Chapter

Recent Trends in the Early Detection of the Invasive Red Palm Weevil, *Rhynchophorus ferrugineus* (Olivier)

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Abstract

Red palm weevil (RPW), *Rhynchophorus ferrugineus* (Olivier), is one of the most invasive pest species that poses a serious threat to date palm and coconut palm cultivation as well as the ornamental Canary Island palm. RPW causes massive economic losses in the date palm production sector worldwide. The most important challenge of RPW detection in the early stages of an infestation is the presence of a few externally visible signs. Infested palm shows visible signs when the infestation is more advanced; in this case, the rescuing of infested palms is more complicated. Early detection is a useful tool to eradicate and control RPW successfully. Until now, the early detection techniques of RPW rely mainly on visual inspection and pheromone trapping. Several methods to detect RPW infestation have recently emerged. These include remote sensing, highly sensitive microphones, thermal sensors, drones, acoustic sensors, and sniffer dogs. The main objective of this chapter is to provide an overview of the modern methods for early detection of the RPW and discuss the most important RPW detection technologies that are field applicable.

Keywords: red palm weevil, date palm, early detection, remote sensing systems, acoustic sensors, ornamental palms

1. Introduction

Smart and precision agriculture are the most evolving trends in the modern agriculture industry. The electronic sensors can be embedded into the plants to obtain necessary data for aiding in decision-making to detect pest infestation or to improve crop quality. Concerning the date palm, there is an increasing demand to apply modern technology and smart agriculture for early detection of the RPW in the date palm plantations or other palms used for landscaping. RPW is the most dangerous pest for palms worldwide, which can cause irreversible damages, particularly at the late stage of infestation. Therefore, RPW, referred to as the palm cancer, is considered one of the most dangerous pests in the Mediterranean, Gulf Cooperation Council, part of Europe, and East Asia facing date and oil palm tree [1]. The most challenging problem in the control of RPW is the early detection of infestation, which is difficult because symptoms caused by the weevil are only visible when an infestation is more advanced. The highly infested palms are often destroyed and removed [2]. For this purpose, there is a requirement to use advanced technology for the early detection of the RPW. Early detection is an effective solution to control and eradicate RPW successfully. So far, the RPW detection occurs depending on the visual inspection by laborers, which is entrusted by private or public organizations. The inspection by laborers is very costly for owners of private farms; it is likely not to be implemented due to the high cost [3]. Therefore, the frequent inspection has never been applied systematically and on a large scale, even when the inspections are compulsory [4]. Although, the early detection of the RPW presence could mean a significant economization in the capital, investment in the farms, and providing job opportunities for agricultural workers [2]. RPW early detection is a major challenge due to the cryptic nature of the weevil in most of its developmental stages. RPW larva is the most dangerous stage in the pest life due to the direct destruction it causes on the infested palms. Thus, most of the early detection methods concentrate on this stage of the RPW life cycle [2, 5], although the presence of RPW adults in the palm plantation is one of the most indicative proofs of the infestation. Governments have successfully and widely used pheromone traps as the primary protocol in the integrated management to control the RPW [6, 7]. For that, the aggregation pheromone traps of RPW were included in the integrated pest management (IPM) as an essential technique to control RPW. There were unique developments in the trap designs, color, and trap density, besides the improvement of trap catching by the addition of kairomones in various forms. However, limited human resources and high transportation costs reduced the rate of monitoring and mass trapping of RPW adults [3]. Recently, there are strong ongoing efforts to develop a reliable and quick system for early detection of RPW using a combination of computer science, sensors, and modern electronic technologies. The most important and promising technologies are X-ray [2, 8, 9], acoustic systems [5, 10–17], remote sensing systems [18–21], and radio telemetry [7]. To control the RPW, it is necessary to implement an innovative and practical early detection method leading to reduce the pest population as much as possible. This action is essential, as the early detection of infested date palm trees allows the owner of farms to sanitize or to eradicate them in the event of a severe infestation. The early detection followed immediately by the palm sanitization and eradication of infested palms' parts allows to limit or prevent the RPW spread to the neighboring plantations, thus eliminating the RPW as quickly as possible [4]. The physical properties of different developmental stages of the weevil, such as sound, thermal and chemical emissions, and images are used in the early detection technologies. The main objective of this chapter is to provide an overview and engineering information about the new trends in early detection of RPW and to discuss the basic principles of the most current and promising technologies for RPW detection.

2. Biology, ecology, and economic importance of RPW

The red palm weevil (RPW), *Rhynchophorus ferrugineus* (Olivier), is the most important invasive species in the genus *Rhynchophorus* that encompasses more than 10 species [22]. RPW is native to South and Southeast Asia, where it feeds on coconut, *Cocos nucifera*, as a key pest. During the past 30 years, the weevil invaded many countries around the world and is now found in 49 countries in Europe, Africa, Asia, and the American continent [23]. As far as the host range of RPW is concerned, 40 palm species are reported, including the date palm, *Phoenix dactylifera,* and the Canary Islands palm, *Phoenix canariensis* (EPPO, 2020). Thus, the international trade of palms for plantation and landscaping purposes had resulted in the vast spread of the weevil [24, 25]. The RPW has a complete metamorphosis development; it undergoes four stages, namely, egg, larva, pupa, and adult stages. The female may lay over 200 eggs in its lifetime. The eggs hatch in 2–6 days into larvae, which last 1–3 months undergoing as many as 8 or 16 larval instars. Fully grown larvae construct a cocoon from palm fibers and undergo pupation. The pupal stage lasts for 15–30 days, after which the adult emerges. The adult weevils can live for up to 3 months, depending on abiotic and biotic factors. Adult males can be distinguished from females by the presence of a tuff of bristles on the dorsal tip of the snout, which is not found in the female [24, 26]. RPW is a multivoltine species and has a high reproductive potential where many generations can be produced per year [26]. RPW infestation on date palms occurs on the trunk near the ground level as well as on young offshoots. Palms younger than 20 years are more susceptible to attack by RPW than older palms. Infestation on male palms occurs at the crown [24]. Symptoms of damage on date palms include oozing out of brown sticky fluid with fermented odor, drying of young offshoots, ejection of chewed palm tissues, and breakage of the trunk in advanced severe infestation (**Figure 1**).

On the other hand, infestation on Canary Island palm is exclusively at the crown level, and the symptoms of damage include the presence of holes on the fronds, asymmetrical growth of the crown, and eventual collapse of the palm in severe infestation [26]. No recent estimate of economic losses on palms in the world due to the invasive RPW is available. However, the severe killing of palms in invaded areas has been reported [24, 25, 27]. The ecological characteristics of high fecundity, high adaptation to the environment, high mobility, and the international trade of infested planting material mediated the introduction and spread of RPW. The weevil is highly invasive and more difficult to control due to the cryptic and endophagous behavior of the immature stages and the partial cryptic behavior of the adult weevils [24]. The concealment of all developmental stages inside the palms makes early detection of the weevil at an early stage of infestation extremely difficult. Currently, the integrated management strategies adopted against RPW include early detection of infested palms, pheromone mass trapping, preventive and curative chemical treatment, removal of severely infested palms, and phytosanitary measures (**Figure 2**) [24]. Phytosanitary measures, public participation in control, and awareness campaigns reduce the probabilities of RPW infestation [28]. Any successful pest invasion passes through three important stages: introduction,

Figure 1.
Visual symptoms of red palm weevil damage on a young date palm.

Figure 2.
Conventional pheromone-food-bait trap for detection and monitoring of adult red palm weevil.

establishment, and spread. Quarantine regulations, invasion monitoring, and eradication are the main management strategies to prevent the establishment and spread of RPW. Eradication of an invasive species depends largely on correct identification and early detection before the species is fully established in the ecosystem.

3. Early detection technologies

Individual visual inspection of palms in public areas or commercial plantations is unfeasible, inaccurate, and highly laborious (**Figure 3**). The direct inspection may be impossible sometimes due to palm trees being not accessible or in cases

Figure 3.
Visual inspection and removal of date palm highly infested by the red palm weevil.

where the infestations occur below the crown of palm trees. This condition requires general scale, areawide detection techniques. Below, we present recently developed detection methods and the ongoing efforts based on the promising technologies for the early detection of the RPW infestations in the palm trees. In particular, we focus here on the most promising technologies such as acoustic systems, remote sensing systems, and the X-ray.

3.1 Acoustic technology

Overview: The acoustic waves have longitudinal and transverse motion shapes in the solid and involve mechanical movements of molecules or atoms, unlike electromagnetic waves that have transverse waves motion in nature and involve the oscillation of magnetic and electric fields. Acoustic waves show numerous properties, including frequency, wavelength, amplitude, and period; through these properties, the sound can be distinguished. The acoustic waves are heard by the human ear as sound at a frequency ranging from 20 Hz to 20 kHz. They can be defined as longitudinal mechanical waves that occur by the pressure oscillation that moves through a gas, solid, or liquid in the pattern of a wave [29]. This definition is extended to the solids where the waves are described as infrasound, sound, or ultrasound based on whether the wave frequency is below, in the range, or higher than the audible limit. In widespread usage, the expression of acoustics refers to all mechanical wave types in gases, liquids, and solids. Ultrasonic is a sound wave that has a frequency higher than the human hearing range. Ultrasonic energy is produced by a longitudinal mechanical wave with a vibration frequency of over 20 kHz with one-dimensional propagation, as shown in **Figure 1**. The signal of acoustic occurs in the field from several sources such as the insect movements and chewing during its feeding, the turbulence of air and gases, flowing of fluids, the impact of solid, and plant movements due to the air. The acoustic waves are a natural phenomenon; it may include just individual frequency as a pure steady-state sine wave (**Figure 4**) or contain multiple frequencies, such as the noise generated by several sound sources [30]. An acoustic sensor is an electronic tool that produces an output signal in response to a specific sound input. The output signal of the acoustic sensor is usually digital voltage pulse stream, electrical current or analog voltage, or an oscillated voltage with frequency suited with the input quantity value. The acoustic sensors are characterized in many various methods, such as sensitivity, accuracy, and selectivity. These characteristics determine the quality of the acoustic sensor in terms of the magnitude measuring of the output signal generated in response to a delivered magnitude input and the minimum limit of change in the input signal that measures and characterizes it. The development of integrated circuits (ICs) decreased the sensor and computing costs and produced economic systems sophisticated to deal with signals from the different acoustic sensors [31]. The detection

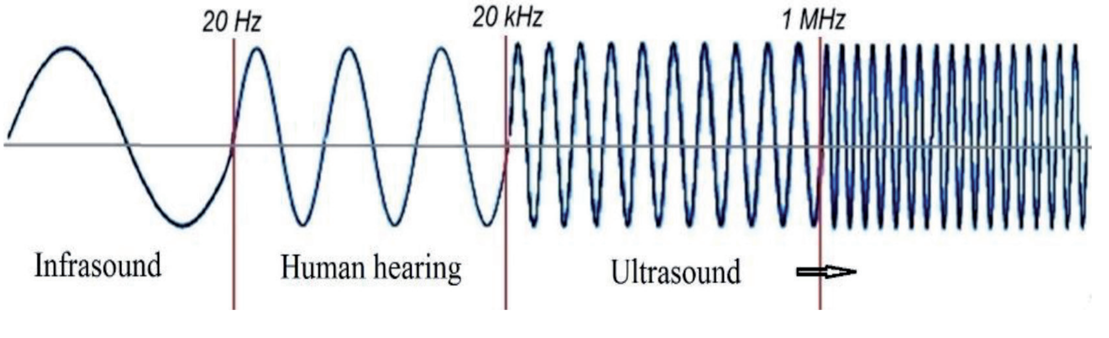

Figure 4.
Sound spectrum.

systems are based on acoustic sensors, due to the insect activities' sound inside the tree, which can be heard by humans. Moreover, under reasonable noise levels, the sound frequency of the insects can be isolated from the background noise sound and regular environment acoustic. The current models of RPW detection principally insert the acoustic probe in the palm trunk to obtain RPW sound in real time. The variations among these models are essentially in signal processing procedures, but all involved systems demand field monitoring. Field location has various background noises; the acoustic inspections must be performed in a quiet background, typically early in the day to improve detectability. With this procedure adoption, acoustic technology has been successful in detecting RPW in field inspections in many countries [3, 15].

Application of acoustic technology: Acoustic technology has the potential to be used in RPW early detection. The most applicable methods of acoustic detection for RPW depend on identifying the gnawing sounds of RPW larvae, which occurs during their movement and chewing inside the infested palm trees. The sounds of the RPW and the sound emitted from the healthy palm trees and the other sound sources are usually difficult to separate. There are many efforts to solve this problem; for example, a research was conducted to develop signal processing software devices that identify signal features and selectively magnify insect-produced sounds that distinguish sounds produced by the target insect from those produced by other sources [14]. However, the workers must recognize where to insert probes of acoustic and must use complicated signal analyses to help identify RPW sounds from other noise of background and insects. The recent decrease in the costs of microcontroller systems and increases in computing power have produced great solutions in the application of acoustic technology for RPW early detection using the acoustic probes [3]. Therefore, a mathematical method was developed to automatically detect the acoustic activity of RPW in palm offshoots and to implement it in a prototype setup. The algorithm successfully obtained detection rates as high as 98.9%. The results show that it is possible to detect the larvae of RPW sounds using the mathematical method using commercial recording devices and speech recognition [32]. Rach et al. designed a bioacoustic sensor, which was placed in the palm tree. The designed sensor was ready to analyze the captured sound signal through long periods. The sound results were connected wirelessly to the control station for stored and finally processed. The prototype was programmed to send warning messages when the sound signal reached the predefined alarm thresholds. The advantage of this prototype is to allow the supervisors to monitor the status of the palm trees orchards online with achieving detection rates over 90% [10]. A piezoelectric sensor was applied in the field to detect the sound of RPW larvae. The results were concluded that the detection using this sensor was efficient in detecting infested trees with the RPW with a sensitivity of 80% [33]. Mao et al. used an optical fiber distributed acoustic sensor as a solution to early detection of the RPW in the lab environment as a condition similar to the farms that include a palm tree infested with RPW. They recorded the sound of RPW through a loudspeaker set inside the palm trunk. For the noise sources, they used a fan to blow the air toward the palm tree and used a loudspeaker to make sounds of the birds around the palm tree. Under these laboratory conditions, they mentioned that the acoustic system could detect the sound of RPW at different positions along with the optical fiber [15]. The optical fiber distributed acoustic sensor has also been used in the Kingdom of Saudi Arabia (KSA) as an alternative technology for the early detection of RPW. The applied sensitive sensor exposes the feeding sound detection created by 12-day-old RPW larvae in the infested palm tree. In comparison with the commonly suggested technologies, this sensing system represents a noninvasive alternative, cost-effective method that could provide monitoring for 1000 palms or even more in real time, for the whole day [5]. The acoustic emissions created by the RPW inside the date palm were measured and recorded successfully. The time-frequency techniques were utilized to carry out the analysis procedure [34]. In another study, the acoustic system was used to detect the infestations of date palm trees by RPW. The system was evaluated in terms of its ability to detect the RPW in the early stage inside the tested palm tree. The technique of signal processing, known as the time-frequency analysis, was assessed in terms of the accuracy of the system in recognizing the RPW acoustic signature after the acoustic signal acquisitions were completed. The system experimented in the laboratory first then operated in the field on infested or suspected palm trees. The results showed that the acoustic monitoring procedure, besides the technique of signal processing, is very hopeful for the early detection of the RPW larva and the adult in the date palm trees [16]. A signal processing system was developed to detect the infestation of RPW based on the bioacoustic characteristics of their feeding sound. The developed system was investigated and had higher than 94% efficiency and can effectively detect the RPW feeding sound in a sound stream of 5 min. The results indicate the effectiveness of the developed system with the selected characteristics, functions of the window, and period of the frame to detect the RPW through the sound of its feeding [35]. In another study, the electronic device based on acoustic sensors was also developed for early detection of RPW larvae in the interior of the date palm trees. The developed device was based on specific frequencies rationally correlated to the larvae of RPW feeding activity. The finding concluded that it is possible to detect larvae activity (2-week old) by investigating the sound intensity of about 2250 Hz in the date palms infested (only with five individuals) under controlled environmental conditions. The other insect's activity artificially located in the interior of date palms did not affect the device's response [13]. The infested palms were detected using a developed acoustic system with accuracy over 97%. Four infested positions of palm trees (at the bases of the two lowermost leaves and at either side of the palm base) were recognized with high accuracy. The device contains a sensor to obtain the sounds of red palm weevil larvae, a set of headphones to receive the output sound by the user, and an electronic unit that processes the received sounds, and it can be installed on the palm [17]. A study was carried under the hypothesis that temporal features and characteristic spectral features in sounds of RPW larvae can be mixed to create improved indicators for automated detection of date palm infestations. For this objective, a signal processing system was developed with the available acoustic technology to detect the presence of RPW larva in the palm tree through its sounds of feeding. The features were extracted, including alternative features such as temporal slope, spread, and roll-off. The results validate the effectiveness of the developed system to detect the existence of the RPW. The economic damage due to RPW in the date palm could be decreased significantly by the bioacoustic identification in an earlier stage of RPW infestation and by applying the suitable treatment [11].

3.2 Remote sensing system

Overview: The remote sensing system has been classified into five groups (**Figure 5**) based on remote sensors. Most of these sensors have been used for plant pest detection to provide information on the processes of physiological and plant chemical parameters under stress resulting from the pest infestation. The thermal remote sensing technology or thermography is a nondestructive method used to define the thermal characteristics of any object. The principle of thermography is dependent on converting invisible radiation patterns (infrared radiation) of any object into visible thermal images [18, 20]. All objects emit infrared radiation energy when it has a temperature above absolute zero. Consequently, irrespective

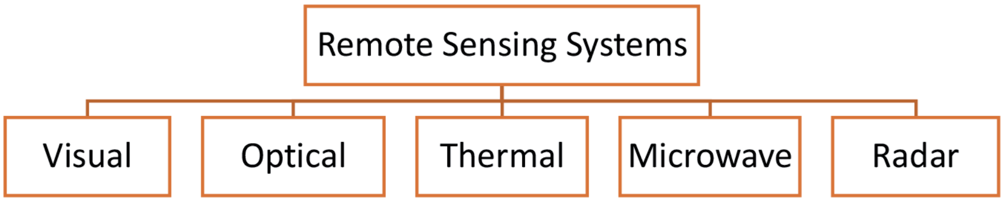

Figure 5.
Remote sensing systems [18].

of ambient light, the thermal cameras can detect all objects. The spectrum and the amount of thermal radiation depend directly on the object's surface temperature, the possibility of the thermal imaging camera to detect the object temperature. The emissivity of the object also influences radiation, which limits the accuracy of the system. On the other hand, the radiation absorption by the atmosphere and the radiation that originates from the surroundings can all affect the accuracy of the thermal imaging. In thermal remote sensing, the patterns of objects' radiation are converted into visible images named thermal images. The thermal images can be obtained by connecting portable thermal sensors with optical systems mounted on an airplane or a satellite. The thermal imaging can be classified depending on the excitation of the samples as two types, namely: active thermography and passive thermography. In the active thermography, an external source is applied to excite the test sample, thus producing temperature variation among the non-defective and defective sections within the sample. The excitation can be achieved through mechanical-, optical-, electromagnetic-, heating-, and convection-based cooling or heating. In the passive thermography, the natural emission of infrared from the object is used to detect any differences in its structure. The temperature difference among the defective objects and their surroundings is used to detect it [36].

Application of remote sensing system and thermal imaging: Remote sensing system and thermal imaging applications are the most alternative approaches for RPW detection, monitoring the physiological changes happening in the palm tree due to RPW infestations [3, 18, 37]. Farquad proposed the use of thermal remote sensing technology (thermography) for RPW early detection in order to take remedial actions at the earliest possible stage for date palm loss reduction [20]. The thermal detection is applied based on two monitoring types: the first type occurs by monitoring the local temperature in the infested part, and the second type occurs by monitoring the water stress of the palm tree. The first type depends on monitoring the local temperature in the palm tree caused by the intensive fermentation of plant tissues due to the feeding activity of the RPW larvae [38]. Unfortunately, this monitoring type is based on the change in the temperature that occurs only inside the palm or in the crown center. Due to the fermenting of the tissues in the heavy infestations. Due to the natural insulation is given by the palm's tissue, the outside surface temperature equilibrates with the ambient temperature causing difficulty in monitoring the internal temperature changes. The internal temperature changes can only be monitored via temperature probes inserted into the palm in the infested part. The second type depends on monitoring the water stress of the palm tree due to injuries in the vascular system of the palm created by larvae tunneling in the palm tissue. The decrease in stomatal conductance of the palm tree increases in the temperature of the palm canopy that can be thermally detected. The temperature changes of the palm canopy were successfully used to detect the RPW infestation in the date palms through the thermal portion inspection of the reflected irradiation spectrum before any appearance of visible detected signs that resulted from RPW infestation. The thermal images of the palm canopy can be obtained remotely by aerial photography using airplanes or drones. Generally, advanced thermal technology offers the potential to obtain spatial data to facilitate the mapping of the wide area at one aerial imaging operation for palm canopy temperatures. Thus, the palm map based on water stress distribution can be provided to recognize palm trees assumed of being infested [3, 39, 40]. Remote detection by thermal imaging based on the irradiation emitted from the thermal spectrum of the physiological changes in infested palms and palm tree canopy can produce great outcomes. The systems of thermal imaging and their application are considered within the promising technology on the RPW early detection. Therefore, the deployment of thermal image systems can obtain a good solution to RPW detection [36]. El-Faki et al. investigated thermal aspect potentials of date palm infested by RPW in early detection. The artificial infestation using males and females of RPW was done for date palm trunk. The effects of three infestations were examined during a 24-day period. The replicated measures analysis indicated that the temperatures of the healthy palms during two seasons were 31.83 and 27.56°C and the temperatures of infested palms through the two seasons were 33.22 and 30.08°C. While the corresponding ambient temperatures were 31.83 and 28.03°C, respectively. They mentioned that the study provides important information for developing a system based on a real-time sensor for nondestructive early detection of RPW [38]. Bannari et al. conducted a study on palm trees using water stress indices to discriminate among different stages of RPW stress attacks. They assessed the different water stress indices using the technology of Worldview-3 data. Based on field identification, five palm tree categories were studied: healthy trees, infested with RPW (treated), infested with RPW (untreated), severely infested, and dead. Spectral determinations were obtained for every sample using the analytical spectral devices. The results revealed that the water stress indices are sensitive to palm water agitation produced by RPW infestation. Based on their results, remote sensing using the Worldview-3 data is a promising alternative technology for RPW detection based on water stress indices [19]. Koubaa 2019 et al. developed a prototype-based smart palm tree monitoring that allows monitoring palm trees remotely using smart agriculture sensors and provides early detection of the RPW. This prototype enables the users to follow their palm farms for early detection of RPW infestations through interactions with date palm farms using mobile and web applications. They used the "Elm company IoT platform" to interface among the user layer and sensor layer. They have collected data utilizing sensors of accelerometer and applied the processing of signal and statistical methods to analyze collected data and to determine the infestation fingerprint [37]. Ghulam Rasool et al. evaluated the efficacy of some noninvasive optical devices including a thermal camera, digital camera, resisttograph, Tree Radar Unit (TRU™), magnetic, near-infrared spectroscopy (NIR), and DNA biosensor to detect RPW infestation (under field conditions) in date palm trees in the Kingdom of Saudi Arabia. They mentioned that after the date palm trees were inspected with the different devices, each tree was dissected in detail to validate each device's accuracy. The results found that the visual RPW detection approach presented the highest accuracy of 87%, followed by accuracies of 77, 73, 73, 61, and 52% for devices of Radar 2000, Radar 900, resistograph, thermal camera, and digital camera, respectively. Absorption spectra produced during near-infrared for the samples of date palm tissue that were infested, wounded, and in control showed a difference in the corresponding peak gradient between 1850 and 1950 nm. Another experiment by Ghulam Rasool et al. also determined the DNA biosensor efficiency for detecting RPW adults as 100%, followed by 83% for pupae, 63% for larvae, 60% for eggs, and 39% for control. Based on the tested device's efficiency, the near-infrared spectroscopy (NIR) and resistograph have the best potential to detect the infestation by RPW in the date palm trees [41]. Massimo et al. also tested a similar noninvasive approach (thermal camera, digital camera, Tree Radar Unit TRU™, a densitometer, and a penetrometer) to detect RPW in Italy and KSA. In Italy, the thermal camera showed a high accuracy of 96.29% and the digital camera showed an accuracy of 92.6% compared to close visual inspection. Tree Radar Unit and densitometer additionally showed great accuracy of 83.33 and 88.9%, respectively. In the Kingdom of Saudi Arabia, the thermal camera showed an accuracy of 77.7% compared to invasive determination. While the digital camera revealed a lower accuracy of 66.7%. TRU™ also provided an accuracy of 74.7% compared to invasive diagnosis. The satisfying conclusions taken using the application of remote sensing are good as a starting point to develop an integrated protocol for the early detection of RPW and control strategies [40]. A study was conducted to analyze the fitness of "8-band WorldView-2 satellite imagery" for detecting the tree infested by bark beetle at two intensity stages of dead and green attack versus the healthy trees. The results showed that "WorldView-2 satellite" information might be helpful for large-scale applications aiming at early detection of bark beetle infestation with the remote sensing data. Despite this, the information seemed uncertain to identify each tree at the green attack of the infestation stage, but this information can be used for the remotely sensed maps of bark beetle infestation, which can be used also positively as a contributor to the bark beetle modeling community. The remotely sensed maps can be used also as an alternative application to cost-intensive record data for GIS modeling approaches [42].

3.3 X-ray

Overview: X-rays are forms of electromagnetic radiation (similar to visible lights), as shown in **Figure 6**, but unlike the visible light, X-rays have higher energy and can pass through most materials and objects including the material to be tested due to its high frequency (10^{18} Hz) and low wavelength (10^{-10} m). X-rays are used in a quick nondestructive test that produces images of the different objects and structures inside the material. The beams of X-ray pass through the material, and they are absorbed in different amounts in the materials they pass through depending on the density of each material. Whenever the material is dense, it appears as white color, while the fatty objects appear as gray shades, and the empty spaces show up as black. X-rays are used to create images of objects, hole space, and tissues in the trunk of palm trees. When X-rays pass through the material, it will also pass through a detector of the X-ray on the other side, creating an image based on the shadows, which are formed by the objects, tissues, and empty spaces inside the material. In agricultural applications, types of detectors of X-rays that produce digital images are used. The digital X-ray image produced from this case is defined as "radiograph" [43].

Application of X-rays: To detect the RPW using a radiograph, two X-rays parts (X-ray source and X-ray detector) are placed around the trunk of the palm tree (in

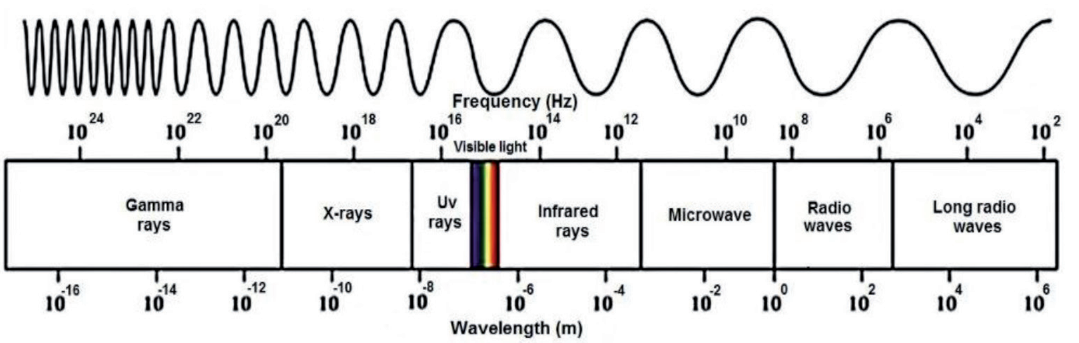

Figure 6.
The electromagnetic spectrum as a function of wavelength (m) and frequency (Hz).

a completely facing) so that the part of the tree to be imaged is located between the source and detector of X-rays. The X-rays will move through the trunk tissues, tunnels (made by insects), and the RPW body (larvae, pupae, or adult stages). Depending on the radiological density of each tissue, the X-rays pass through it; the X-ray will be absorbed in various amounts. Both the atomic number (proton's number in the nucleus of atoms) and the material density to be imaged limit the radiological density. The objects, such as the RPW, contain protein and fatty substances in all stages, which have a higher atomic number than the trunk's tissues. Therefore, the RPW's body will absorb X-rays and produce more contrast than any tissue on the X-ray detector; thus, the adult, pupae, or larvae of RPW will appear whiter than all other tissues on the radiograph detector.

On the other hand, when the X-rays move quickly through less radiologically in the material, such as the wood materials and trunk tissue, the material is displayed in shades of dark gray on the radiograph. On the contrary, when the X-rays pass through empty holes and tunnels resulted from the insects, the X-rays do not absorb it, and these holes will be displayed in black color on the radiograph. Alghamdi mentioned that using X-ray imaging systems can present direct and easy results with some modifications where the sensitivity is very low for light elements [44]. Ma et al. carried out a simulation using X-rays CT applied for small size RPW detection with the Monte Carlo method; the simulation demonstrated that the cone-beam CT reconstruction from the projections' finite number might be sufficient for the RPW detection. They determined that the technique is applicable in the farms with a simple modification of the available X-ray apparatus [2]. Haff and Slaughter constructed a high-resolution X-ray imaging system using a low-energy X-ray image intensifier, CCD camera connected with a PC, and a high-resolution real-time X-ray (low-energy and high-current X-ray source) to detect the granary weevil in the wheat kernels. The field of view was 6 cm^2, which is enough to inspect approximately 350 grains in a single frame with exposure time of 149 ms. The percentage of images correctly classified averaged 90.2% for the film observations compared to 84.4% for the real-time system [9].

4. Conclusion

Red palm weevil (RPW) causes massive economic losses in the date palm production sector as well as ornamental palms used in landscape worldwide. The most important challenges of RPW detection in the early stages are the presence of a few externally visible signs upon which detection can be based. Early detection is essential to initiate a rapid response to the eradication and effective treatment of RPW. The most effective techniques currently used for early detection of the RPW rely mainly on visual inspection and pheromone trapping. Dependence on the traditional method of visual inspection of palm trees to detect the RPW and other pest infestations is both time consuming and laborious. Additionally, visual inspection is only effective in a more advanced stage of infestation. Recently, the emphasis has been on using the modern technologies and development of systems and devices for early detection of the infestations in palm trees, especially the infestation by RPW. The most important applications of experimented technology were X-rays, remote sensing systems, acoustic sensors and software, bioacoustic applications, thermal image, X-rays, CT, etc. Modern alternative techniques have been undertaken for the early detection of the RPW infestations to reduce the dependence on visual inspection, which is expensive and requires highly trained labor. Most modern detection methods have their strength and weaknesses. However, an effective, applicable, and direct method for early detection of RPW, at all life stages inside the palm trees, remains to be developed. Therefore, to increase the overall reliability and efficiency of early detection, there is a need for further research and experiments to develop and produce reliable, easy-to-handle, and cost-effective portable detection systems for RPW early detection. Based on the findings of previous studies, we particularly mention promising technologies such as acoustic and remote sensing systems, thermal imaging, and the X-rays.

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Conflict of interest

The authors declare no conflict of interest.

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