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Evaluation of Red Palm Weevil (*Rhynchophorus ferrugineus*) Management Approaches in Date Palm Trees

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Abstract

Red Palm Weevil (RPW*), Rhynchophorus ferrugineus*, is a highly destructive pest that affects various species of palm trees, particularly date palms. This infestation results in considerable annual economic losses for date palm cultivators, impacting both the global market and the Middle Eastern region. It is also reported to be a global condition, affecting over 35 countries. Researchers and cultivators have implemented many strategies to manage this detrimental pest, primarily relying on chemical insecticides, until the development of the male aggregation pheromone in 1993. This review article evaluates the existing research on various control approaches to assess the efficacy of different control alternatives and suggests a comprehensive strategy for managing RPW in date palms. Control strategies for *R. ferrugineus* encompass early identification, biochemical assessments, soil analysis, physical control, chemical insecticides and bio-insecticides, and also pesticide applications. Moreover, biological control agents include the utilization of natural enemies like viruses and bacteria in addition to gene silencing technology.

Keywords: Palm trees; *R. ferrugineus*; insecticides; biological control; chemical control; early detection

1. Introduction

The date palm, scientifically known as *Phoenix dactylifera* L. (*Arecales: Arecaceae*), is regarded as a cultural legacy of several countries across the globe. It is the most ancient fruit harvest documented and has been farmed in the Middle East and North Africa for 5,000 years [1]. The date productions from palm trees are regarded as the most significant agricultural products in the Middle East and Arab Gulf region, owing to their substantial nutritional benefits and

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widespread utilization in these areas [2]. Indeed, dates possess various therapeutic properties, including antibacterial, antifungal, antiulcer, and anticancer effects [3].

The red palm weevil (RPW), known as *Rhynchophorus ferrugineus* (Olivier) (*Coleoptera: Curculionidae*), is an invasive pest that has inflicted considerable harm upon date palm farms in several nations globally, resulting in considerable economic losses and ecological imbalances[2,4]. The RPW has been documented in several geographical areas, including 28 Asian nations, six African countries, one North American country, two Central American and Caribbean countries, fourteen European countries, and five Oceania countries. In addition, it causes harm to around 40 palm species in various agroecosystems. It is estimated that with infestation rates of 1% and 5%, the annual financial loss incurred from the destruction of heavily infested palm trees across six Gulf nations varies between US$ 5.18 million and US$ 25.92 million. The RPW undergoes multiple developmental stages prior to reaching maturity, with the larval stage being the most critical and perilous among them, as larvae consume the palm's internal tissues and excavate tunnels inside it [2,5,6].

There are various techniques that have been established to identify and control RPW infestations in palm trees. These techniques encompass early detection such as visual inspection, acoustic sensors, trapping, endoscope inspection, and the use of microwaves, electricity, biochemical analysis, and soil analysis. However, the early identification of infestations poses a significant challenge as it is usually recognized only after a palm tree has endured considerable harm. Currently, the utilization of chemical insecticides and pesticides is a primary strategy for RPW control. However, growing apprehensions regarding the environmental pollution linked to these treatments have surfaced [6–9]. In order to tackle these problems, it is essential to move to alternative insecticides that are less hazardous and confer more environmental safety [10]. Researchers have undertaken investigations on botanical bio-pesticides as potential substitutes for the hazardous pesticides now in use [5,11,12]. Moreover, the use of biological control agents, such as natural enemies and gene silencing technology to manage insect pests has expanded recently [13–15].

This review intends to thoroughly assess different sustainable management approaches for the control of RPW. These methods, which emphasis ecologically friendly and cost-effective strategies, include chemical, biological, physical, and cultural controls.

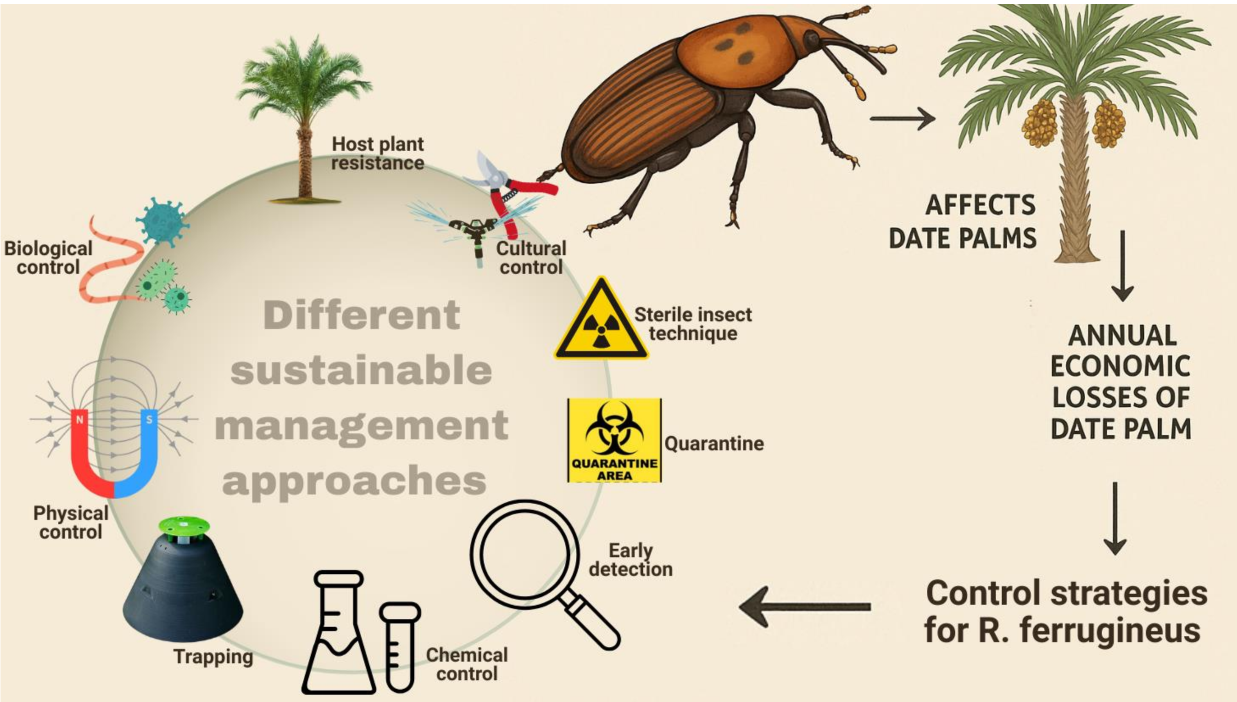

Fig.1. Different sustainable management approaches

2. Different management strategies of Red Palm Weevil (*R. ferrugineus*) in date palm tress

2.1.Early detection

According to the current state of knowledge, combining different detection methods can result in an almost complete success rate, even though no single method can accurately identify the infestation [16]. The key to effective palm weevil control is early identification of infested palms and monitoring adult weevils via pheromone trapping. In addition, there are numerous technologies available for early detection such as the use of sniffer dogs, visual inspection using drones equipped with high-resolution cameras or by cutting observation windows in the crowns of palms, identification of important volatile compounds and metabolomics indicators, acoustic detection, thermal and spectral imaging, and data mining techniques[14,17].

2.1.1. Visual inspection

Visual examination of the base, offshoots, stem, and crown of palm trees is considered one of the most popular detection approaches for RPW infestation[16]. A thick brown liquid and several holes in the tree trunk indicate that the tree is infested with RPW. Additionally, weevil remains have been found under the infested tree [18]. Although visual inspection of date palms is a time-consuming and arduous process to assess infestation, it is an essential component of help when used with pheromone traps[16]. Al-Shawaf et al. 2012 reported that regular maintenance of infestation levels below the 1% threshold can be achieved by conducting monthly inspections of severely affected date plantations. The reason for this is that infestations are identified prior to the emergence of adult pests, which typically occurs around 45 days after egg laying. This emphasizes the need for regularly inspecting date palms in the susceptible age range in order to detect infestations and prevent the accumulation of pests in landscapes [8].

2.1.2. Pheromone traps

Rochat et al. 1991 determined that the aggregation pheromone 'rhynchophorol' released by RPW male pests for *Rhynchophorus palmarum* is (2E)-6-methyl-2-hepten-4-ol. Additionally, Hallett et al. 1993 found and produced the aggregation pheromone 'ferrugineol' (4-methyl-5-nonanol) produced by a different RPW male. Since then, the pheromone technology has been widely employed for the management of both *R. palmarumin* on oil palm and *R. ferrugineus* on date and coconut palm [22]. *R. ferrugineus* is drawn to the aggregation pheromone produced by males of adults to attract both genders to host trees suitable for larval nourishment. The combination of the aggregation pheromones of adults and the odor of stressed palms can be useful in luring adults to traps. In order to get the best outcomes, pheromone traps should be routinely checked for captured adults, cleaned, refilled with food bait, and depleted pheromones [16]. Sabbahi et al. 2021 investigated that the pheromone-food-bait funnel trap shows great potential in its ability to decrease populations of RPW, therefore protecting date palm trees against infestations. Moreover, Arafa 2020 indicated that traps supplied with ethyl propionate, ferrugineol, ethyl acetate, and sugar beet juice captured significantly higher numbers of RPW adults in comparison with other chemical materials.

2.1.3. Thermal detection

Thermal imaging is another substitute approach used to monitor palm tree physiological changes. Two strategies have been assessed: the first method by monitoring the localized elevation of the temperature of the stem ranges from 4 to 26°C above the ambient level, resulting from intense plant tissue fermentation after larval feeding activity. The second method involves monitoring water stress in palm trees due to vascular system damage brought on by larvae digging through the tissues of the stem [16]. In addition, the elevation in temperatures can be detected using probes placed into the stem of the palm [25]. Moreover, technological developments in remote thermal imaging provide the opportunity to monitor the variability of canopy temperature over wide areas by providing spatial information on surface temperature. This technique requires additional testing and refinement to identify palms infested with *R. ferrugineus* at an early stage of attack[26]. Also, infrared cameras were employed to detect a rise in temperature in infested palm trees [8].

2.1.4. Spectral imaging

The spectral elements of the real larval sound were investigated. Specifically, a commercial voice recorder having a frequency response ranging from 50 Hz to 20,000 Hz (ICDUX570, Sony) is placed next to approximately 12-day-old larvae on a genuinely infested trunk of a tree. The audio recorder uses the uncompressed linear pulse-code modulation (LPC) format to capture the sound of the larvae so that the audio file is always of the highest quality. We have chosen this particular RPW life stage to assess the efficacy of our acoustic sensor to identify larvae sound early on, potentially saving and curing the palm tree. Within the trunk, the larvae are eating and roaming about without restriction during the recording period. Consequently, the sounds produced by the larvae in the lab were very comparable to those that were recorded during an actual infestation. By mimicking the infestation process in closely controlled experimental conditions, this was done. where a 0.5 s recording is associated with each larva period, the age of the larvae may be properly regulated. According to the findings, 400 Hz is where most of the visual strength of the larval sound is concentrated [27].

2.1.5. Acoustic detection

An auditory sensor is valuable for monitoring the activity of insect borers inside tree trunks. Compared to numerous additional RPW detection techniques, acoustic sensors are less damaging to palm trees and make it possible to monitor RPWY larval growth and activity over various instars. A microcomputer-based, cloud-integrated, IPM-focused bioacoustics monitoring system was created for farming. Sutanto et al. 2023 methods were created to identify traits in palm trunks that distinguish RPW feeding and movement noises from background noise. To ascertain the probability that sounds identified from a palm tree indicate that an RPW infection is present, one first analyzes and compares each spectrum with the spectral profiles (means) of the recording using the DAVIS signal processing system and then looks at the temporal pattern in sound impulse trains (bursts) that match the established RPW profile of sound impulses produced by RPW [29]. Low-cost detection systems with integrated signal processing and memory storage are now feasible thanks to microcontroller platforms like the Arduino Uno and Atmel SAMG55. Since a lot of field studies presently use GPS coordinates to map infestations, adding GPS features to the application might improve how the new devices are used [16].

Weevil surveillance systems do not now rely heavily on acoustic sensors. Here, the purpose of the seismic sensor is to detect vibrations in the stem that are mechanically brought on by weevil larvae activity. The purpose of seismic sensors is to identify mechanical vibrations that occur in solid materials like wood, rock, or earth [30]. Regarding date palms in urban and plantation environments, the primary commercially available sensor is the Io Tree Agrint seismic sensor, made by Agrint, Rockville, MD, USA. We have presented a distributed acoustic sensor (DAS) based on fiber optics for an early RPW detection approach. This technique has the ability to quickly examine a huge farm by noninvasively winding a single optical line around the palm trees. The study was carried out under controlled environmental circumstances, involving healthy and afflicted trees accurately discriminated utilizing a simple and effective signal processing technique.

2.1.6. Chemical detection

Based on the theory that infected palm trees release distinctive volatile compounds, the chemical method of pest detection has potential. These volatiles could come from infected palm wounds, the frass of *R. ferrugineus*, or the plant itself. Thick, disgusting-smelling liquids that leak brown are frequently connected to hands that have been infected with R. ferrugineus. Although it is said that palm trees create very little voltage, as the pest infestation spreads, some variations in volatile emission can be seen. Therefore, it is feasible to employ particular olfactory sensors, like an electronic nose or tongue, for chemical detection. Scenting dogs, however, has proven an effective means of detecting *R. ferrugineus* infestations in trees using chemical means. German shepherd, labrador, and golden retriever dogs have all successfully scented and identified the seeping substance that infected palms with *R. ferrugineus* produced. Even in cases where palms were infected with a single larva, canines were 70-80% accurate in identifying the contaminated plants after training. There are still a few hazards to be aware of a dog implementation needs qualified personnel [16].

2.1.7. Using data mining technique

Data mining is the best method. The scientists have developed a three-layer artificial neural network (ANN) for red palm weevil identification. It combines the Powell-Beale restarts technique for feedforward supervised learning with a conjugate gradient. This method doesn't rely on images because its primary goal is early detection and prediction before symptoms manifest, which improves system efficiency by lessening computational and storage requirements.

Data mining is the process of locating hidden links and patterns in vast volumes of data. With encouraging results, data mining techniques have also been applied to agricultural challenges. Ten state-of-the-art classification algorithms multilayer perceptron (MLP), bagging, PART, KSTAR, AdaBoost, Naive Bayes (NB), J48 decision tree and others were evaluated in this work using SVM, logistic regression, and random forest using artificial neural networks and image recognition (ANN) approaches to categorize the RPW and set it apart from other insects that inhabit the environments of palm trees. The most successful approach for identifying RPW was found to be a three-layer artificial neural network (ANN) with the method of Conjugate Gradient with Weller/Beale Restarts. Pathologies, including leaf spots and additional symptoms, were identified using photographs of palm palms. Both regular and thermal. Utilizing support vector machines (SVM), discriminate between blight spots and leaf spot infection, while convolutional neural networks (CNNs) were utilized to distinguish between RPW infestations and leaf spot infections using picture data, providing high accuracy in visual classification tasks.

The accuracy ratio success rates for the CNN and SVM algorithms were 92.8 percent and 97.9 percent, respectively. In order to remotely monitor palms, a smart prototype based on the Internet of Things (IoT) has also been proposed for the early detection of red palm weevil invasion (Kurdi et al., 2021; Wang et al., 2021). The data is collected using accelerometer sensors, which are then processed 25 utilizing statistical and signal processing methods to determine the assault fingerprint. A solution for the early identification of RPW in big farms is presented using a hybrid machine learning (ML) and fiber-optic distributed acoustic sensing (DAS) system. The gathered data facilitated precise classification, with CNN attaining 99.7% accuracy and ANN achieving 99.9%, highlighting their efficacy in the early and reliable identification of RPW in palm plants.

2.2. Chemical control

Chemical control represents a widely employed strategy for managing populations of the RPW. Insecticides can be applied using different methods, such as spray application, soil drench, or using a trunk microinjection technique. Nevertheless, various challenges and factors need to be considered when implementing chemical control methods for this pest. For instance, the high cost of insecticides, coupled with their overuse, poses a threat to the environment and could be a factor in the rise of chemical resistance in weevil populations [31,32].There are some important points that must be considered: suitable insecticide choice, their application time, the insecticide penetration ability, strategies for managing resistance, environmental impacts, adherence to regulatory standards, ongoing monitoring and evaluation, and principles of IPM [6].

2.2.1. Synthetic pesticides

The most widely used technique of control for *R. ferrugineus* is the use of synthetic pesticides, which have multiple applications [16]. A variety of insecticides have demonstrated efficacy in combating the RPW, such as cypermethrin, malathion, beta-cyfluthrin, chlorpyrifos, fenitrothion, imidacloprid, deltamethrin, carbaryl, and dimethoate [4]. Mohammed et al. 2020 assessed the susceptibility of weevil larvae to various popular pesticides and indicated that Fiprol was more efficacious than Imidacloprid and Dueracide. Rasool et al. 2024 tested the toxicity of six insecticides: imidacloprid, fipronil, deltamethrin, thiamethoxam, emamectin benzoate, and fenitrothion against RPW 8th instar larvae through dietary incorporation under controlled laboratory conditions and found that, all evaluated pesticides showed efficacy against RPW larvae and are suitable alternatives for managing this pest in date palm orchards in Saudi Arabia. Typically, the use of synthetic insecticides, which are commonly utilized to manage insect infestations, can lead to resistance and harm beneficial pest populations, pollute the environment, and pose risks to human health. Therefore, it is imperative to move to environmentally friendlier, less hazardous pesticides in order to address these problems [10].

2.2.2. Nano-pesticides

Nanoparticles signify an advanced class of technologies for environmental remediation, offering a cost-efficient approach to address some of the most difficult challenges associated with environmental cleanup. Also, they aid in the creation of new insecticides. Nanotechnology provides environmentally friendly materials that possess insecticidal properties, enabling pest management while minimizing environmental impact [34]. Abd El-Fattah et al. 2021 evaluated the toxicological effects of Imidacloprid and nano- chlorpyrifos, revealing that the nano- chlorpyrifos toxicity was greater than that of the others. The damage comprised cytoplasmic vaccination, analysis, and destruction of epithelial cells' nuclei. In addition, compared to adults, larvae were more susceptible to overall damage. Habood et al. 2022 evaluated the pesticidal effect of nano-chitosan against adult male and female RPW larvae at varying concentrations. It was discovered that nano-chitosan disrupted the physiology of both female and male *R. ferrugineus* larvae, changing their biology and even resulting in their death.

2.2.3. Preventive and curative insecticides

Preventive and therapeutic insecticidal measures are crucial for effective management of the RPW [31,32]. Preventive insecticides are administered every three months, particularly throughout the activity periods of the peak of *R. ferrugineus*, which occur from April through June and September through November. Curative pesticide can be administered either via spraying or through injection into the stem. The curative insecticide application via stem injection during the early phase of infestation is recognized for its effectiveness in preserving trees. This method has been extensively utilized to combat *R. ferrugineus* [8,16]. For stem injection, it is essential to mark points around the tree trunk, either at the base of the trunk or in a spiral pattern, relying on the insecticide type being used and the specific pattern of infestation observed. Injection treatments involve administering an insecticide into the palm by means of holes made in the stipe, which can be achieved through drilling or percussion methods leading to the formation of wounds [36].

2.2.4. Using essential oils

Essential oils, commonly referred to as volatile oils, are natural substances that encompass a range of chemical substances capable of either attracting or repelling insect pests[11]. Yan et al. 2021 indicated that eugenol and thymol demonstrate efficacy against the RPW and warrant further investigation as potential botanical insecticides for future RPW management. Ibrahim et al. 2023 indicated that the combination of certain volatile oils significantly enhances the attraction coefficient, an effect that is not observed when each oil is used individually, thereby improving the overall efficacy of the oils. Another study conducted by [5] showed that the oil extracted from *Jatropha curcas* seeds exhibits promising insecticidal and repellent properties against the RPW, suggesting its potential as an environmentally friendly solution for managing this pest.

Chemical insecticides are accessible for the management of RPW; nevertheless, the insect population has developed resistance to these substances, resulting in damage and the expansion into new regions [5].

2.3. Trapping

Several programs have been designed to detect, tracking, and managing pest weevil populations, particularly those of *R. ferrugineus.* Hoddle et al. 2024 delineated essential components of efficient capturing methodologies, encompassing trap design, coloration, density, service frequency (e.g., bait replenishment), placement, lure attractiveness, and durability. Manee et al. 2023 with the use of dry traps (ElectrapTM) and attract and kill (trap-and bait-free trapping), some progress has been made in overcoming this difficulty. Naveed et al. 2023 state that any integrated pest management program (IPM) should include trapping devices as an effective method of controlling the red palm weevil (RPW), *R. ferrugineus* Olivier, using both preventive and curative methods. The three primary parts of semiochemical based weevil trapping devices are the kairomone (coattractant), the aggregation pheromone, and the trap. Bucket traps buried are typically used for these objectives, although in recent years, enhancements (color, surface, retention system, and even new trap designs) have been included[38].

2.4. Physical control

Massa et al. 2011, 2017 reported that the utilization of microwaves has garnered significant scholarly interest, particularly concerning electromagnetic fields within 300 MHz to 300 GHz in frequency. Microwave radiation is expected to elicit an increase in temperature within the insect's physiology to a fatal threshold while concurrently preserving the integrity of plant tissues. Niamouris and Psirofonia 2017 proposed the application of electricity for the containment of RPW. In their research, they generated an electric flow through hollow electrodes. This system demonstrated considerable effectiveness in managing larvae, achieving a mortality rate of 84.8% and pupae, with a mortality rate of 96.5%, whereas adults exhibited no sensitivity to the treatment. Another study conducted by [9] assessed the vulnerability of the *R. ferrugineus* to electric discharges administered to both larval and adult stages, with the intention of ultimately incorporating electricity in conjunction with another method as a component of a comprehensive control way. The findings from the test of adults indicated that the overall egg quantity produced by each mating pair, as well as the number of larvae that emerged, was approximately 1.5 times greater in control group than in the electrified samples. The length of the electric discharge administered to the larvae had a negligible impact on the mortality rate; however, the electric voltage exerted a significant influence on mortality, with rates of 87% at 10 V and 99% at 15 V. In addition, a notable electric current was detected in a functional segment of the stem, located 10 cm from the electrical source, delivering a direct current at a voltage of 250 V. The aluminum mesh sheet emerged as the most effective material for the containment of both larval and adult specimens among the various materials assessed for the transportation of palm residues.

2.5. Biological control

A wide range of RPW natural enemies, such as 28 birds, entomopathogenic nematodes (EPN), bacteria, fungi, viruses, and yeasts, have been documented in numerous places [22]. It should be mentioned that more counter methods have been researched and created. These tactics consist of sterile backcrosses, chemo sterilization, the sterile insect method and biological control using entomophagy's and entomopathogens. Additionally, integrated pest management programs may incorporate two or more of the aforementioned control measures. Solano-Rojas et al. 2021 using phylogenomic data, found that future pest species and natural enemy connections could be more accurately predicted. These findings could be applied to biological control initiatives that aim to eradicate pest *Rhynchophorus* species. Hoddle et al. 2024 highlighted the helpful role that parasites, predators, and viruses play in controlling pests and that the term "biocontrol" is known as biological control. The biocontrol is defined by living things referred to as “natural enemies,” which is particularly crucial in lowering the palm weevil population. Worldwide research has shown that the use of a variety of possible biological agents and natural enemies, including parasitoids, predators, infections, and vertebrates, is successful in controlling palm weevil populations. Currently, international development organizations and policymakers are actively promoting integrated pest management (IPM), a method that relies less on insecticides and more on biological control [12].

2.5.1. Using natural enemies

Research indicates that over five natural adversaries, particularly R. ferrugineus, target *Rhynchophorus* species. These adversaries include bacteria, fungi, nematodes, parasitic wasps, mites, and vertebrates. The majority of RPW life stages are hidden inside palm tree trunks, which increases the challenge of targeting them and may exacerbate the pest's impact. Other factors that may influence the effectiveness of biocontrol include the absence of newly introduced or well-adapted natural enemies in recently infested areas. If these agents are absent or ineffective, RPW infestations are likely to persist [7].

2.5.2. Nematodes

Nematodes are diminutive, multicellular, non-segmented, worm-like animals classified within the phylum Nematoda. They live in symbiotic relationships with other organisms and have evolved to adapt to various environmental conditions. According to Nurashikin-Khairuddin et al. 2022, the use of entomopathogenic nematodes is significantly safer than conventional chemical pesticides when used in spray applications. Mendel et al. 2024 demonstrated that RPW insects can be fatally affected by two entomopathogenic fungal species, namely Beauveria bassiana and Metarhizium anisopliae, as well as the entomopathogenic nematode Steinernema carpocapsae. Liu et al. 2021 reported that adult R. ferrugineus can be parasitized by Teratorhabditis synpapillata, Sudhaus, and Praceroceilenchus ferruginophorus. Therefore, it is advised that entomopathogenic nematodes (EPNs) be utilized as biological agents to mitigate R. ferrugineus populations. Adult RPWs have been found to be infected by several EPN isolates, including Heterorhabditis bacteriophora, H. indica, S. abbasi, S. carpocapsae, S. feltiae, and S. riobravis, which are known for their high mortality effects on RPWs. Trunk injection of EPNs, particularly Steinernema carpocapsae, has been successfully tested in field trials, either alone or in combination with Beauveria bassiana (Bals, 2015). This method has shown high efficacy in reducing RPW populations. One of the most promising strategies for sustainable RPW control is the introduction of biological control agents, including predators such as Anisolia marina, Chelisoches morio, Platymeris laevicollis, Xylocorus galactinus, and Scolia erratica, as well as nematodes like *Heterorhabditis Adult RPWs have been found to be infected by several EPN isolates, including *Heterorhabditis bacteriophora,H. indica, *S. abbasi, S. carpocapsae, S. feltiae,* and *S. riobravis*, which are known for their high mortality effects on RPWs. Trunk injection of EPNs, particularly Steinernema carpocapsae, has been successfully tested in field trials, either alone or in combination with Beauveria bassiana (Bals, 2015). This method has shown high efficacy in reducing RPW populations.

2.5.3. Viruses

All stages of *R. ferrugineus* development were infected by the extremely powerful cytoplasmic polyhedrosis virus, and infection of older larvae in a lab led to deformed development of the adult. The cytoplasmic polyhedrosis virus (CPV) is the only virus identified in RPWs, according to viral control [16]. First identified in Kerala, India, this potent virus infected RPWS at various phases of growth. Later larval stage infections resulted in the appearance of malformed adults and a significant drop in insect populations [6].

2.5.4. Bacteria

Bacillus thuringiensis, *B. sphaericus*, *B. laterosporus*, *B. megatherium*, *Pseudomonas aeruginosa*, and *Serratia marcescens* are among the entomopathogenic bacteria (EPB) that are found to be pathogenic to *R. ferrugineus*. After 15 days of treatment, *B. thuringiensis* caused 94%

of the larval instars to die, suggesting that it could be used as a bio-agent for *R. ferrugineus* management [16]. Even though a wide variety of bacteria can infect insects, only those belonging to the Bacillus and Serratia genera in the order Eubacteriales have been officially recognized as effective insecticides [45] . Phoenix dactylifera trees are prevalent in Saudi Arabia. In a recent study, three bacterial isolates—*Bacillus thuringiensis*, *Klebsiella pneumoniae*, and *Serratia marcescens*—were identified via 16S rDNA sequencing and evaluated in vitro for their bioactivity against *Rhynchophorus ferrugineus*. All isolates exhibited significant insecticidal activity, with *B. thuringiensis* demonstrating the highest mortality rate (100%) within four days of treatment, followed by *S. marcescens* and *K. pneumoniae* within five and six days, respectively. The most effective concentration was 1×10^8 CFU/mL [46].

2.5.5. Fungi

The effectiveness of entomopathogenic fungi (EPFs) as biocontrol agents is becoming more widely acknowledged [47] . For instance, Bardan et al. (2020) used Beauveria bassiana at a dosage of 1 x 10^8 CFU/mg to show insect suppression. They used a huge iron pin to make holes around the infestation site, and then they used plastic pipe to inject the bioinsecticide. Other EPFs, such as Metarhizium anisopliae and M. pingshaense, have been demonstrated to be pathogenic against pests like *Rhynchophorus ferrugineus*. To increase *B. bassiana's* resistance to UV light and prolong its shelf life, a new microencapsulation method has been created. It is necessary to conduct more study on how to combine this technology with Integrated Pest Management (IPM) techniques [16]. EPFs are thought to be very efficient substitutes for traditional synthetic pesticides, such as Beauveria bassiana s.l. (Ascomycota: Hypocreales) and Metarhizium anisopliae s.l. (Ascomycota: Hypocreales) [48].

Fusarium oxysporum ZZ-L134 and Metarhizium anisopliae ZZ-A1 were the two new entomopathogenic fungal strains identified by rDNA-ITS S057 ence amplification, growth characteristics, and morphology from dead infected RPWs. Twelve days after treatment with a concentration of 1.0× 1010 conidia/ml, bioassays revealed that M. anisopliae ZZ-A1 strain had significantly higher corrected mortality low median lethal concentration (LC50) and median lethal time (LT50) values in fourth instar RPW larvae (90.92 vs. 77.28%) [29].

2.5.6. Predators

Xylocorus galactinus (Fieber) is one of the pest's frequent predators. *Platymeris laevicollis* Distant, a predatory beetle, fed on *R. ferruginousus*. Al-Zyoud et al. 2021 *Anisolabis maritima*, an earwig, and *Xylocorus galactinus*, an anthocorid, are known to prey on weevil eggs, larvae, and pupae. *A. maritima* exhibited a greater level of predatory efficiency [45].

2.5.7. Parasitoids

The parasitoids *Billaea menezesi* (Guimarães) and *Billaea rhynghophorae* (Blanchard) (Diptera: Tachinidae: Dexiini) are potentially important natural enemies of *R. palmarum*. For *B. menezesi*, parasite rates as high as 72% have been reported [14].

Although the scollid wasp *Scolia erratica* Smith (Hym., Scoliidae) is thought to ectoparasitoid red palm weevil larvae [45] sarcophagid fly *Sarcophaga fuscicauda* Butler attacks adult red palm weevils. *Tetrapolypus rhynchophori* Ewing, *Rhynchopolipus swiftae* Husband & O'Connor, and Rhynchophori (Ewing) are known to parasitize adults [16]. However, using natural enemies to control an organism economically has not been implemented at a significant scale in the field, and the difficulty of implementing this method is exacerbated by concealed life stage.

2.5.8. Gene silencing technology

RNA interference (RNAi) was used to silence genes. The six RferOR genes were successfully knocked down by dsRNA injection, with knockdown rates ranging from 75% to 80%. 56.25% of RPWs with PerOR1 silent were found to be non-responsive to pheromone cues. The RfVg gene silencing was employed by Antony et al. 2021 as a ferruginous management tactic. Utilizing diverse delivery methods such as injection, feeding, and drops, the gene silencing strategy has been successfully demonstrated against multiple targeted genes in insects, such as the Vitellogenin gene [49]. Because the olfactory co-receptor (Orco) and the OR protein form a heterodimer that aids in selectivity and sensitivity, Orco silencing may prevent the insect from responding to pheromones, which may offer a newly sophisticated method for controlling pests. Orco is a good target candidate, according to a number of authors [50]. Crop protection commonly uses RNA interference, or 'RNAi', which disrupts the plant by silencing the gene. *R. ferrugineus* already had its olfactory sensing genes discovered (Antony et al. 2021; Soffan et al. 2016). In comparison to control weevils (not injected), RferOrco (Olfactory Co-receptor (Orco) gene from the red palm weevil) expression was considerably lower in pupae of R. ferrugineus with its dorsal abdomen after dsRNA injection. Applications of olfactory disruption appear to have the potential to effectively contribute to the creation of a unique pest-management plan aimed at eliminating *R. ferrugineus* [52].

2.6. Host plant resistance

Through extensive interactions with herbivores over millions of years, plants have developed a wide array of defense systems to counter pest invasions [53]. Robust host plant resistance is crucial for effectively controlling *R. ferrugineus* in date palms. Several studies have demonstrated that date palm cultivars characterized by elevated sugar levels exhibit improved growth and development of *R. ferrugineus.* However, its development is inhibited by date palm cultivars such as Mazafati, which have hard tissues and high calcium levels [22,54,55]. Findings from preference for oviposition and regulated olfactometer investigations indicate that the widely used Khlas date palm cultivar is strongly favored by *R. ferrugineus* [56]. While our understanding of host plant resistance mechanisms related to antixenosis and antibiotic actions is well-established, the current utilization of this resistance in the control of *R. ferrugineus* is limited [16,56,57].

2.7. Cultural control

Both the infestation of *R. ferrugineus* in agricultural settings, and the effectiveness of visual examination are influenced by cultural practices. Hence, it is essential to establish branch management, adopt appropriate irrigation techniques, ensure field sanitation, perform frond pruning, and regulate palm tree density in order to effectively control the spread of *R. ferrugineus* from infected palms, reduce the likelihood of pest infestations, and improve the overall management of *R. ferrugineus.* Once infested, the trees need to be burned, buried deeply, or chopped into little pieces. Green palm leaf pruning must be avoided. This is because pruning provides a significant attraction for adults of *R. ferrugineus* and can facilitate egg deposition by females. During adult activity, pruning should be refrained from. Consequently, treatment should be done during the winter months, when the adults are dormant, and involve directly applying an insecticide to the tree's pruned or cut areas. Avoiding mechanical injury to palms controls the pest infestation as female *R. ferrugineus* are inclined to deposit their eggs in the softer tissues of trees [8,16,58].

2.8. Sterile insect technique (SIT)

According to Alphey 2016, in 1950, the initial SIT program was created to manage the new world screwworm, Cochliomyia hominivorax. Afterwards, this method has been effectively used to eradicate a variety of pests in other nations. SITs are biological control methods that involve the use of radiation to render male insects sterile. Large amounts of sterile male pests are generated in laboratory conditions and subsequently released into specific farms of date palm. In these farms, male pests copulate with wild females, resulting in the production of unfertilized eggs that do not progress to the larval stage. Additionally, SITs can be employed to improve conventional biological control strategies for the management of the RPW. In particular, females that mate with irradiated males may generate non-viable eggs, which could be useful targets for the deposition of egg parasitoids [60,61]. A study was conducted by Alnafisah and El-Shahed 2024, who sought to provide a more extensive mathematical model that considers the several phases of RPW life cycle. Furthermore, this model integrates three distinct methodologies: mechanical injection, pheromone traps, and sterile insect technology revealed that the parameters of the SIT, the mechanical injection, and the pheromone trap are crucial factors in managing the RPW in comparison with other methods.

2.9. Quarantine

RPW is classified as a quarantine pest in almost all of the countries [62]. Abraham et al. 1998 demonstrated the need for enforcing strict quarantine measures as the primary component of *R. ferrugineus* control. The movement of palm offshoots leads to the pest establishment in previously unaffected areas. In addition, it's critical to implement stringent quarantine regulations in order to oversee palm nurseries and implement *R. ferrugineus* IPM, banish the transmission of the pest through plant materials and sustain the desired level of control. Application of insecticides to date palm offshoots is regarded as an effective quarantine method [16,63,64]. Abdel-Baky et al. 2022 aimed to generate IPM control strategies for RPW by analyzing infestations and control methods from 2015 to 2020. The goal was to create an all-encompassing strategy for the future that reduces damage of RPW while safeguarding human health and the environment by reducing the use of hazardous chemical pesticides, and their finding revealed that the implementation of the quarantine and control protocols for RPW in Qassim province resulted in a reduction in the population of the invasive pest.

3. Conclusion

The cultivation of global date palms is seriously threatened by the Red Palm Weevil (RPW), particularly in the Middle East and North Africa. Its destructive behavior emphasizes the need for prompt diagnosis and efficient management, especially while it is still a larva. Biological control agents, botanical bio-pesticides, and nanotechnology are examples of environmentally benign alternatives to conventional chemical control approaches, which are becoming less problematic because of worries about resistance and the environment. Cutting-edge methods like data mining, gene silencing, thermal and acoustic imaging, and more hold enormous promise for improving early detection and control initiatives. To manage RPW infestations and protect the date palm sector, a comprehensive strategy that integrates these cutting-edge treatments within an Integrated Pest Management (IPM) framework is necessary for long-term sustainability.

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4. Statements and Declarations

Ethics approval This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to participate Not applicable.

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Generation of AI No generative AI was used in the preparation of this manuscript.

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