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REVIEW ARTICLE

Comprehensive review of the red palm weevil: Invasion biology, distribution and management strategies

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Abstract

The red palm weevil (*Rhynchophorus ferrugineus* (Olivier)) is one of the most destructive pests of palm trees worldwide, with severe ecological and economic impacts. This review synthesizes current knowledge on its invasion history, global distribution, host range, biology and damage mechanisms, while assessing advances in detection, monitoring and integrated pest management (IPM). Since its first record in India in 1790, human-mediated trade of infested palms has facilitated its spread across Asia, the Middle East, North Africa and Europe, with Oman reporting infestations since 1993. Temperature, humidity and other environmental factors strongly influence its lifecycle and dispersal, often enabling hidden infestations that remain undetected until irreversible damage occurs. Conventional management approaches primarily insecticides face limitations due to resistance, environmental risks and high costs. Recent advances in eco-friendly biological agents, pheromone trapping, RNA interference, remote sensing and artificial intelligence (AI) offer promising pathways to strengthen IPM frameworks. Case studies in the Gulf highlight both successes and persistent challenges, particularly in farmer participation, surveillance systems and cost-effective implementation. Future directions should prioritize reliable early-detection technologies, predictive modeling of pest distribution under climate change, enhanced quarantine measures and the integration of AI- and Internet of Things (IoT)-based monitoring tools. A coordinated regional strategy, supported by sustainable policies and farmer engagement, is critical to reducing the global threat of red palm weevil (RPW).

Keywords: distribution; integrated pest management; *Phoenix dactylifera*; predictive modeling; red palm weevil; *Rhynchophorus ferrugineus*

Introduction

Red palm weevil (RPW; *Rhynchophorus ferrugineus* (Olivier)) is a highly destructive and aggressive pest affecting palm trees worldwide (1). Rhynchophorus palm weevils belong to the Curculionidae family, which includes 10 known species (2-4). These species are classified into 3 primary regions: America, home to species such as *R. cruentatus* and *R. palmarum*; Africa, where *R. quadrangulus thrives* and tropical Asia, where *R. ferrugineus* and *R. vulneratus* are found (4).

R. ferrugineus (Olivier), *R. vulneratus* (Panzer) and *R. palmarum* (L.) have successfully established populations outside their native habitats (5). *R. ferrugineus* was 1st officially recorded outside its native Asian range in the Middle East in 1985 (5, 6). In desert, semiarid and Mediterranean climates, *R. ferrugineus* and *R. palmarum* have formed permanent populations, showcasing wide ecological adaptability among certain tropical palm weevil species (7-9). However, despite the wide movement of plant material from its original range, *R. cruentatus* remains largely confined to its native habitat along the Florida, South Carolina and Texas coasts, with no sustained expansion documented (5, 7).

RPW was 1st taxonomically described by Olivier in 1790 (10). Research indicates that this insect was initially identified as the most destructive pest of coconut palms in India in 1889 (11). The earliest documented information on RPW was published in 1891 in the Indian Museum archives and was later updated by Lefroy in 1906 (12). Significant damage to coconut and date palms was 1st recorded in the Indian subcontinent between 1906 and 1917 (10).

Despite extensive research on RPW, there remains a limited understanding of the effectiveness of integrated pest management (IPM) strategies across various climatic regions, which affects the long-term control of the pest (3). This knowledge gap underscores the necessity for further studies to develop tailored IPM strategies that can more effectively manage RPW populations and mitigate their damage to palm trees. Additionally, controlling these weevils is both costly and challenging because they often develop resistance to insecticides and detecting their infestations at early stages is difficult, ultimately reducing the efficacy of control programs (5). Furthermore, despite the availability of numerous preventive and curative measures, many countries face difficulties in managing RPW infestations, primarily due to a lack of awareness and knowledge about these measures, poor adoption rates and weak coordination among all stakeholders involved (13).

This article provides a comprehensive review of the RPW, covering its invasion pathways, geographical spread, host range, habitat, biology, lifecycle, impact, detection, monitoring, control and management strategies, while also highlighting future research needs and prospects. Distinctively, it emphasizes Oman and the wider Gulf region, integrating biological and ecological insights with emerging technological innovations such as artificial intelligence (AI), Internet of Things (IoT)-enabled monitoring and RNA interference. In addition, it addresses socio-economic challenges that shape management outcomes, critically examining policy gaps, farmer engagement barriers and implementation issues. By combining scientific, technological and practical dimensions, this review offers a holistic perspective rarely found in existing RPW literature and contributes to advancing sustainable control strategies.

Invasion pathways

Given the extensive adaptability of RPW, understanding the pathways of its rapid global spread can provide crucial insights into the factors exacerbating its impact. The widespread distribution of RPW underscores the significant role of human activities in its expansion (Fig. 1). In most countries, RPW infestation initially started through the following means:

a. Palm trees imported for decorative purposes: Infested palms were introduced for ornamental use and subsequently spread to date palm plantations (14).

b. Trade in planting materials: Trade in planting materials played a critical role in accelerating the pest's global spread (15).

c. Shipment of infested palm trees and shoots: Over the past 3 decades, RPW has primarily spread across nations through the shipment of infested palm trees and shoots for date production and horticulture (16).

The various pathways of spreading RPW underscore its ability to persist across various climates, resulting in extensive geographical distribution. These pathways include the transportation of infested plant material, trade operations and the natural migration of adult weevils. This widespread dispersal has resulted in the creation of RPW populations in a variety of conditions, from tropical and subtropical to temperate climates. The adaptability of RPW to different environmental conditions emphasizes the need for comprehensive management strategies. Here, we list some examples of its spread among countries around the world:

a. United Arab Emirates: The UAE was among the first Gulf countries to detect RPW, likely introduced via infested ornamental palm seedlings from Southeast Asia. Its proximity to Al Buraimi Governorate in Oman may have facilitated early cross-border spread, contributing to the 1993 record in Oman (14, 17).

b. Saudi Arabia: RPW spread to Qatif through accidental human mediation, primarily via infested palm seedlings imported by commercial nursery owners from India and Pakistan, with regional trade routes possibly contributing (14, 18).

c. Iran: The pest entered Iran through agricultural imports from Qatar and the UAE (14).

d. Egypt: RPW was introduced to Egypt through imported offshoots from Saudi Arabia and the UAE. This marked the beginning of its rapid spread across the country. Eventually, the infestation extended beyond Egypt's borders. Its spread across Spain and other Mediterranean countries was facilitated by the importation of infested palms from Egypt and local ornamental palm nurseries (11, 14).

e. Croatia: The pest was likely brought to Croatia through exports from Spain and Italy (15).

f. Tunisia: Tunisia traced the pest back to illegally imported ornamental palm trees from Italy (14).

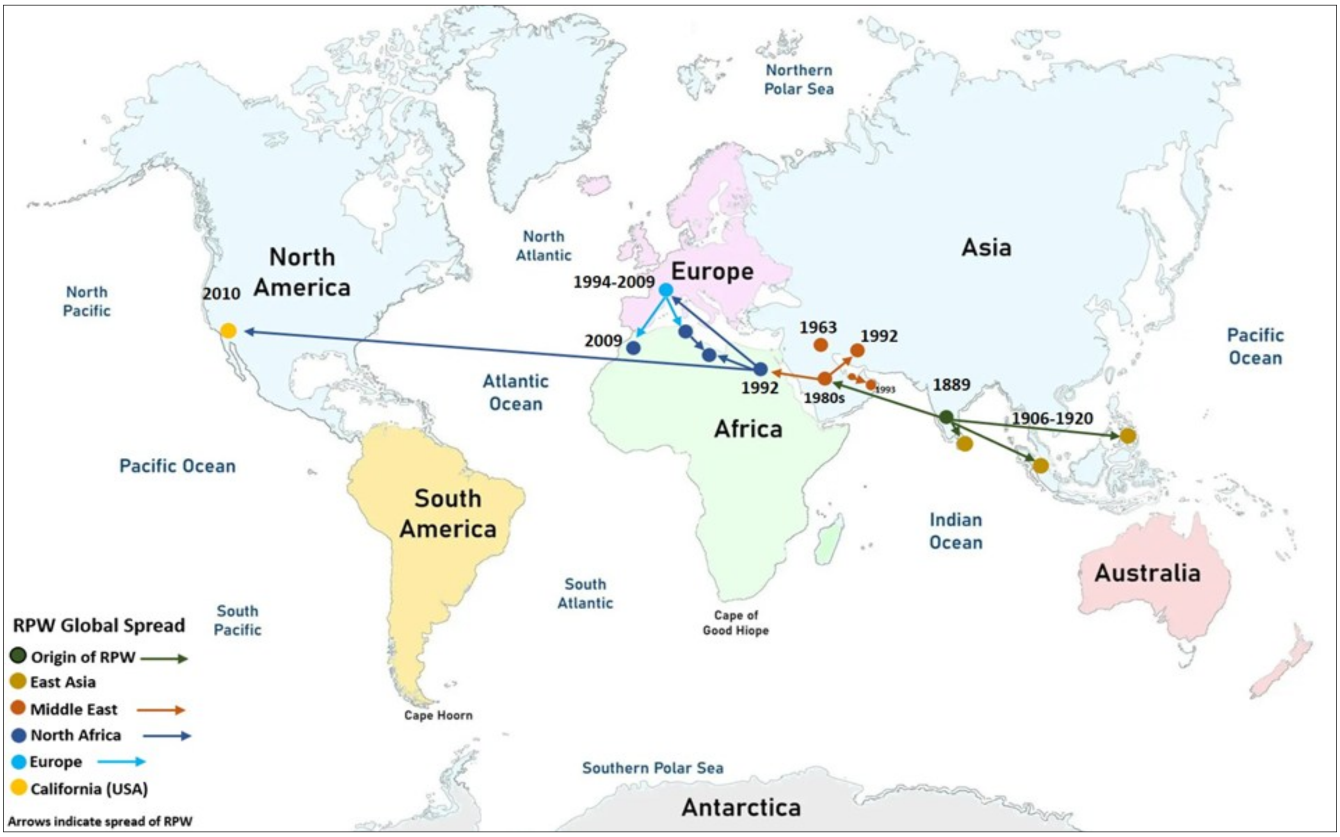

Fig. 1. Global expansion of RPW (*R. ferrugineus*) through international trade and agricultural exchange. Map by Alaufi, 2025.

g. Libya and South America: RPW infestations in these regions were believed to have been introduced by date palms shipped from Egypt for landscaping purposes (19). Mediterranean Countries: RPW's initial spread reached nearly all Mediterranean countries with Algeria remaining uninfested primarily via infested palm imports.

Geographical distribution

Following its initial infection in India, RPW spread across East Asia, reaching Ceylon and the Philippines in 1906 and Indonesia in 1920 (11). RPW was 1st reported in Iraq in 1963 (20) (Fig. 2). By the mid-1980s, RPW had spread to several regions. It expanded its reach to the Middle East, particularly the Gulf region, with observations in the UAE in 1985, Saudi Arabia in 1986, Qatar in 1989, Oman in 1993, Kuwait in 1993, Bahrain in 1995 and Iran in 1992. It later extended to North Africa in 1992 and Southern Europe in 1994 (2, 11, 21). In subsequent years, RPW was detected in several countries: France, Greece and Italy in 2006; the islands of Cyprus, Malta, Syria and Turkey in 2007; Portugal in 2008; the Netherlands Antilles, Albania, Libya, Morocco and Spain in 2009; California, USA, in 2010 and Tunisia in 2011 (10).

The RPW was 1st recorded in Oman in 1993, specifically in the Buraimi Governorate, within the Wilayat of Mahdha (22, 23). This event not only signified the start of its spread throughout the country but also set the stage for its subsequent appearance in other regions in Oman (Fig. 3). Over the following years, RPW spread to the Al Batinah Governorate, initially affecting Shinas and Sohar in 1995 and 1996 respectively. It further expanded its reach to Saham, Al Khaboura and Liwa in 1998 and was also recorded in the Al Dhahirah Governorate, particularly in the wilayats of Yanqul and Waqba (22). In 2009, RPW was first discovered in the Al Dakhiliyah Governorate, leading to its spread across the remaining wilayats in North Al Batinah (24). In subsequent years, it was found in the governorates of North and South Al Sharqiyah, as well as South Al Batinah, in 2012 and 2013 respectively (25-27). Between 2014 and 2020, the weevil spread throughout Oman's wilayats (28-30). Finally, it was reported in the Muscat Governorate, particularly in the Seeb Wilayat, in 2021 (30).

Host range and habitat

As RPW continues to spread across diverse regions, its ability to infest various host species and thrive in multiple habitats becomes increasingly apparent. Reports indicate that RPW has spread across the Old World and has been identified in 40 palm species within 16 distinct genera across nearly 60 countries (31, 32). Interestingly, RPW has also been observed infesting the century plant (*Agave americana*) from the Agavaceae family (33). Additionally, it targets various palms from the Arecaceae family worldwide, including the sugar palm (*Arenga saccharifera*), coconut palm (*Cocos nucifera*), Canary Island date palm (*Phoenix canariensis*) and both Washingtonia species (*Washingtonia filifera* and *W. robusta*) (34). RPW primarily attacks coconut palms (*C. nucifera*) in the Indian subcontinent and China, date palms in the Arabian Peninsula and Pakistan and the Canary Islands date palm (*P. canariensis*) in Spain (35).

Biology and damage symptoms of RPW

Morphology and life cycle

RPW's choice of hosts and habitats directly influences its lifecycle, as environmental conditions play a significant role in its reproductive cycles and developmental stages. RPW devastates palm trees by feeding on them internally (36). The weevil's life cycle typically ranges from 48 to 165 days, depending on environmental conditions and host plant, with most studies reporting durations of approximately 2

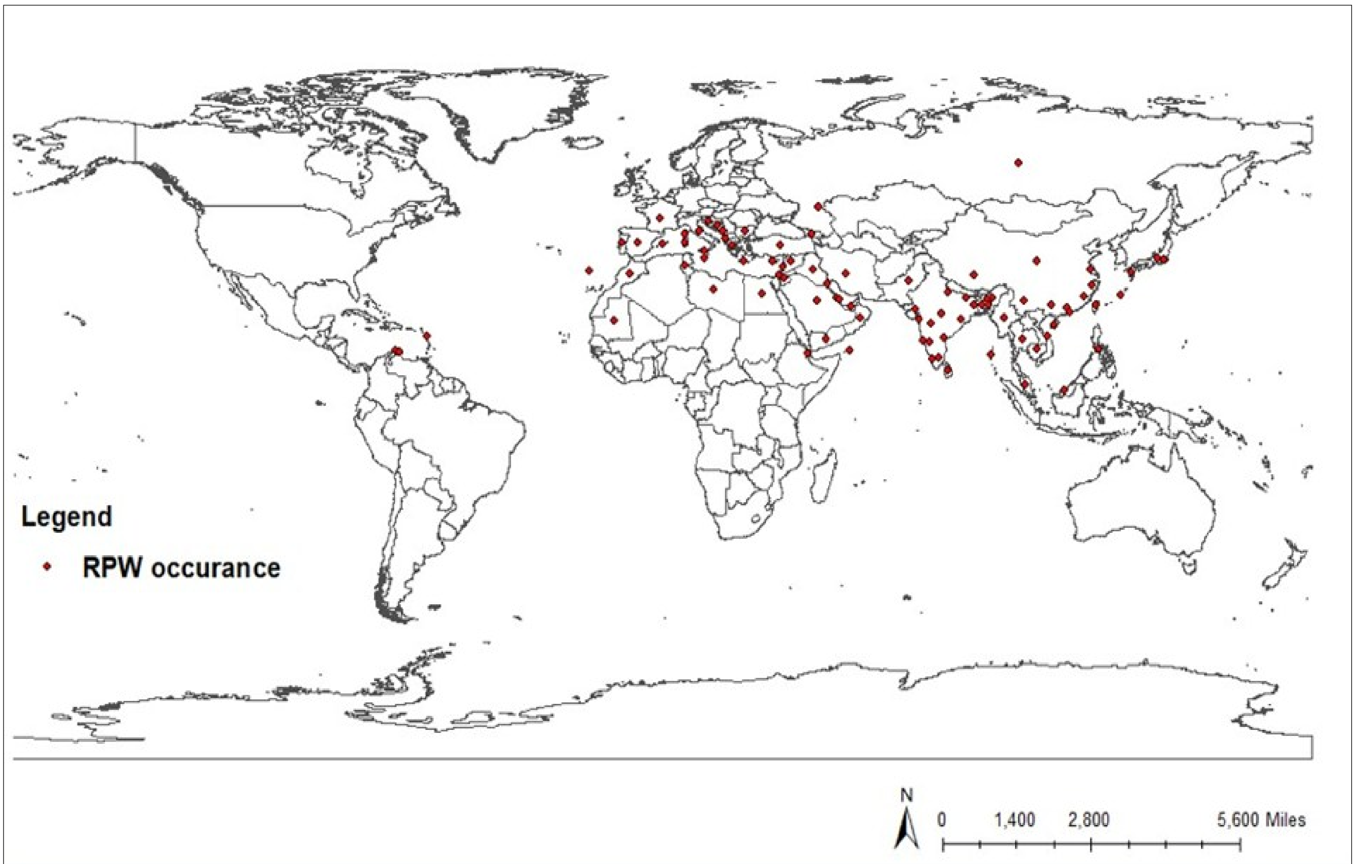

Fig. 2. Geographic distribution of the red palm weevil, based on data from the Invasive Species Compendium. https://www.cabi.org/isc/datasheet/47472 (Accessed 22 August 2024). *Map by Alaufi, 2025.*

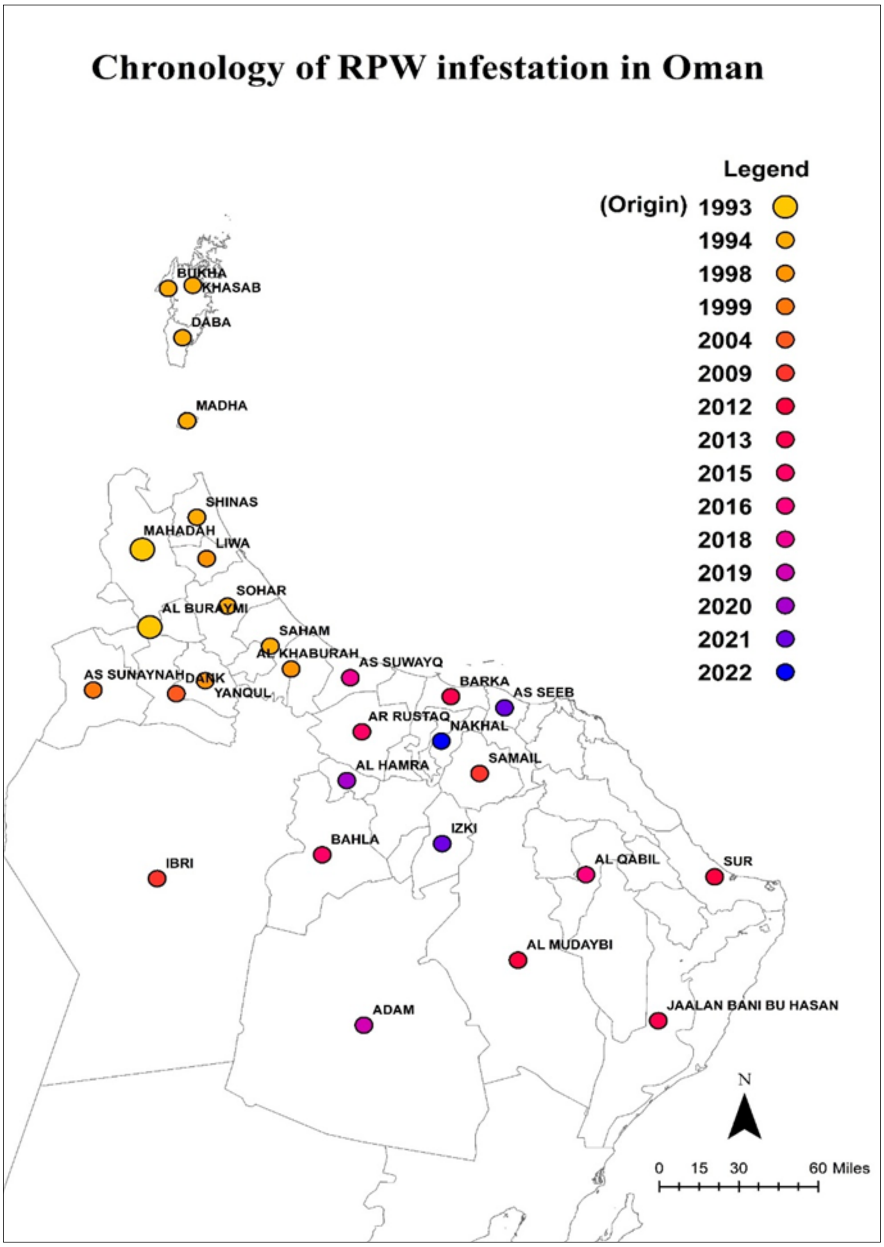

Fig. 3. Chronology of the red palm weevil infestation in Oman, indicating the beginning of the initial infestation in 1993. Map by Alaufi, 2025.

to 3 months (3, 10, 18) (Fig. 4). It can deposit up to 58-760 eggs throughout its lifetime (10, 21, 37). RPW females lay their eggs in a variety of palm tissue openings, including cracks, crevices, beetle-made tunnels, mechanical wounds, frond detachment sites and even rodent-created cavities (10, 18, 37). RPW eggs are creamy white, oblong and shiny; they hatch in 3–5 days and the resulting legless grubs grow up to 50 mm long, developing over 24–128 days (38). The hatched larvae burrow into the palm core, feeding on its inner parts before eventually forming a protective cocoon and emerging as adult weevils (10, 38). The pupa usually stays inside the cocoon for a period of 11-50 days before emerging as an adult (32). The newly developed red-brown weevil has a long, curved snout and males and females can be identified by soft hair on the nose (10) (Fig. 5).

Adult RPW are most active in the Middle East during March-May and October-November; however, activity patterns vary by region due to climatic and ecological factors. In southern Japan, internal trunk warmth enables extended seasonal activity into the winter months (39). In other regions, correlations between adult flight activity and weather parameters-including temperature, humidity and wind velocity-were found to be weak or statistically insignificant (40, 41). Additionally, RPW reproductive cycles are temperature-dependent, with less than one generation per year expected in areas with mean annual temperatures below 15 °C and more than 2 generations in areas above 19 °C, partly due to the presence of non-flying individuals within the population (33, 42).

Damage symptoms

Unfortunately, RPW infestations often go unnoticed until the late stages, when severe tissue damage has already occurred, making it too late to restore the palm tree's health (43). The damage and symptoms caused by RPW infestation can vary from leaking brown fluid to wilting offshoots (42) (Fig. 6). Tunnels may be found in infested trunks, empty pupal cases found nearby and frass at entry points (10, 33). In severe cases, the trunk may collapse (1, 31). There have been widespread reports indicating that these symptoms result in the palms collapsing and eventually dying (10, 22) (Fig. 7). Given the challenges of the early detection of RPW, frequent visual inspections (at least every 2 months) of susceptible palms under 20 years of age, specifically those of coconut and date palm species, are required (42).

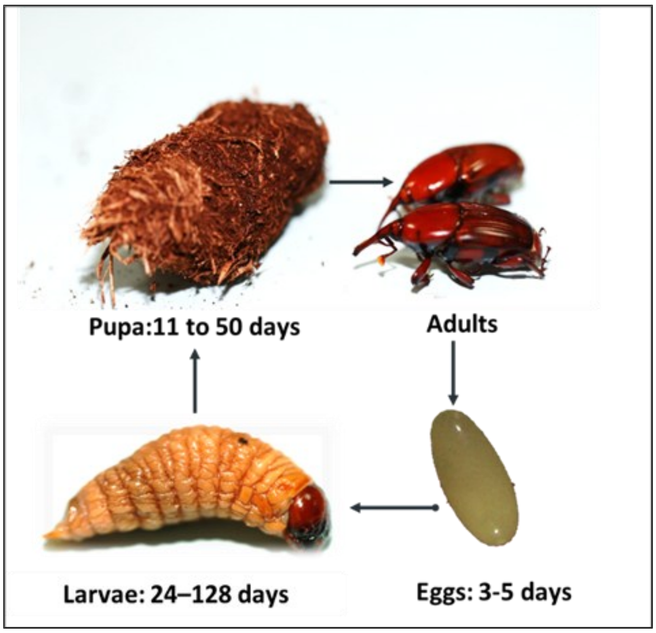

Fig. 4. Life cycle of *R. ferrugineus* Photo by Alaufi, 2019.

Fig. 5. The male weevil is distinguishable from the female by the presence of soft reddish-brown hairs on the dorsal side of its elongated snout. Photo by Alaufi, 2019.

Fig. 6. Viscous fluids ooze from the tunnels due to larvae inside the palm tree. Photo by Alaufi, 2015.

Fig. 7. The RPW causes significant damage to palm tissue and weakens the structure of the palm trunk, causing the palm to collapse and eventually die. Photo by Alaufi, 2013.

Bioecological factors influencing RPW life

RPW is a significant economic pest whose lifecycle is heavily influenced by temperature fluctuations (44). As poikilothermic insects, their development accelerates with rising temperatures, affecting reproductive cycles and egg deposition rates (1). Studies in the Mediterranean region confirm that RPW development is temperature-dependent (35, 38). Trees infested with RPW are typically warmer by 1 °C -2 °C compared to healthy ones, indicating the role of temperature in host recruitment (45). Laboratory findings show that temperatures above 40 °C are lethal to RPW eggs and colder climates halt egg laying and hatching (46, 47). Research from Pakistan has linked infestations to higher temperatures, with increased humidity having a contrary effect, highlighting the need to consider multiple environmental factors (48). Additionally, soil moisture is crucial to RPW spread, as shown by studies in Saudi Arabia (49).

Various biotic and abiotic factors, including gender, ambient temperature, relative humidity and solar radiation, affect the flight behavior and dispersal of RPW (50). The weevil's behavior is greatly influenced by its climate, with differences observed in temperate, arid, subtropical and tropical settings (39, 51-53). In Saudi Arabia's arid climate, the weevil has active phases in April, May, September and November, coinciding with warmer temperatures. Moreover, a previous study showed an inverse correlation between relative humidity and the number of RPWs caught in traps, suggesting that variations in humidity levels could affect the weevil's behavior (54). Weather conditions significantly affect the behavior of RPW, with a direct correlation to temperature and an inverse connection to rainfall (52, 55). Subsequent investigations revealed that higher humidity levels reduce the flight ability of RPW, while solar radiation significantly impacts the emergence of adult weevils, especially in sunny conditions. Consequently, the activity patterns of RPW vary annually according to the specific weather conditions of the monitored area (50).

In Egypt, it was discovered that the number of RPW adults caught in pheromone traps was highest in the hot summer months and lowest in December and January when the daily temperature was less than 14 °C on average (56). Additionally, another study found that increased temperatures and wind speeds were correlated with higher adult RPW capture rates, while lower temperatures and relative humidity levels had minimal negative effects (41). Furthermore, it was found that increased temperatures, greater sunlight and stronger winds were associated with a rise in adult captures, while higher humidity was correlated with a decrease in captures (57). However, the fluctuation in the population of RPW was affected differently by the daily average temperature and relative humidity levels (58). Similarly, temperature had a positive effect on trap captures of both male and female RPW, while higher relative humidity was associated with reduced trap efficiency (59). RPW adults in the Valencia region are most active in the autumn at approximately 20 °C and less active in the colder winter months (60).

An old investigation of RPW demographic patterns in Oman disclosed pronounced population fluctuations throughout the year, with notable peaks in March, May, August and October, while December and January exhibited lower numbers (22). Concurrently, daily behavioral patterns indicated heightened activity during the twilight hr of sunrise and sunset. A separate study in Oman corroborated these findings and identified a secondary peak in activity between 6 AM and 9 AM and 6 PM and 9 PM (18). In a recent study conducted in the UAE, researchers found that the peak capture time for RPWs occurred between 3:00 AM and 6:00 AM, aligning with cooler temperatures (17). During this period, 85.72 ± 3.39 % of the weevils were captured.

In summary, the factors affecting the movement of adult RPW are multifaceted and complex, involving temperature, humidity, solar radiation, winds and rainfall. High temperatures promote the weevil's flight and spread, while low temperatures hinder it. Increased humidity is less favorable for the weevil's dispersal. Notably, solar radiation, especially on sunny days, correlates with the weevil's ability to move and fly. Conversely, there is an inverse relationship between the flight and spread of RPW, winds and rainfall. Heavy rain and strong winds can disrupt the weevil's flight activity.

Impact and damage

The biological resilience and adaptability of RPW translate into significant economic damage, particularly in major date-producing regions, as detailed in the following section. RPW infestations have resulted in significant economic damage to date palm production in the Gulf region, with documented losses in yield, tree survival and control expenditures. Initially, the infestation caused significant economic damage, with many *P. canariensis* and *P. dactylifera* palms being attacked, leading to severe damage (50). Moreover, RPW inflicts severe economic damage to date palm production in the Gulf with direct losses estimated between USD 1.74 and USD 8.69 million annually, affecting yield and farmers' revenues (36). This substantial economic loss is further exacerbated by eradication costs that range from USD 5.18 million to USD 25.92 million, depending on the extent of the infestation (61). Infestations have caused a severe reduction in plantation yields, from only 0.7 t to 10 t ha^{-1} (33). Furthermore, RPW has had a devastating impact on palm tree populations, with close to 50000 palm trees being eradicated in Spain from 1996 to 2010 due to the infestation, with more than 90 % of losses recorded between 2005 and 2010 (6). Similarly, the failure to eradicate RPW in the Valencia area resulted in a substantial economic loss, with a total cost of 27 million euros, highlighting concerns for the Mediterranean region (38). Moreover, the potential economic impact of palm eradication in Oman was estimated at USD 130000-700000 emphasizing the need for effective management strategies (61).

According to unpublished reports from the Ministry of Agricultural Wealth, Fisheries and Water Resources (MAFWR) for the years 2012 and 2017, the infestation of RPW in Oman significantly increased by approximately 68 %, with the number of affected date palms rising from 149 to 10196 which is a significant change (62, 63) (Fig. 8). For example, considering the Sohar and Saham Wilayats located in North Al Batinah, the infestation in Sohar grew from 2 to 338 date palms and the number of affected villages surged from 2 to 29, a comparison that highlights the spread of the infestation. This trend is mirrored in Saham; the infestation began with a single village in 2012, where 50 date palm trees were affected, but after 5 years, the number of villages infested with RPW increased to 21 and the number of date palms infested grew to 748 (Fig. 9 & 10). In 2022, Oman reported a significant number of palm trees infested by RPW, with approximately 38328 palms infested and 6774 palms being cut to prevent further spread, underscoring the need for rapid intervention (64). RPW infestation can significantly reduce a palm tree's yield potential, slow down plant growth and ultimately lead to

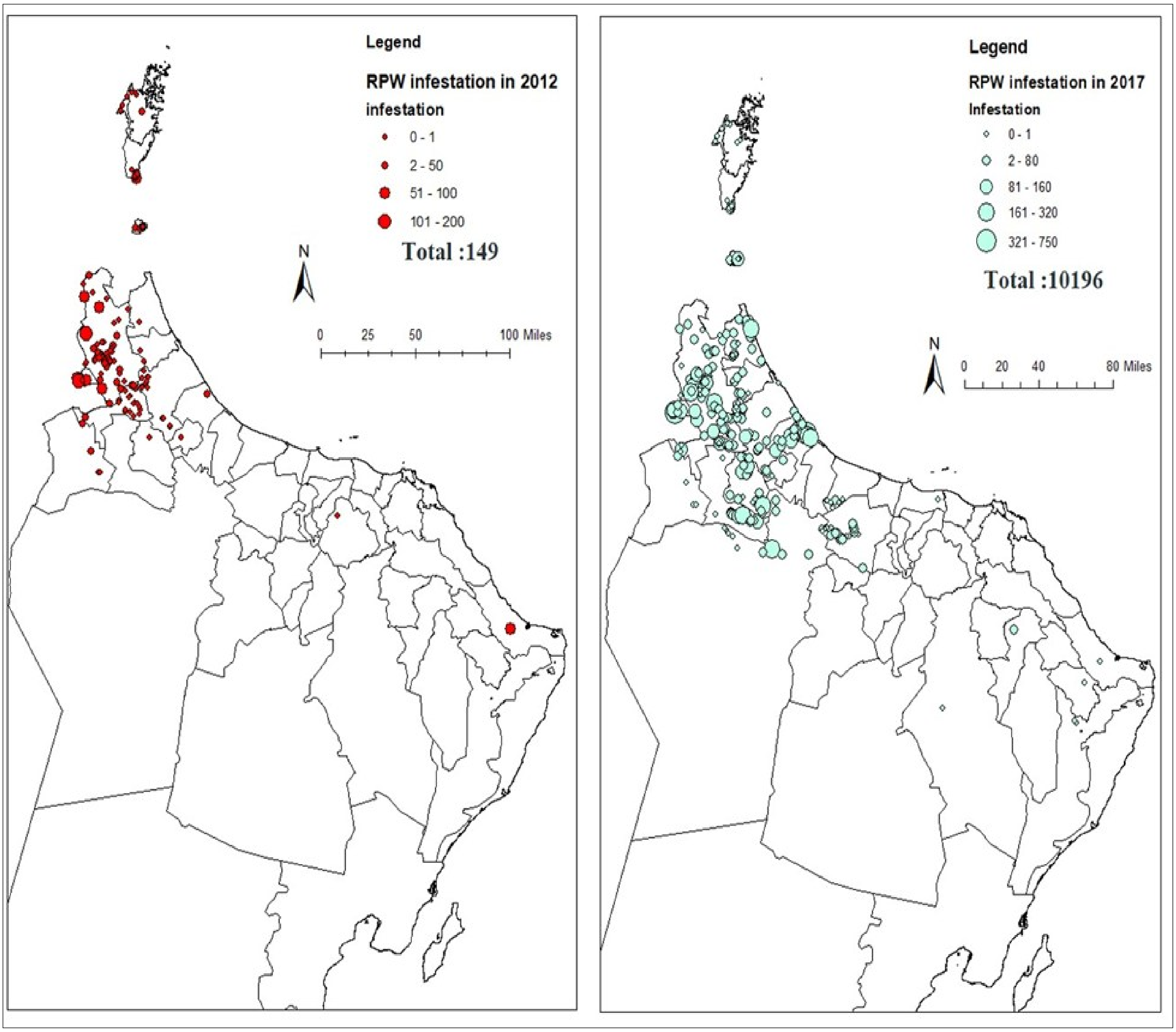

Fig. 8. A comparison of date palm infestations with RPW between 2012 and 2017 in Oman. Map by Alaufi, 2025.

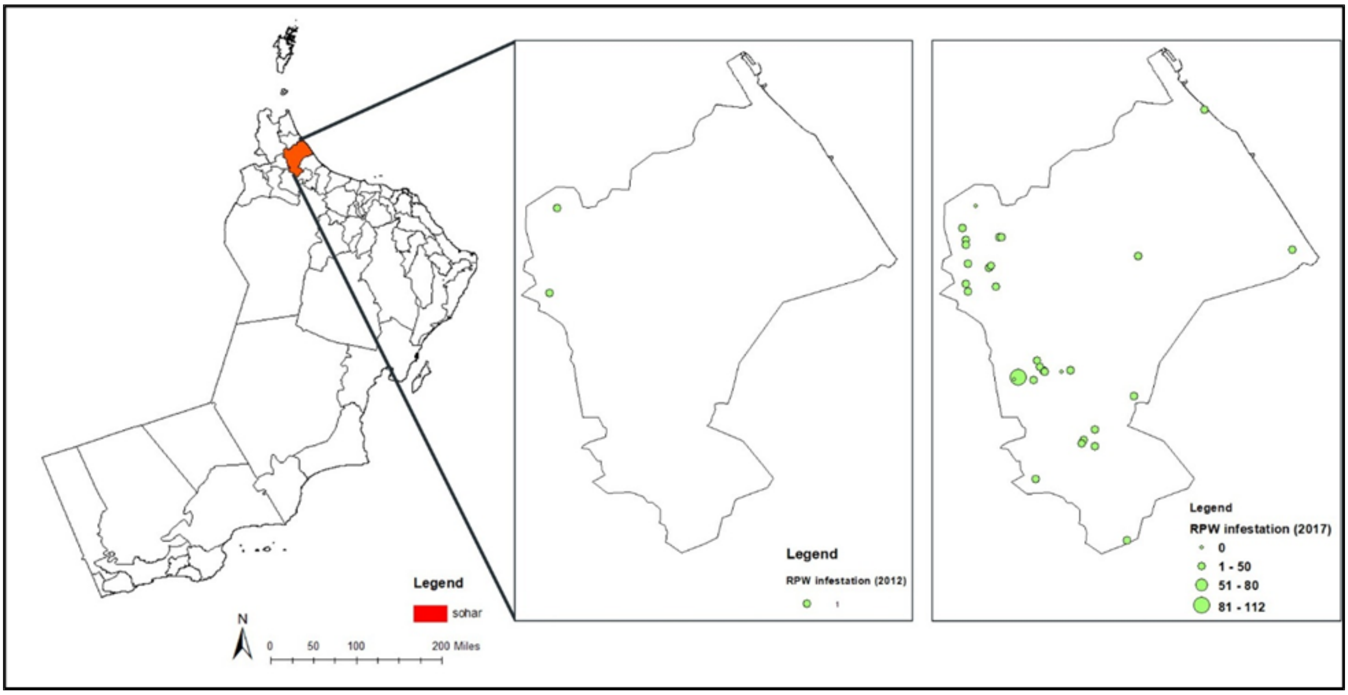

Fig. 9. The map shows the number of infested date palms with RPW in the Wilayat of Sohar (North Al Batinah) between 2012 and 2017, where the number of infected date palms was 2 and rose to 338 date palms. Map by Alaufi, 2025.

Fig. 10. Evolution of RPW infestation in Saham, North Al Batinah (2012-2017), where the number of infested date palms was 50 and rose to 748 date palms. Map by Alaufi, 2025.

its demise and death (33, 42). Moreover, the presence of RPW larvae can cause the green leaves of the plant to detach easily when pulled (51). Additionally, affected palm trees may experience a decrease in overall leaf count due to the early drying of lower layers and the delayed growth of new leaves (33).

Detection and monitoring

The significant economic toll from RPW infestations calls for more efficient detection and monitoring practices, particularly given the difficulty of early identification. Early identification of RPW infestation in palm trees is crucial for preserving the tree and enabling effective pest control measures, as early-stage detection ensures that the apical meristem (palm heart) remains undamaged and the trunk structurally stable-making recovery possible (32, 33). At this stage, insecticide application can be effective in eliminating the infestation and restoring the tree's health (65). Therefore, efforts are being made to develop devices for the early detection of RPW infestation, as signs only become apparent in the later stages of the attack (32). Monitoring RPW can be achieved through individual tree examinations or by using baited pheromone traps to capture adult weevils (1, 33). These pheromone traps are designed to facilitate the entry of adult weevils while ensuring ease of handling and service (32). Moreover, trained dogs can effectively detect foul odors from RPW-infested trees (37, 42) and larvae-feeding activities within stems can be identified using acoustic detection, although this method offers limited benefits (1, 33).

Scientists are using computer science, sensors and advanced electronics to create fast and efficient automated methods for detecting RPW (43). Moreover, promising technologies, such as acoustic devices, X-ray imaging, remote sensing and radio telemetry, are leading the way in controlling this pest (1, 33, 42). Additionally, thermal imaging is effective for identifying infested date palms (2, 43). With advancements in artificial neural network (ANN) technology, it may be possible to detect RPW in its initial stages (43). Earlier, it was found that the InceptionResNet-V2 classifier achieved 97.18 % accuracy on TreeVibes audio recordings, outperforming other models and is expected to be used in date palm farms for RPW detection (66). The advanced data mining techniques were used to forecast RPW infections with up to 93 % accuracy by analyzing plant size and temperature data from individual trees (67).

Control and management strategies

In addition to robust monitoring systems, effective control and management strategies are essential to prevent further spread and economic loss due to RPW. Effective prevention of RPW infestation requires strict plant and field sanitation, as well as proactive measures to prevent the weevil's entry into palm trunks through wounds or cuts (10, 33). Moreover, current efforts in the Gulf and Asia to control RPW are moving away from insecticide reliance toward IPM strategies, focusing on pheromone traps and biological control (3). Initially, RPWs were managed using various methods (10).

Sterile insect technique

The sterile insect technique, conceived in the 1930s-1940s, was explored in India during the 1970s, achieving a 90 % sterility rate through X-ray exposure. However, despite these efforts, there is no record of successful field control due to the secretive nature of RPW (10).

Pheromone trapping

Additionally, pheromones, identified with advanced equipment, are used for detection and mating disruption, with new eco-friendly, safe and cost-effective behavior-modifying chemicals emerging (10). The 1st pheromone from male RPW was identified in 1993 as an aggregation pheromone, with an additional pheromone and another was later found, both eliciting strong electrical responses in the antennae of both sexes (10, 32). Consequently, the use of pheromones and baits has led to a remarkable decrease in the number of RPW infestations (37). RPW traps also utilize plant substances and fermenting odors enhanced by kairomones for the control and surveillance of the weevil in Asia and the America (1, 3).

Chemical treatments

Experts have developed various methods for managing RPW using synthetic insecticides (10). These techniques include wound dressing, axil filling, spraying, dipping, trunk injection, drenching, fumigation and soil application (3, 31, 32). As part of the chemical control program, cypermethrin is sprayed on the palm, canopy, stem and crown of the tree, while methamidophos or monocrotophos is injected into the trunks (11, 37). In addition to the previously mentioned examples of fighting RPW, several plants, such as French marigold, Ceylon, citronella grass, clove and cardamom, have shown effectiveness as insecticides for managing RPW (37).

Biological control

Researchers are exploring environmentally friendly biological control agents against RPW (10). Moreover, RPW's natural enemies include nematodes, bacteria, viruses and generalist insect predators, with 2 mite species possibly parasitizing the adult weevils (3). However, despite identifying various natural enemies of RPW in multiple countries, none have been utilized due to their hidden presence (1). Additional challenges involve effectively administering the biological control agent to the pest within the palm and maintaining its efficacy, particularly in arid and hot climate conditions in some countries (68). Examples of the natural enemies of RPW include 2 nematode parasites that are closely related species within the genus *Praecocilenchus-P. rhaphidiophorus* and *P. ferruginophorus* (3, 32, 37). Furthermore, a bacterial infection caused by *Pseudomonas aeruginosa* was detected in RPWs in Kerala, India, in 1995 and the cytoplasmic polyhedrosis virus that infected all stages of the insect was isolated from the same region in 1990 (3, 37). The fungus *Metarhizium anisopliae* was successfully cultured on rice and released into palm fronds, infecting scarabaeid beetles and, incidentally, some RPWs (3, 37, 42). Researchers have demonstrated that entomopathogenic fungi, such as *Metarhizium anisopliae* and *Beauveria bassiana*, are effective in controlling RPW, both in laboratory and field conditions (69). Additionally, indigenous and commercial entomopathogenic nematodes have shown significant potential in managing this pest (70).

Host plant resistance

Several date palm cultivars possess traits that suppress RPW development, including high calcium content, hardened tissues and oviposition antixenosis (33, 65). However, these resistance mechanisms remain underutilized in current IPM strategies (33). While they contribute to reduced pest preference and partial inhibition, they are not yet applied as practical control measures. Despite documented antixenosis and antibiotic effects, host plant resistance is still a neglected component in RPW management programs (71). Genetic engineering such as *Bacillus thuringiensis* (Bt) endotoxin expression in palms, offers promising potential for long-term IPM enhancement (52).

Microwave treatment

However, multiple experimental studies have demonstrated the method's efficacy under controlled conditions. For instance, microwave heating has been shown to induce lethal hyperthermia in RPW adults and larvae without damaging palm tissues (37). Additionally, validated thermal models and laboratory trials confirm that exposure at 5.4W cm^{-2} for up to 30 sec can impair reproductive capacity, suggesting potential for disrupting both current and future infestations (72). Another study using Phoenix canariensis confirmed selective heating effectiveness, reinforcing its viability as a non-chemical option in pesticide-restricted environments (73). While further field validation is needed, these findings support the inclusion of microwave treatment as a promising component within integrated pest management frameworks.

Phytosanitary/quarantine

Emphasizing quarantine and surveillance while enhancing capacities is essential for areas that do not yet have the pest and are at risk of infestation (2). Maintaining clean palm and field conditions is crucial for managing RPW in date plantations, involving techniques such as varietal selection, managing grove humidity through spacing and irrigation and pruning fronds and offshoots (74). Previous study documented RPW control programs in Oman, which involved implementing quarantine laws to prevent the introduction of infested plant material (17, 22). The programs also utilized pheromone traps and trunk injection methods to monitor and control the weevil population (17, 18).

The integrated pest management program

IPM programs for RPW have effectively reduced infestations in various countries and we will review some case studies of these successes. The RPW-IPM program in Al-Ahsa oasis, Saudi Arabia, which covers three million palms over 4000 ha, employs traps, inspections and treatments to control RPW, leading to significant reductions in trap captures and insecticide applications (33, 75). Large-scale studies in the UAE revealed that insecticide sprays and pheromone trapping reduced date palm infestations by approximately 36 % and 64 % respectively, over 2 years (21). A study from the UAE reported that pheromone trapping, even without insecticides, achieved a 71 % reduction in date palm infestations across 6 farms over 1 year (51). While this result highlights the potential of pheromone-based strategies under specific conditions, it is generally accepted that such methods are most effective when integrated with complementary IPM components (52). In Oman, the introduction of a pheromone-based RPW-IPM resulted in a notable decrease in infested date palms, decreasing from 24 % in 1998 to only 3 % in 2003 (22). Furthermore, continuous trapping of RPW over time has effectively reduced infestation levels in various coconut plantations, including those in Sri Lanka, India and Costa Rica (52, 76 –78). Notably, Sri Lanka recorded a decrease in infestation levels, India prevented new infestations and Costa Rica reduced *R. palmarum* infestation by 90 %. The Canary Islands' government implemented a 10-year regional eradication program for RPW, which successfully eliminated the invasive pest from the archipelago, with the last infestation site declared free of the pest in 2016 (79).

IPM approaches for controlling RPW highlight reducing chemical input through environmentally compatible methods (3). These methods include pheromone traps, surveillance technologies and biological control approaches, such as enhancing local natural enemies, introducing host-specific enemies and developing biopesticides (10, 32). These methods could also involve removing infested fronds and offshoots, as well as adjusting irrigation practices (37). Additionally, stakeholders and farmers can be trained on best practices and weevil traps and infestation reports can be monitored to refine the control strategy (1). While IPM has emerged as the most effective and practical solution in many contexts, its implementation has also faced challenges, including low farmer participation, unclear operational guidelines and variable adoption across regions (80). These limitations suggest that IPM's effectiveness is not always universal, but rather contingent on adequate institutional support, farmer engagement and localized adaptation (42).

Future directions and research priorities

Although there have been improvements in methods for controlling RPW infestation, there are still significant gaps, especially in terms of long-term management solutions and efficient early identification. These gaps include the need for more sustainable pest control approaches, increased farmer education and engagement, the integration of advanced technologies, including AI and machine learning (ML) and the creation of cost-effective and adaptable solutions. Future research directions should further explore these areas, with the goal of improving both the effectiveness and efficiency of existing measures while reducing environmental impact and solving socioeconomic difficulties.

Major gaps and challenges of the RPW-IPM strategy

This section summarizes the main gaps in the current RPW-IPM strategy. The implementation of early detection, surveillance and monitoring programs for RPW faces several challenges (68). These challenges include the lack of a reliable detection device, low farmer participation, unclear guidelines for categorizing palm stages of attack and the absence of standardized surveillance and monitoring programs (1, 42, 68). Moreover, pheromone trapping and semiochemical control methods have limitations, such as labor-intensive and costly maintenance, low farmer participation, inadequate data collection and the lack of smart traps that can transmit data, along with insufficient scientific assessment of new traps and lures (1, 68).

Furthermore, the use of preventive and curative chemical treatments for RPW is problematic due to the overuse of insecticides, the lack of effective natural alternatives and the development of resistance in RPW to commonly used insecticides. Improper use of insecticides leads to environmental contamination and food chain pollution, causing issues with insecticide residues on dates that hinder trade (1, 42, 68). The removal and disposal of severely infested palms are challenging due to varying protocols, high costs of palm shredders, delayed removal and the escape of adult weevils during transportation (68). These issues hinder effective eradication efforts and increase the risk of further RPW spread (1, 42, 68). Phytosanitary and quarantine regulations against RPW are not adequately enforced at the national and regional levels, leading to inconsistent treatment protocols and weak enforcement due to insufficient staff oversight of the gaps (68). Furthermore, obtaining certified planting material is a significant challenge, undermining the effectiveness of phytosanitary measures (1, 42, 68).

The use of geographic information systems and periodic validation of RPW management programs are hindered by the lack of data on georeferenced localization of palms and RPW-IPM components, as well as insufficient validation of programs at local and national levels (1, 68). The inefficiency and lack of sustainability of known biological control agents are obstacles to their effective use in the field for controlling RPW, limiting their potential as viable control strategies (1, 42, 68). Lastly, agricultural practices in many areas receive very little attention from farmers and other stakeholders, as their influence on RPW infestation and its management is largely ignored (1, 42, 68).

In this regard, the literature highlights various successful early detection techniques that are efficient, user-friendly and cost-effective, including biological and physiological indicators, thermal imaging, chemical signatures, acoustics, laser-induced remote sensing, breakdown spectroscopy and near-infrared spectroscopy (13). Despite these advancements, the failure to control RPW often stems not from a lack of technology but from socio-economic and operational challenges. There is a notable lack of quantitative data on the economic and social impacts of RPW at both local and national levels (68). Collecting this data is urgently needed, as it will help justify the cost/benefit ratio for controlling this pest through analysis, identify weaknesses in current control programs and develop effective socio-economic solutions. Furthermore, to maximize the effectiveness of early detection techniques, it is crucial to increase farmer involvement in detecting RPW-infested palms, develop standardized protocols for visual inspections and monitoring and utilize geographic information systems to record detected infestations (13). A variety of new tools for managing RPW through IPM have recently become available on the market. However, these tools require thorough testing and validation at both the national and regional levels to ensure that only effective, affordable and user-friendly technologies reach farmers (68).

Prospects of the RPW-IPM strategy

Scientists have developed various methods and technologies for detecting, monitoring and managing RPW, which need to be rigorously evaluated and tested for their feasibility in the field as user-friendly, cost-effective and quick solutions (42). The future of RPW management may hold promising prospects, including the validation of management programs, the testing of innovative technologies and the use of RNA interference (RNAi) technology in practical field applications (2). Additionally, RNAi technology can be developed to enhance semiochemical-based strategies against RPW in date palms by disrupting gene function (42).

The IPM program can be improved by intensifying the search for effective natural enemies, breeding palm varieties that are tolerant or resistant, developing biocontrol techniques and creating a detection tool for RPW infestation (42). Further research is urgently needed to explore the use of plant extracts, Sterile Insect Technique (SIT) and gene silencing technology, as well as to develop transgenic plants as new, efficient and eco-friendly methods for eliminating RPW(71). A comprehensive assessment of attract-and-kill technology and dry traps using electromagnetic technology should be conducted, covering all untested areas (42, 74).

Further studies are required for the deployment of drones integrated with artificial intelligence and the IoT for the early detection, control and supervision of RPW infestations in date palm plantations (81). The future of data collection for RPW-IPM programs may depend on developing and validating mobile apps that allow for georeferenced data recording at field locations using smartphones (2). It is also crucial to gather data on the socioeconomic implications of RPW control and to improve farmer engagement in control programs, which are equally critical components of the overall strategy (82).

Numerous statistical and ML techniques have been developed, often in collaboration with geographic information systems and remote sensing technologies, to predict species distribution (83). Predictive geographic models are crucial in ecology for analyzing invasive species spread, climate impact and species diversity distribution patterns (84). Bioclimatic, species distribution and ecological niche models are instrumental in predicting shifts in invasive species ranges by profiling their known locations against environmental factors (85). Species distribution models, such as ANUCLIM/BIOCLIM, CLIMATE, CLIMEX, DOMAIN, GARP, HABITAT and

MaxEnt, are used to forecast a species' potential distribution by assessing climate suitability, with CLIMEX, GARP, HABITAT and MaxEnt being the most commonly used tools (86, 87). In developed nations, species distribution models, such as CLIMEX and MaxEnt, are increasingly employed to forecast the spread of environmentally destructive pests, import biocontrol agents and investigate species interactions (88).

MaxEnt was employed algorithms and environmental data to forecast the global distribution of *Oryctes monoceros* and *Oryctes rhinoceros*, suggesting their potential presence in major palm cultivation zones and highlighting vulnerability to these beetles (89). The CLIMEX model was later used to assess historical and predicted climatic data, which revealed the global distribution risk of the coconut hispine beetle (*Brontispa longissimi*) (90). Genetic Algorithm employed for Rule-Set Prediction to predict the expansion of the insect *Brontispa longissimi* in China (91). For instance, GLM, MaxEnt and BRT models were employed, alongside 4 GCMs, to predict Dubas bug threats in Oman by 2050 and 2070, suggesting that northern Oman is particularly vulnerable and advocating for IPM over climate models for effective control (92). Similarly, another study using the MaxEnt model forecasted minor fluctuations in habitat suitability for Northern Garra fish in Oman's Hajar Mountains between 1981 and 2100, with some regions potentially experiencing marginal changes in optimality (93). A recent study applied the MaxEnt model to predict a rise in *Ceratocystis fimbriata* affecting Oman's mangoes until 2040, followed by a trend toward less conducive environments through 2060 (94). Another study used ordinary least squares and geographically weighted regression in ArcGIS to predict the future distribution of 3 biological control agents of the Dubas bug in Oman, demonstrating the effectiveness of spatial analysis and modeling in understanding the distribution of Dubas bugs and their natural enemies (95).

There is a lack of references in the current literature on the use of modeling software to predict the incidence of RPW in the Gulf countries. According to research conducted globally, numerous studies have examined the applications of models in predicting RPW outbreaks, which may be worth referencing in this context. A previous study highlighted the effectiveness of employing CLIMEX 1.1 to predict the dissemination of *R. ferruginous* in China, integrating historical (1981–2010) and projected (2011–2040) climatic data in conjunction with a robust suite of 17 environmental variables encompassing thermal parameters, thermal stress and soil moisture and stress factors (87). The findings suggest that if moderately suitable habitats decline, the habitat of RPW, currently confined to central China up to 40.1° N, may shift northward. Notably, a separate investigation found that MaxEnt outperformed GARP, exhibiting higher significance in all tests and accurately predicting RPW's distribution across North America and Southeast Asia using 7 parameters related to heat, cold and water stress (21). Furthermore, researchers employed MaxEnt to forecast the dissemination of three invasive species in China's palm-growing regions, predicting a substantial decline in suitable habitats for RPW by 2081-2100 under the SSP585 climate scenario, utilizing 19 environmental variables encompassing climate factors (19), terrain factors (3), disturbance factors (2) and habitat factors (3) (96). Moreover, investigators in China designed a Poisson regression-based GLM to forecast red palm weevil infestations in coconut plantations and developed a map to highlight high-risk locations.

Conclusion

The RPW remains one of the most destructive invasive pests of palm species, with severe ecological and economic impacts across Asia, the Middle East, North Africa and southern Europe. While IPM approaches combining pheromone traps, biological agents and targeted chemical use have shown promise, their long-term effectiveness is limited by weak quarantine enforcement, low farmer participation, inconsistent adoption and the absence of scalable early-detection technologies. Emerging tools such as AI, IoT-based monitoring, RNAi and predictive ecological modeling hold considerable potential to transform RPW management, but require field validation, cost-effective deployment and institutional support to be fully impactful. Building on these insights, several research and policy implications emerge. For researchers, future priorities lie in developing affordable detection technologies, advancing biological control options adapted to Gulf conditions, modeling pest dynamics under climate change and identifying resistant palm cultivars. Policymakers must strengthen quarantine enforcement, regulate planting material, incentivize IPM adoption, invest in digital surveillance platforms and foster regional collaboration. Farmers and extension services play a critical role by adopting integrated monitoring practices, reducing reliance on insecticides and engaging in cooperative management schemes. Together, these actions can bridge the scientific, regulatory and operational gaps that currently undermine RPW control, paving the way toward a more sustainable and coordinated management strategy.

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Authors' contributions

MA conceived the review article and drafted the main body of the manuscript. AAR, MMAW and KMAK contributed to the review and revision of the manuscript. MMAW made the final revision. All authors reviewed and approved the final version of the review article.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

1. Gadelhak GG, Enan MR. Genetic diversity among populations of red palm weevil, *Rhynchophorus ferrugineus* Olivier (Coleoptera: Curculionidae), determined by random amplified polymorphic DNA polymerase chain reaction (RAPD-PCR). Int. J. Agric. Biol. 2005;7 (3):395-99.
2. El-Shafie HAF, Faleiro JR. Red palm weevil *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae): global invasion, current management options, challenges and future prospects. In: Invasive

species-introduction pathways, economic impact and possible management options. London: IntechOpen; 2020. https://doi.org/10.5772/intechopen.93391

3. Murphy ST, Briscoe BR. The red palm weevil as an alien invasive: Biology and the prospects for biological control as a component of IPM. Biocontrol News Inf. 1999;20(1):35-46.
4. Wattanapongsiri A. A revision of the genera *Rhynchophorus* and *Dynamis* (Coleoptera: Curculionidae). Dept Agric Sci Bull. 1966;1(1):328.
5. Hoddle MS, Antony B, El-Shafie HAF, Chamorro ML, Milosavljević IM, Löhr B, et al. Taxonomy, biology, symbionts, omics and management of *Rhynchophorus* palm weevils (Coleoptera: Curculionidae: Dryophthorinae). Annu Rev Entomol. 2024;22(1):455-79. https://doi.org/10.1146/annurev-ento-013023-121139
6. CABI. PRA for the accidental introduction of *Rhynchophorus ferrugineus* (red palm weevil) into Ghana. 2021.
7. Hunsberger AGB, Giblin-Davis RM, Weissling TJ. Symptoms and population dynamics of *Rhynchophorus cruentatus* (Coleoptera: Curculionidae) in Canary Island date palms. Fla Entomol. 2000;83(3):290-93. https://doi.org/10.2307/349634
8. León-Quinto T, Serna A. Cryoprotective response as part of the adaptive strategy of the red palm weevil, *Rhynchophorus ferrugineus*, against low temperatures. Insects. 2022;13(2):134. https://doi.org/10.3390/insects13020134
9. Weissling TJ, Giblin-Davis RM. Water loss dynamics and humidity preference of *Rhynchophorus cruentatus* (Coleoptera: Curculionidae) adults. Environ Entomol. 1993;22(1):93-8. https://doi.org/10.1093/ee/22.1.93
10. Hussain A, Rizwan-ul-Haq M, Aljabr A, Al-Ayedh H. Managing invasive populations of red palm weevil: A worldwide perspective. J Food Agric. Environ. 2013;11(2):456-63.
11. Abbas M. IPM of the red palm weevil, *Rhynchophorus ferrugineus.* In: Ciancio A, Mukerji K, editors. Integrated management of arthropod pests and insect borne diseases. Dordrecht: Springer; 2010. p. 209-33. https://doi.org/10.1007/978-90-481-8606-8_9
12. Rabha H, Chakrabarty R, Acharya GC. New distributional record of red palm weevil, *Rhynchophorus ferrugineus* (Olivier) infesting arecanut in Assam, India. J Plantation Crops. 2013;41(2).
13. Kassem HS, Alotaibi BA, Ahmed A, Aldosri FO. Sustainable management of the red palm weevil: The nexus between farmers' adoption of integrated pest management and their knowledge of symptoms. Sustainability. 2020;12(22):1–16. https://doi.org/10.3390/su12229647
14. Ferry M. The world situation and the main lessons of 30 years of fight against the red palm weevil. Arab J. Plant Prot. 2019;37(2):109–18. https://doi.org/10.22268/AJPP-037.2.109118
15. Milek TM, Šimala M. First records of the red palm weevil, *Rhynchophorus ferrugineus* (Olivier, 1790) and the palm borer, *Paysandisia archon* (Burmeister, 1880) in Croatia. Zbornik Predavanj Referatov. 2013;11:366–68.
16. Manee MM, Alqahtani FH, Al-Shomrani BM, El-Shafie HAF, Dias GB. Omics in the red palm weevil *Rhynchophorus ferrugineus* (Olivier) (Coleoptera: Curculionidae): A bridge to the pest. Insects. 2023;14(3):255. https://doi.org/10.3390/insects14030255
17. Na SM, Im GI, Lee WS, Kim DG. Assessment of attractant combinations for the management of red palm weevils (*Rhynchophorus ferrugineus*) in the United Arab Emirates. Insects. 2024;15(4):218. https://doi.org/10.3390/insects15040218
18. Kinawi MM. Date palm and date pests in Sultanate of Oman. Muscat: Royal Court Affairs; 2005. p. 82–102.
19. Dalbon VA, Acevedo JPM, Santana AEG, Goulart HF, Laterza I, Riffel A, et al. Early detection and preventive control of *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae): A quarantine pest in Brazil. Arab J Plant Prot. 2019;37(2):130–5. https://doi.org/10.22268/AJPP-037.2.130135
20. Ezaby E, Khalifa FAO, Assal AE. Integrated pest management for the control of red palm weevil in the UAE Eastern region, Al-Ain. In: Proc. First Int. Conf. Date Palms; 1998. p. 269–81.
21. Fiaboe KKM, Peterson T, Kairo MTK, Roda L. Predicting the potential worldwide distribution of the red palm weevil *Rhynchophorus ferrugineus* (Olivier) (Coleoptera: Curculionidae) using ecological niche modeling. Fla Entomol. 2012;95(3):659–73. https://doi.org/10.1653/024.095.0317
22. Al-Khatri SA. Date palm pests and their control. Khalifa Int. Award Date Palm Agric Innov. 2009;1(4):62–7.
23. Al-Zadjali TS, Abd-Allah F, El-Haidari H. Insect pests attacking date palms and dates in Sultanate of Oman. Egypt J Agric. Res. 2006;84(1):51–9. https://doi.org/10.21608/ejar.2006.228947
24. Oman. Ministry of Agriculture, Fisheries and Water Resources. Announcement of agricultural quarantine areas Act, 2009 (Act No. 31 of 2009). Government Gazette No. 885; 2009.
25. Oman. Ministry of Agriculture, Fisheries and Water Resources. Announcement of agricultural quarantine areas Act, 2012 (Act No. 124 of 2012). Government Gazette No. 974; 2012.
26. Oman. Ministry of Agriculture, Fisheries and Water Resources. Announcement of agricultural quarantine areas Act, 2013 (Act No. 90 of 2013). Government Gazette No. 1007; 2013.
27. Oman. Ministry of Agriculture, Fisheries and Water Resources. Announcement of agricultural quarantine areas Act, 2012 (Act No. 267 of 2012). Government Gazette No. 992; 2012.
28. MAFWR. MAFWR 44/2014 announcement of agricultural quarantine areas. OG 1046; 2014.
29. MAFWR. MAFWR 272/2020 announcement of agricultural quarantine areas. OG 1370; 2020.
30. MAFWR. MAFWR 52/2021 announcement of agricultural quarantine areas. OG 1390; 2021.
31. Faleiro JR. Insight into the management of red palm weevil *Rhynchophorus ferrugineus* Olivier: Based on experiences on coconut in India and date palm in Saudi Arabia. Fundación Agroalimed. 2006;35–57.
32. Giblin-Davis RM, Faleiro JR, Jaques JA, Peña JE, Vidyasagar PSPV. Biology and management of the red palm weevil *Rhynchophorus ferrugineus*. In: Peña JE, editor. Potential invasive pests of agricultural crops. Wallingford: CAB International; 2013. p. 1–34. https://doi.org/10.1079/9781845938291.0001
33. El-Shafie HAF. Area-wide integrated management of red palm weevil *Rhynchophorus ferrugineus* (Olivier 1790) (Coleoptera: Curculionidae) in date palm plantations: A review. Persian Gulf Crop Prot. 2014;3(1):92–118.
34. Malumphy C, Moran H. Red palm weevil *Rhynchophorus ferrugineus.* Plant Pest Notice. 2007;50:1–3.
35. Dembilio Ó, Jaques JA. Bio-ecology and integrated management of the red palm weevil *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae) in the region of Valencia (Spain). Hellenic Plant Prot. J. 2014;5:1–12.
36. Balijepalli SB, Faleiro JR. Is policy paralysis on quarantine issues in the Near East and North Africa region leading to the buildup and spread of red palm weevil *Rhynchophorus ferrugineus*? Arab J Plant Prot. 2019;37(2):89–100. https://doi.org/10.22268/AJPP-037.2.089100
37. Aziz AT. Red palm weevil, *Rhynchophorus ferrugineus*, a significant threat to date palm tree, global invasions, consequences and management techniques. J. Plant Dis. Prot. 2024;131(1):9–26. https://doi.org/10.1007/s41348-023-00805-w
38. Dembilio Ó, Jacas JA. Basic bio-ecological parameters of the invasive red palm weevil *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae) in *Phoenix canariensis* under Mediterranean climate.

Bull Entomol Res. 2011;101(2):153–63. https://doi.org/10.1017/S0007485310000283

39. Abe F, Hata K, Sone K. Life history of the red palm weevil, *Rhynchophorus ferrugineus* (Coleoptera: Dryophtoridae), in Southern Japan. Fla Entomol. 2009;92(3):421–25. https://doi.org/10.1653/024.092.0302

40. Solaiman R, Abd El-Latif N. Seasonal flight activity and some attractants potency on the red palm weevil, *Rhynchophorus ferrugineus* using pheromones trap at Fayoum Governorate, Egypt. J Plant Prot Pathol. 2013;4(11):1011–23. https://doi.org/10.21608/jppp.2013.87668

41. Arafa O, Barakatt M. Effect of weather factors on seasonal population fluctuation of red palm weevil, *Rhynchophorus ferrugineus* adults attracted to pheromone traps at El-Sharkia Governorate, Egypt. Egypt J Plant Prot Pathol. 2021;12(12):843–8. https://doi.org/10.21608/jppp.2021.220017

42. Al-Dobai S, Elkahky M, Faleiro R. Proceedings of the Scientific Consultation and High-Level Meeting on Red Palm Weevil Management. Rome: FAO; 2019. https://openknowledge.fao.org/items/de5be236-6d39-4929-9874-dd44b0622baf

43. Karar ME, Reyad O, Abdel-Aty AH, Owyed S, Hassan MF. Intelligent IoT-aided early sound detection of red palm weevils. Comput Mater Continua. 2021;69(3):4095–111. https://doi.org/10.32604/cmc.2021.019059

44. Sable MG, Rana DK. Impact of global warming on insect behavior: A review. Agric Rev. 2016;37(1):81–4. https://doi.org/10.18805/ar.v37i1.9270

45. Salama HS, Zaki FN, Abdel-Razek AS. Ecological and biological studies on the red palm weevil *Rhynchophorus ferrugineus*. Arch Phytopathol Plant Prot. 2009;42(4):392–99. https://doi.org/10.1080/03235400601121521

46. Avand-Faghih A. The biology of red palm weevil, *Rhynchophorus ferrugineus* Oliv. in Saravan region (Iran). Appl Entomol Phytopathol. 1996;63:16–8.

47. Ezaby E. A biological in-vitro study on the red Indian date palm weevil. Arab J Plant Prot. 1997;15(2):84–7.

48. Manzoor M, Ahmad JN, Ahmad SJN, Naqvi SA, Umar UUD, Rasheed R, et al. Population dynamics, abundance and infestation of the red palm weevil in Pakistan. Pak J Agric Sci. 2020;57(2):381–91. https://doi.org/10.21162/PAKJAS/20.6928

49. Aldryhim Y, Al-Bukiri S. Effect of irrigation on within-grove distribution of red palm weevil. Agric Mar Sci. 2003;8(1):47–9. https://doi.org/10.24200/jams.vol8iss1pp47-49

50. Masó Á. Factors influencing the mobility of red palm weevil adults. Spain: Universitat Politécnica de Valéncia; 2015.

51. Conti F, Sesto F, Raciti E, Tamburino V, Longo S. Ecological factors affecting spread of red palm weevil in eastern Sicily. Palms. 2008;52(3):127–32.

52. Faleiro JR. A review of issues and management of the red palm weevil in coconut and date palm. Int J Trop Insect Sci. 2006;26(3):135–54.

53. Vidyasagar P. Impact of mass pheromone trapping on red palm weevil in Saudi Arabia. The Planter. 2000;76:347–55. https://doi.org/10.56333/tp.2000.011

54. Ajlan A, Abdulsalam K. Efficiency of pheromone traps for controlling red palm weevil under Saudi Arabia conditions. Bull Entomol Soc Egypt Econ Ser. 2000;27:109–20.

55. Faleiro JR. Pheromone technology for management of red palm weevil - Technical Bulletin. 2005;4:40.

56. El-Garhy ME. Field evaluation of aggregation pheromone of the red palm weevil in Egypt. Brighton Crop Prot Conf. 1996;3:1059–64.

57. Hussain A, Elsharabasy S, Megahed M, Abd Elmagid M. Population abundance of red palm weevil adults in Baharia Oases, Egypt. J Plant Prot Pathol. 2016;7(10):649–54. https://doi.org/10.21608/jppp.2016.52097

58. Darwish A, Halawa S, Abdallah F. Population fluctuation of red palm weevil in two Egyptian regions. Ann Agric Sci. 2020;58(3):641–48. https://doi.org/10.21608/assjm.2020.131636

59. Ávalos JA, Balasch S, Soto A. Flight behaviour and dispersal of red palm weevil using mark-release-recapture. Bull Entomol Res. 2016;106(5):606–14. https://doi.org/10.1017/S0007485316000341

60. El-Sabea AMR, Faleiro JR, Abo-El-saad MM. Economic threat of red palm weevil to date plantations of Gulf region. Outlooks Pest Manag. 2009;20(3):131–34. https://doi.org/10.1564/20jun11

61. Ministry of Agriculture, Fisheries and Water Resources. Brief report on integrated management programme for red palm weevil. Oman; 2012.

62. Ministry of Agriculture, Fisheries and Water Resources. Brief report on integrated management programme for red palm weevil. Oman; 2017.

63. Ministry of Agriculture, Fisheries and Water Resources. Brief report on integrated management programme for red palm weevil. Oman; 2022.

64. Dembilio Ó, Jaques JA. Biology and management of red palm weevil. In: Wakil W, Faleiro JR, Miller T, editors. Sustainable Pest Management in Date Palm. Cham: Springer; 2015. p. 13–36. https://link.springer.com/chapter/10.1007/978-3-319-24397-9_2. https://doi.org/10.1007/978-3-319-24397-9_2

65. Eldin HA, Waleed K, Samir M, Tarek M, Sobeah H, Salam MA. A survey on detection of red palm weevil inside palm trees. In: ACM International Conference; 2020 Nov 11-13; Cairo, Egypt. New York: ACM; 2020. https://doi.org/10.1145/3436829.3436861

66. Kurdi H, Al-Aldawsari A, Al-Turaiki I, Aldawood AS. Early detection of red palm weevil infestation using data mining. Plants. 2021;10(1):1–8. https://doi.org/10.3390/plants10010095

67. Faleiro JR, Ferry M, Yaseen T, Al-Dobai S. Overview of the gaps, challenges and prospects of red palm weevil management. Arab J Plant Prot. 2019;37(2):170–7. https://doi:10.22268/AJPP-037.2.170177

68. Sabbahi R, Hock V. Entomopathogenic fungi against the red palm weevil: Lab and field evidence. Crop Prot. 2024;177:106566. https://doi.org/10.1016/j.cropro.2023.106566

69. Husain M, Rasool KG, Sutanto KD, Omer AO, Tufail M, Aldawood AS. Laboratory evaluation of indigenous and commercial entomopathogenic nematodes against red palm weevil, *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae). Insects. 2024;15(4). https://doi:10.3390/insects15040290

70. Al-Zyoud F, Shibli R, Ghabeish I. Current status, challenges, management and future perspectives of the red palm weevil *Rhynchophorus ferrugineus* Olivier (Coleoptera, Curculionidae) eradication - A review. J Exp Biol Agric Sci. 2021;9(6):697–714. https://doi:10.18006/2021.9(6).697.714

71. Massa R, Panariello G, Pinchera D, Schettino F, Caprio E, Griffo R, et al. Experimental and numerical evaluations on palm microwave heating for red palm weevil pest control. Sci Rep. 2017;7(1). https://doi:10.1038/srep45299

72. Massa R, Caprio E, de Santis M, Griffo R, Migliore MD, Panariello G, et al. Microwave treatment for pest control: The case of *Rhynchophorus ferrugineus* in *Phoenix canariensis*. EPPO Bull. 2011;41(2):128–35. https://doi:10.1111/j.1365-2338.2011.02447.x

73. Al-Dosary NMN, Al-Dobai S, Faleiro JR. Review on the management of red palm weevil *Rhynchophorus ferrugineus* Olivier in date palm *Phoenix dactylifera* L. Emirates J Food Agric. 2016;28(1):34–44. https://doi:10.9755/ejfa.2015-10-897

74. Moneim A, Al-Shawaf A, Al-Abdan S, Al-Abbad AH, Abdallah A Ben, Faleiro JR. Validating area-wide management of *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae) in date plantations of Al-

Hassa, Saudi Arabia. Indian J Plant Prot. 2012;40(4):255–9.

75. Faleiro JR, Satarkar VR. Attraction of food baits for use in red palm weevil *Rhynchophorus ferrugineus* Olivier pheromone trap. Indian J Plant Prot. 2005;33(1):23–5.

76. Oehlschlager AC, Chinchilla C, Castillo G, Gonzalez L. Control of red ring disease by mass trapping of *Rhynchophorus palmarum* (Coleoptera: Curculionidae). Fla Entomol. 2002;85(3):507–13. https://doi:10.1653/0015-4040(2002)085[0507:CORRDB]2.0.CO;2

77. Rajapakse CNK, Gunawardena NE, Perera G, Rd C. Pheromone baited trap for the management of red palm weevil, *Rhynchophorus ferrugineus* F. (Coleoptera: Curculionidae) population in coconut plantations. Cocos. 2010;13:54–65. https://doi:10.4038/cocos.v13i0.2177

78. Fajardo M, Rodríguez X, Hernández CD, Barroso L, Morales M, González A, et al. The eradication of the invasive red palm weevil in the Canary Islands. In: Area-Wide Integrated Pest. Boca Raton (FL): CRC Press; 2021. p. 539–50.

79. Cinnirella A, Bisci C, Nardi S, Ricci E, Palermo FA, Bracchetti L. Analysis of the spread of *Rhynchophorus ferrugineus* in an urban area using GIS techniques: A case study in Central Italy. *Urban Ecosyst.* 2020;23(2):255–69. https://doi:10.1007/s11252-019-00920-3

80. Hammami Z, Krizhanovsky E, Elbattay A, Singh RK. Study on the effectiveness of different control techniques for red palm weevil (*Rhynchophorous ferrugineus*). Khalifa Int Award Date Palm Agric Innov. 2024;16:48–61.

81. FAO. Red Palm Weevil: Guidelines on management practices. Rome: FAO; 2020. https://doi.org/10.4060/ca7703en

82. Austin MP. Spatial prediction of species distribution: An interface between ecological theory and statistical modelling. Ecol Model. 2002;157(2–3):101–18. https://doi:10.1016/S0304-3800(02)00205-3

83. Phillips SJ, Dudík M, Phillips SJ. Modeling of species distributions with Maxent: New extensions and a comprehensive evaluation. Ecography. 2008;31(2):161–75. https://doi:10.1111/j.0906-7590.2008.5203.x

84. Taylor S, Kumar L. Sensitivity analysis of CLIMEX parameters in modelling potential distribution of *Lantana camara* L. *PLoS One.* 2012;7(7):e40969. https://doi:10.1371/journal.pone.0040969

85. Chejara VK, Kriticos DJ, Kristiansen P, Sindel BM, Whalley RDB, Nadolny C. The current and future potential geographical distribution of *Hyparrhenia hirta*. Weed Res. 2010;50(2):174–https://doi:10.1111/j.1365-3180.2009.00765.x

86. Ge X, He S, Wang T, Yan W, Zong S. Potential distribution predicted for *Rhynchophorus ferrugineus* in China under different climate warming scenarios. PLoS One. 2015;10(10). https://doi:10.1371/journal.pone.0141111

87. Byeon D, Jung S, Lee WH. Review of CLIMEX and MaxEnt for studying species distribution in South Korea. J Asia-Pac Biodivers. 2018;11(3):325–33. https://doi:10.1016/j.japb.2018.06.002

88. Aidoo OF, Ding F, Ma T, Jiang D, Wang D, Hao M, et al. Determining the potential distribution of *Oryctes monoceros* and *Oryctes rhinoceros* using machine learning with high-dimensional multidisciplinary environmental variables. Sci Rep. 2022;12 (1):17439. https://doi:10.1038/s41598-022-21367-1

89. Zou Y, Ge X, Guo S, Zhou Y, Wang T, Zong S. Impacts of climate change and host plant availability on the global distribution of *Brontispa longissima* (Coleoptera: Chrysomelidae). Pest Manag Sci. 2020;76(1):244–56. https://doi:10.1002/ps.5503

90. Li H, Jianghua S, Hongxiang H, Hui X, Dayong X. Prediction of potential distribution of the coconut leaf beetle in China. For Pest Dis. 2005;24(6):5–7. https://doi:10.3969/j.issn.1671-0886.2005.06.002

91. Shabani F, Kumar L, Al Shidi RHS. Impacts of climate change on infestations of Dubas bug (*Ommatissus lybicus* Bergevin) on date palms in Oman. PeerJ. 2018;6:e5545. https://doi:10.7717/peerj.5545

92. Al Adhoobi AS, Al Jufaili SM, Al Ruheili A. Predicting habitat distributions for the endemic fish *Garra shamal* (Teleostei: Cyprinidae) in the Omani Hajar Mountain under present and future climate change scenarios using MaxEnt. J Surv Fish Sci. 2023;10 (1):3591–600.

93. Al-Ruheili AM, Boluwade A, Al-Subhi AM. Predicting mango sudden decline due to *Ceratocystis fimbriata* under a changing climate. Arab J Plant Prot. 2021;39(3):215–23. https://doi:10.22268/AJPP-039.3.215223

94. Al-Kindi KM, Al-Wahaibi AK, Kwan P, Andrew NR, Welch M, Al-Oufi M, et al. Predicting the potential geographical distribution of parasitic natural enemies of the Dubas bug (*Ommatissus lybicus* de Bergevin) using geographic information systems. Ecol Evol. 2018;8(16):8297–310. https://doi:10.1002/ece3.4286

95. Zhang Y, Wan Y, Wang C, Chen J, Si Q, Ma F. Potential distribution of three invasive agricultural pests in China under climate change. Sci Rep. 2024;14(1):13672. https://doi:10.1038/s41598-024-63553-3

96. SABTU NBM. Predictive model for red palm weevil population in coconut using environmental variables and regression method [thesis]. Malaysia: Universiti Teknologi Malaysia; 2021.

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