environment is possible by exploiting sound intensity within the palm tree (Gutiérrez *et al.*, 2010).

Mankin *et al*. (2011) found that RPW larval sounds typically are produced as bursts (trains of 7-200 individual, 3-30 ms impulses spaced < 0.25s apart) interspersed by longer, quiet intervals. Meanwhile, if there are many older larvae inside the palm trunk, the human ear can detect the sound of the larvae. However, it may be too late to save the tree since the tree is in the late stage of attack where the condition is severe with a high mortality rate.

According to Mankin *et al*. (2011) acoustic detection experiment of putting a sensitive microphone in the palm tree with soft tissue for the acoustic detection experiment is the most challenging. Therefore, a laser vibrometer (PDV-100, Polytec, Waldbronn, Germany) was used to record sound from infested palms and act as a non-contact acoustic sensor. It was reported that the acoustic detection tool exhibited a reliable signal-to-noise ratio, comparable or superior to other acoustic methods tested in previous studies (Mankin *et al.*, 2011). Furthermore, two categories of RPW larval feeding sounds were recorded by the digital laser vibrometer. According to the author, the first recording was basic sound of very short ‘clicks’ or ‘snaps’ lasting 1 to 4 ms and had an energy range between 1 to 8 kHz. While the second recording sound had longer-lasting sound termed as ‘rasps’ or ‘bites’ which were seemingly fused from short sound events and their maximum energy was below 3 kHz, although some frequency peaks reached up to 16 kHz. The sound lasted on average 440 ms (±260 ms; n=45) and were sometimes repeated regularly.

The approach of using a digital laser vibrometer allows one to sense the sound energy of larvae from the outer surface of the palm trunk. Thus, it is more effective and less of a hassle compared to the method of inserting a tactile microphone into the base of the palm trunk, which could injure the trunk and might attract adult RPW to infest the palm. Yet, using a digital laser vibrometer could improve the signal-to-noise ratio so that the activity of young larvae RPW can be detected effectively. However, several problematic issues arise with the acoustic detection method. First is the ambient interference with the low energy frequency produced by younger larvae, and second is that inspection needs to be done individually for each palm tree. The third problem arises from the RPW life cycle itself that is during the egg and pupae period, the RPW is in the dormant stage and not able to be detected by the acoustic method since there is no sound produced during those periods. Apart from that, this method is not suitable for large areas and only practical for *in-situ* conditions. Still, the acoustic detection method can be explored further since this method is capable of detecting 2 weeks old RPW larvae inside the palm trunk or base.

IoT and wireless sensor network-based detection

Recently, IoT and Wireless Sensor Network (WSN) technologies for early detection of RPW such as IoT image-based sensors for monitoring traps and IoT acoustic sensor detection networks, have been developed and applied in the field. IoT and WSN have proved to be useful in specific applications requiring monitoring in real-time data. Smart agriculture is becoming an evolving trend in the agriculture industry, whereby sensors equipped with the IoT and WSN are being embedded into plants to collect data in real-time. Thus, those data help managers make the right decision to ensure high quality crops can be produced while minimising the impact and losses from pest attack. For example, like putting image sensors inside the pheromone trap to capture the image of RPW and could act as an early solution to detect the RPW population within the plantation (Al-Saqer & Hassan, 2011; Lopez *et al.* 2012). The solution uses a low-cost system based on battery-powered wireless image sensors, which can capture and send the trap contents to a remote-control station with a specific frequency demanded by the trapping application. These image sensors accurately monitor the RPW population with a higher temporal resolution. During this monitoring process, no human intervention is required. This solution is capable of reducing the monitoring cost involving the human workforce. In addition, monitoring data will be available in real-time through an internet connection which forms the IoT and Wireless Image Sensor Network (WISN). This solution is programmable, and with an advanced image recognition algorithm, a success rate of approximately 95 per cent can be reached in identifying individual RPW. However, the initial cost in setting up the facilities, i.e. on the ground hardware, cloud computing, and software in covering larger plantations to increase the efficiency and effective rates of the system is quite high.

Apart from that, integration of acoustic sensor devices with IoT and WSN have been developed by Srivastav *et al.* (2013), Rach *et al.* (2013) and Srinivas *et al.* (2013). The integration of the devices can distinguish various pest sounds, which gives this technology an edge over others. The system employs an acoustic device sensor for monitoring the pest's noise level. Whenever the noise level crosses the threshold, it will notify the palm management of the specific area where the infestation occurs. The system consists of a sound probe, a microphone, a processor for local computation, a solar panel for energy, sensor, and a wireless interface for sending the data to a control station. Thus, a complete IoT system for detecting RPW early infestation can be implemented effectively with the current cloud computing system. Extensive experiments showed that the sensor has an accuracy of 90 per cent. Using this technology, the mobility to check every part of the palm tree and performing a visual survey is reduced significantly. The system functioning as the acoustic sensor node will be attached to the palm's trunk and connected to the base station. The base station will be notified when each sensor records the infestation noise sound within the trunk and transmit the noise levels whenever the noise level crosses a predefined threshold level. Then, the base will transmit the information to the IT control room. This will indicate to the palm workers precisely the infestation location and allow them to identify and take necessary actions to control the pest outbreak. The system can cover a large area of palm plantation with very low energy consumption and could be a most cost-effective solution in the long run.

Anis *et al.* (2020) have developed a proof-of-concept of IoT prototype-based smart palm tree monitoring that allows monitoring palm trees remotely using smart agriculture sensors and provides early detection of the RPW. The technology used an industrial-level IoT platform to integrate and interface the sensor and the user layers. This prototype allows users to use either web-based or mobile phone apps-based to interact with the palm tree and be notified on the early detection of RPW in the field. The example of an intelligent palm IoT framework system that has been developed by Anis *et al.* (2020) (*Figure 5).* The system can monitor, manage, and detect the RPW infestation in real-time. With the combination of advancing signal processing and probabilistic method techniques, accuracy in determining the infestation fingerprint of RPW can be achieved. However, the proposed IoT system is still facing several challenges, such as finding robust and reliable sensors to increase the accuracy in detecting the RPW activity inside the trunk. Thus, filtering the signal and extracting data from the raw noise or sound is quite a challenge for a non-skilled worker. Automation in processing a large amount of information and data of the IoT system is necessary if involving more extensive areas of plantation and application in the real-time mode of surveillance. Still, this IoT-based system to detect and monitor the RPW infestation in the palm plantation is promising and practical for actual implementation.

X-ray/radiograph scanning method

The X-ray or radiograph is a widely used technique for medical imaging and has been used in agriculture to detect insect pest infestation; however, it is relatively limited (Haff & Slaughter, 2004). The X-ray/radiograph commonly has been used for checking goods for any contraband, including illegal agricultural products through airports, seaports, shipping, and border customs. An X-ray is a form of electromagnetic radiation (similar to visible lights), but unlike visible light, X-rays have higher energy, high frequency (1018 Hz), and low wavelength (10-10 m) and can pass through most materials and objects that will be tested. X-ray is a type of non-destructive method that is capable of producing inside images of the different objects and structures.

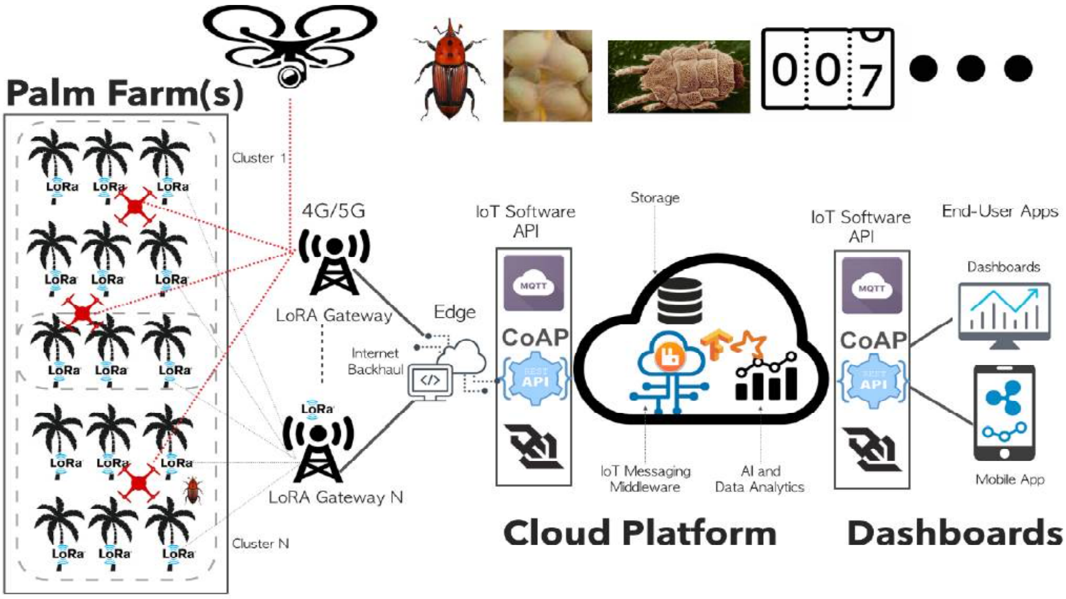

Figure 5 Smart Palm IoT Framework for RPW early detection (Adapted from Anis et al., *2020)*

In pest infestation detection, X-rays are used to create images of objects, space of hole, and tissues in the trunk of palm trees. The beams of X-ray pass through the object; whenever the object's material is dense, it appears as white colour, while the fatty objects appear as gray shades, and the empty spaces are seen as black. Preliminary studies carried out under laboratory conditions revealed promising results. Tofailli (2010), Ma *et al.* (2012) and Alghamdi and Monte Carlo (2012) carried out a simulation using X-rays CT for small size RPW detection within the date palm tree. The simulation demonstrated that the cone-beam CT reconstruction from the projections' finite number might be sufficient for RPW detection. Results could identify images of the larval stages and holes created by RPW larvae inside the date palm trunk (Ma *et al.*, 2012). However, further studies are needed to improve the methodology for imaging the tree and devising a system compatible with palm tree imaging under field conditions, even though this technique is applicable in the plantation with a simple modification of the available X-ray apparatus.

Chemical odour and canine detection

The plant usually will release some quantities of volatile chemical signal/odour whenever it is harmed by insect bites or physical deterioration. High volatile chemical signals/odours will be released for a more severe wound. The chemical signal/odour varies among the different plant species, and palm trees also contain their chemical signal specifically preferred by RPW for consumption. So basically, the chemical signal/odour is referred to as a palm tree infected by RPW where the RPW produces or emits volatile organic compounds (VOCs). Those chemical signals/odours directly come from the weevils themselves, weevil's frass, a thick brown liquid composed of chewed plant tissue with fermenting odour oozing out from the wounds of the infested tree, or other herbivore-induced odour. Those specific signals/odours emitted from infested palms chewed by RPW have possibilities to be explored further to enhance the RPW detection procedure through chemical odour and canine detection method.

Recently, canine detection has been used as a method to detect RPW's signal/odour. Commonly, dogs are used by police reinforcement to trace smells of various materials such as explosives, drugs, and invasive species due to their high ability to smell. Even infested plant material was detected by using dogs previously (Schlyter, 2012). Some breeds of dogs such as Golden Retrievers, Beagles, Rottweilers, and Labradors have been used and much preferred for sniffing tasks because of their easy disposition, proven performance, and public favour. RPW detection using canine detection is feasible and studies by Nakash *et al.* (2000) confirm the ability of Labrador Retrievers to detect the oozing secretion collected from RPW infested date palm. However, a dog needs to be trained for 6 months for the real and actual environmental situation. So, high accuracy to detect the infested palm tree regardless of the weevil instar and larvae that exist within the trunk can be achieved.

Experiments related to using dogs as an effective and low-cost procedure to detect RPW infested palms are indicated in *Table 3*. The experiment showed promising results, where the dog was able to detect the RPW infestation inside the palm trunk within 2 hours of operating in the plantation. However, under natural conditions, different volatile palms respond differently to the RPW infestation and require specific indicators for each palm. Thus, using canines for detection has its disadvantages, for example, physiological constraints where a dog cannot work for an extended period of hours in a hot temperature. Another disadvantage is that the accuracy and rangeability of dog detection is still in question and need to be determined for crown infestation. Moreover, there might be a setback using dogs to sniff each palm tree to detect the RPW infestation in large areas of the plantation. This is because the palm plantation acreage has hundreds to thousands of palm trees, and it does not seem feasible to use a dog for the big scale operation due to its inability to work for an extended period/hour. However, using dogs for detection of chemical volatile cues for inspection at nurseries, quarantine facilities, and a small acreage of palm plantations is suitable.

Overall techniques/methods comparison

Even though various intensive efforts have been developed to detect RPW as early as possible, however, some of those techniques are impractical, less feasible, and have set backs. Considerable enhancement in the

TABLE 3
TIME INTERVAL FOR LABRADOR RETRIEVER TO DETECT RPW INFESTATION

Response categories	*Time interval after infestation (hours)*			
	2 hours	*24 hours*	*48 hours*	*120 hours*
True positive (%)	90	77	90	87
False negative (%)	10	23	10	13
False positive (%)	2	1	1	0
True negative (%)	98	99	99	100

TABLE 4
PROS AND CONS OF VARIOUS EARLY RPW DETECTION METHODS

Parameter	*Visual inspection*	*Pheromone trapping*	*Acoustic detection*	*Chemical odour and canine detection*	*Thermal sensing*	*Satellite remote sensing*	*IoT and WSN*	*X-ray/ radiograph scanning*
Cost	Expensive	Affordable	Moderate	Affordable	Affordable	Moderate	Moderate	Expensive
Labour/worker	Intensive	Intensive	Low if automatic	Medium	Low	Low	Low if automatic	Intensive
Trained labour/ worker	Medium	Medium	Medium	Yes	Yes	Yes	Medium	Yes
Individual examination	Required	Required	Required	Required	Required	Required	Not necessary	Required
Customise equipment	No	Yes	Yes	Using dog only	Yes	Yes	Yes	Yes
Accuracy	Medium accuracy based on human judgement	Low for larvae but high for adult RPW	> 80 % under controlled environment	>90% depends on breed of dog and training	> 90 %	55% - 90%	> 95 %	Unknown
Early detection	Late	Late since trap adult only	2 weeks old larvae	Within hours or a day	25 days	25 days	2 weeks old larvae	2 weeks old larvae
Coverage	Small areas	Large areas	Large areas	Small areas	Large areas	Large areas	Large areas	Small areas
Suitability	Quarantine/ targetted areas	Open areas	Quarantine/ targetted areas	Quarantine/ targetted areas	Open areas	Open areas	Quarantine/ targetted areas	Quarantine/ targetted areas

effectiveness, efficiency, sensitivity, and accuracy in detecting the RPW are still required in all the above methods. All the methods discussed above are summarised in *Table 4*.

CONCLUSION

This study is a continuous effort to identify reliable methods and techniques that currently exist to enhance the efficiency and efficacy of the RPW early detection process in palm plantations. All the above-mentioned techniques have the potential to assist in the detection process. However, the techniques and technologies cannot function very well if applied solely in the field. So, the best answer for improving the sensitivity and efficiency of detection in the field is by combining all the techniques and technologies available so that an optimal solution is reached. In conclusion, this review article could become a reference in developing new work frames to manage the RPW infestation in palm plantations effectively.

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