WS5 Recommended Integrated RPW Technology Bundle for Growers: Based on Existing Technologies

TECHNOLOGY VALIDATION REPORT

For controlling RPW

Arash Nejatian

Hamadttu ElShafie

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Arash Nejatian, Activities Coordinator officer, ICARDA Arabian Peninsula Regional Program, Corresponding Author
Hamadttu ElShafie, C4RPWC Technical Lead

HEADQUARTERS - LEBANON

Street address: Dalia Building 2nd Floor, Bashir El Kassar Street, Verdun, Beirut, Lebanon 1108-2010, Office Tel.: +961 1 813303

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Contents

1. Introduction

Red Palm Weevil (*Rhynchophorus ferrugineus*, RPW) remains one of the most destructive pests of date palm production systems, particularly in arid and semi-arid regions where date palm is economically, culturally, and strategically important. The pest is difficult to control because its most damaging stages occur inside the palm trunk, where larvae feed internally and infestation symptoms often become visible only after significant damage has occurred. As a result, conventional control approaches based only on visual inspection or reactive treatment are often too late, costly, and insufficient.

Effective RPW management therefore requires a technology-based, integrated, and preventive control strategy. No single technology can fully address the RPW challenge. Prevention, early detection, targeted treatment, sanitation, and removal of severely infested palms must be combined into a coordinated management package. This report assesses available and emerging technologies for RPW control and classifies them according to their function, technology readiness, deployment feasibility, and validation potential.

The report builds on the technology profiling and prioritization work conducted for RPW infestation solutions. The source material identified and assessed technologies across the RPW control value chain, including prevention, detection, treatment, and revival/removal. The technologies were also classified by technology family, including digital, biotechnology, and material-based solutions. The prioritization spreadsheet further evaluates technologies according to effectiveness, environmental impact, infrastructure readiness, talent readiness, and financial feasibility, with separate sheets for TRL 1–6 and TRL 7–9 technologies.

The purpose of this report is to translate the available technology profiling information into a practical technology assessment and validation framework. The report does not treat all technologies equally. That would be a bad decision-making approach. Instead, it separates technologies that are ready for field deployment from those that require controlled validation, pilot testing, or continued research. This distinction is critical for designing realistic RPW control programs, especially under UAE or GCC test-bed conditions.

2. Methodology

2.1. Overall Assessment Approach

The methodology used in this report follows a structured technology assessment framework. Technologies were reviewed, classified, and assessed according to their relevance to RPW control, their maturity level, and their practical feasibility for field deployment. The assessment combines evidence from the technology profiling document, the technology prioritization spreadsheet, and expert-based interpretation of field applicability.

The source technology database includes both mature and emerging technologies. Mature technologies include chemical injection, mass trapping, micro/drip irrigation, acoustic detection, biopesticides, and biological control agents. Emerging technologies include RNA interference, genetic engineering, molecular diagnostics, biosensors, and advanced remote sensing tools. The prioritization database classifies technologies into TRL 1–6 and TRL 7–9 groups and evaluates them using scoring criteria such as effectiveness, environmental impact, infrastructure readiness, talent readiness, and, for mature technologies, financial feasibility.

2.2. Technology Identification

Technologies were identified from the provided MEWA RPW technology profiling material and the associated prioritization spreadsheet. The original technology profiling process compiled RPW-related technologies from scientific literature, patents, and technology databases. These technologies were then aggregated, de-duplicated, and mapped into a structured framework for RPW control.

The technologies considered in this report include chemical pesticides, mutation breeding, genetic engineering, microwave disinfestation, irrigation management, trapping systems, molecular diagnostics, microbial solutions, detection sensors, digitalized traps, remote sensing, bio-nanotechnology, biopesticides, RNA interference, fertilizers, and removal/disposal practices.

2.3. Technology Mapping Across the RPW Control Value Chain

Each technology was mapped according to its main role in the RPW control value chain:

Prevention: Technologies that reduce the probability of infestation or make palm trees and farm conditions less favorable for RPW establishment. Examples include good agricultural practices, micro/drip irrigation, preventive chemical injection, repellents, and resistant planting material.

Detection: Technologies that support early identification of RPW infestation before severe external symptoms appear. Examples include visual inspection, pheromone traps, acoustic sensors, seismic sensors, thermal imaging, radar, drones, satellite imagery, and molecular diagnostics.

Treatment: Technologies used to suppress, kill, or manage RPW populations after infestation or pest presence has been confirmed. Examples include trunk injection, attract-and-kill systems, biopesticides, entomopathogenic fungi, nematodes, nano-based treatments, microwave disinfestation, and RNAi-based approaches.

Revival and Removal: Technologies and practices used to recover affected palms where possible, support palm health, or safely remove and dispose of severely infested palms. Examples include fertilizers, biofertilizers, nano-fertilizers, microwave treatment, and disposal protocols.

2.4. Technology Family Classification

Technologies were grouped into three broad technology families:

Technology Family	**Description**	**Examples**
Digital	Technologies based on sensing, monitoring, data capture, AI, or remote diagnostics	Acoustic sensors, seismic sensors, drones, satellite image analysis, digitalized traps
Biotechnology	Biological, microbial, genetic, or molecular technologies	Bt, fungi, nematodes, RNAi, molecular diagnostics, genetic engineering
Materials / Chemical / Physical	Technologies based on chemicals, physical devices, irrigation infrastructure, or material-based interventions	Chemical injection, microwave disinfestation, nanochitosan, TiO_2 nanoparticles, drip irrigation

2.5. Technology Readiness Level Classification

Technologies were classified according to their Technology Readiness Level (TRL). For this report, the TRL scale is grouped into three practical categories:

TRL Group	Interpretation	Report Classification
TRL 1–3	Concept, laboratory evidence, early-stage research, or proof of principle	Research-stage technology
TRL 4–6	Validated in laboratory or relevant environment but not yet fully proven under field deployment	Pilot / validation-stage technology
TRL 7–9	Demonstrated, commercialized, or ready for operational deployment	Deployment-ready technology

This classification prevents a common mistake: mixing mature technologies with theoretical concepts. For example, Emamectin Benzoate, micro/drip irrigation, mass trapping, and several microbial biocontrol agents are classified as TRL 7–9, while RNA interference, genetic engineering for pest resistance, and molecular receptor-based diagnostics remain mostly at TRL 1–3 or TRL 4–6.

2.6. Assessment Criteria

Each technology is assessed using the following criteria:

Effectiveness: The ability of the technology to prevent infestation, detect RPW accurately, kill RPW life stages, reduce population pressure, or support palm recovery.

Environmental Impact: The expected direct or indirect environmental effects of the technology, including pesticide toxicity, non-target effects, residue risks, and ecological safety.

Infrastructure Readiness: The level of infrastructure required for deployment, including equipment, laboratories, irrigation systems, digital platforms, sensors, drones, or specialized machinery.

Talent Readiness: The level of technical expertise required to apply, operate, interpret, or maintain the technology. Some technologies require only basic instruction, while others require PhD-level molecular biology, entomology, or data science expertise.

Financial Feasibility: For TRL 7–9 technologies, cost per tree, cost per treatment, cost per hectare, or required capital investment is considered. The prioritization spreadsheet includes financial feasibility assumptions and derived costs for mature technologies.

Ease of Deployment or Experimentation: For mature technologies, the focus is ease of deployment. For emerging technologies, the focus is ease of experimentation or validation under local conditions.

Regulatory Feasibility: Technologies involving pesticides, genetically modified organisms, irradiation, RNAi, or molecular manipulation may face regulatory restrictions. These restrictions affect whether a technology can be deployed immediately, tested under controlled conditions, or kept at research level.

2.7. Validation Logic

Technologies are assigned to one of four validation pathways:

Validation Pathway	Meaning
Immediate deployment	Technology is mature, commercially available, and operationally feasible
Field validation	Technology is promising but requires local testing under UAE/GCC date palm conditions
Controlled pilot	Technology needs structured trials before broader use
Research only	Technology is not ready for operational deployment and should remain under laboratory or institutional research

2.8. SWOT Analysis Method

Each technology profile will include a SWOT analysis covering:

SWOT Element	Focus
Strengths	Technical advantages, maturity, efficacy, ease of use
Weaknesses	Cost, operational limitations, training needs, incomplete evidence
Opportunities	Scaling potential, integration into RPW bundles, digital monitoring, farmer adoption
Threats	Regulatory barriers, environmental risks, misuse, low adoption, inconsistent field performance

2.9. Output of the Assessment

The final output of the methodology is a structured technology-by-technology assessment. Each technology will be presented in a consistent one-page format covering:

1. Technology name
2. Technology family
3. RPW control category
4. TRL classification
5. Description
6. Application in RPW control
7. Target RPW life stage
8. Evidence of effectiveness
9. Deployment requirements
10. Validation status
11. SWOT analysis
12. Recommendation

This format will make the report usable for decision-makers. Anything less structured will become a pile of information, not an assessment report.

3. Technology Classification by Control Category and TRL

The technologies assessed in this report were classified according to their primary role in the Red Palm Weevil control value chain and their level of readiness for deployment. This classification is essential because RPW control requires different types of interventions at different points in the infestation cycle. Some technologies are designed to prevent infestation before it occurs, some support early detection, others are used for treatment after infestation is confirmed, and a final group supports palm recovery, disposal, or removal of severely infested trees.

The technology profiling framework used in the source material organizes RPW control technologies into four main intervention categories: Prevention, Detection, Treatment, and

Revival & Removal. Across these categories, technologies were further grouped into technology families, including digital technologies, biotechnology-based solutions, material-based technologies, conventional chemical approaches, irrigation and water-management systems, and traditional good agricultural practices. The original profiling exercise identified 52 selected technologies after reviewing scientific literature, patents, and innovation sources, and mapped them across the RPW control value chain.

3.1. Prevention Technologies

Prevention technologies aim to reduce the risk of RPW infestation before the pest establishes itself inside the palm trunk. These technologies are particularly important because RPW damage is often hidden during the early stages, and once larvae penetrate the trunk, control becomes more difficult and costly.

The prevention category includes both mature and emerging technologies. Mature prevention technologies include chemical trunk injection, micro/drip irrigation, good agricultural practices, and semiochemical-based preventive tools. Among these, Emamectin Benzoate, micro/drip irrigation, and preventive management practices are classified as TRL 7–9, meaning they are commercially available, field-tested, and ready for deployment under operational conditions. The MEWA profiling document identifies Emamectin Benzoate as a mature, fully commercialized pesticide with global suppliers, and micro/drip irrigation as a mature technology with multiple suppliers globally.

In contrast, prevention technologies such as genetic engineering for pest resistance, precision-guided sterile insect technique (pgSIT), and incompatible insect technique (IIT) remain at lower readiness levels. These technologies are scientifically promising, but they are not yet ready for field-level RPW management. They require specialized laboratories, advanced molecular expertise, regulatory clearance, and further validation specifically for RPW and date palm systems. Therefore, they are classified mainly as TRL 1–3 or TRL 4–6, depending on the level of evidence available.

The prevention category therefore contains two very different groups: technologies that can be deployed immediately and technologies that should remain under research or controlled pilot testing. Treating these groups equally would be a weak assessment. The practical priority should be given to mature, field-applicable technologies such as improved irrigation management, sanitation, preventive chemical injection where permitted, and trap-based prevention strategies.

3.2. Detection Technologies

Detection technologies are central to RPW control because early detection determines whether a palm can be treated successfully or whether infestation progresses to severe damage. Since larvae feed inside the trunk, external symptoms often appear late. Detection technologies therefore aim to identify infestation before visible decline becomes irreversible.

Detection technologies include visual inspection, mass trapping, service-less and digitalized traps, acoustic sensors, seismic sensors, thermal imaging, radar, resistograph, densitometer, near-infrared spectroscopy, LiDAR, drones with sensors, satellite image analysis, X-rays, and molecular or biosensor-based diagnostics.

Several detection technologies are already close to operational deployment. Mass trapping, service-less and digitalized traps, acoustic sensors, seismic sensors, drones with sensors, radar, resistograph, and densitometer are generally classified as TRL 7–9 or near-deployment technologies. The profiling material describes mass trapping as a commercialized approach requiring low expertise and low monetary cost, while acoustic sensors are described as one of the most promising methods for RPW infestation detection, with reported high accuracy in field experiments.

Other detection tools are better treated as validation-stage technologies. Thermal sensors, satellite image analysis, near-infrared spectroscopy, and some drone-based analytics have strong potential but still require local calibration and field validation under date palm conditions. These technologies are best classified as TRL 4–6 when the hardware is mature but the RPW-specific application is not fully validated.

The lowest-readiness detection technologies include RferOR1 pheromone receptor diagnostics, X-ray-based field detection, and genetically engineered E. coli biosensors. These approaches may be scientifically interesting, but they are not yet practical for farm-level RPW control. They require laboratory infrastructure, specialized expertise, and additional development before field deployment. These should be classified as TRL 1–3 or early TRL 4–6, not as operational tools.

For a practical RPW program, the detection category should be built around a layered approach: routine visual inspection, trap monitoring, and deployable sensors, supported by digital data systems. High-tech tools such as satellite analytics or molecular diagnostics should support validation and surveillance, not replace field-based detection.

3.3. Treatment Technologies

Treatment technologies are used once RPW presence has been confirmed or when infestation pressure is high enough to justify direct intervention. The treatment category includes chemical, biological, physical, semiochemical, nano-based, and molecular approaches.

Mature treatment technologies include chemical injection, Attract and Kill, biopesticides, entomopathogenic fungi, entomopathogenic nematodes, Bt, and microwave disinfestation. Several of these are classified as TRL 7–9 because they are commercially available, tested, and deployable. For example, the profiling material describes Bacillus thuringiensis, Metarhizium anisopliae, Beauveria bassiana, Heterorhabditis bacteriophora, and Steinernema carpocapsae as biological control agents with strong environmental profiles and practical application methods.

Chemical treatments such as Emamectin Benzoate, Thiamethoxam, and Imidacloprid are also mature, but their prioritization must be handled carefully. They may be effective, but they bring toxicity, environmental, residue, and regulatory concerns. Thiamethoxam, in particular, is not a clean recommendation because the source material notes that although it shows efficacy against RPW, it may also cause partial to total canopy collapse. A report that recommends it without caution would be technically sloppy.

Biological and bio-based treatments are strong candidates for integrated pest management. Bt, Metarhizium anisopliae, Beauveria bassiana, Lecanicillium lecanii, and selected nematodes offer lower environmental risk and can be integrated with preventive and monitoring systems. However, field performance can vary depending on temperature, humidity, formulation, application method, and infestation stage.

Validation-stage treatment technologies include nanochitosan, Nano TiO_2, Novaluron, and some bio-nanotechnology products. These technologies show promising experimental results, but they still need structured field validation before broad deployment. They should be classified mainly as TRL 4–6.

Research-stage treatments include RNA interference, gut microbiota manipulation, serine protease inhibitors, picrotoxin, essential oils, chitinase extracts, and several molecular or genome-based approaches. These technologies are scientifically valuable but not ready for operational deployment. Most are still laboratory-based, require specialized expertise, and lack robust field validation. They should be classified as TRL 1–3 unless field evidence becomes available.

3.4. Revival and Removal Technologies

Revival and removal technologies address the final stage of RPW management. This category includes practices that support palm recovery when damage is limited, improve palm vigor, or remove and dispose of palms that are too severely infested to save. This category is often underestimated, but it is critical. Leaving heavily infested palms in the field is not management; it is pest multiplication.

Mature technologies and practices in this category include removal and disposal of severely infested palms, farm sanitation, traditional fertilizers, biofertilizers, and some physical treatment methods such as microwave disinfestation. These are generally classified as TRL 7–9 where products and practices are already commercially available and operationally feasible.

Fertilizer-based revival technologies should not be oversold. They may support palm recovery and improve vigor, but they do not control RPW by themselves. Similarly, nano-fertilizers may have future value but should be treated as supportive technologies rather than direct RPW control tools unless clear evidence is available. Their classification may range from TRL 4–6 to TRL 7–9, depending on the product and field evidence.

The strongest recommendation in this category is strict sanitation and removal of palms that cannot be recovered. This is not glamorous technology, but it is one of the most important parts of area-wide RPW suppression. Any technology bundle that ignores disposal protocols will fail.

3.5. Summary of TRL-Based Classification

Overall, the assessed RPW technologies fall into three readiness groups.

Deployment-ready technologies, TRL 7–9, include chemical injection where permitted, mass trapping, service-less/digitalized traps, micro/drip irrigation, acoustic and seismic detection systems, selected mechanical sensors, entomopathogenic fungi, entomopathogenic nematodes, Attract and Kill, and removal/disposal practices.

Pilot and validation-stage technologies, TRL 4–6, include thermal imaging, satellite image analysis, drone-based analytics, near-infrared spectroscopy, Bt, nanochitosan, Nano TiO_2, Novaluron, and selected biosensor technologies.

Research-stage technologies, TRL 1–3, include genetic engineering for pest resistance, RNA interference, pgSIT, IIT, molecular receptor diagnostics, gut microbiota manipulation, genome-based biotech, picrotoxin, serine protease inhibitors, and several plant-extract biopesticides.

This classification provides the decision logic for the rest of the report. The priority should not be to test everything. That would waste time and budget. The priority should be to deploy mature technologies immediately, validate promising technologies under local field conditions, and keep low-readiness concepts within research programs until they have credible field evidence.

The following tables summarize the assessed RPW control technologies according to their position in the control value chain—prevention, detection, treatment, and revival/removal—and their estimated Technology Readiness Level (TRL). This classification is intended to separate technologies that are already mature and suitable for immediate deployment from those that still require field validation, controlled piloting, or further research. Deployment priority was assigned based on practical readiness, expected effectiveness, operational feasibility, environmental considerations, and relevance to integrated RPW management. This table should not be read as a simple technology inventory; its purpose is to guide decision-making by identifying which technologies can be deployed now, which should be tested under local conditions, and which should remain within research programs until stronger field evidence is available.

A. Prevention Technologies

Technology	Category	TRL	Deployment Priority
1. Emamectin Benzoate	Chemical pesticide / trunk injection	TRL 7–9	High
2. Thiamethoxam	Chemical pesticide	TRL 7–9	Low / caution
3. Imidacloprid	Chemical pesticide	TRL 7–9	Medium
4. Micro/Drip/subsurface Irrigation	Irrigation management	TRL 7–9	High
5. Genetic Engineering for Pest Resistance	Plant resistance	TRL 1–3	Low / research
6. pgSIT	Mutation breeding / genetic control	TRL 1–3 / 4–6	Research
7. IIT / Wolbachia-based technique	Genetic population suppression	TRL 4–6	Research

B. Detection Technologies

Technology	Category	TRL	Deployment Priority
8. Visual Inspection	Traditional detection	TRL 7–9	High
9. Mass Trapping	Semiochemical detection	TRL 7–9	High
10. Service-less / Digitalized Traps	Digital trap	TRL 7–9	High
11. Acoustic Sensors	Digital detection	TRL 7–9	High
12. Seismic Sensors	Digital detection	TRL 7–9	High / validation needed
13. Densitometer	Mechanical sensor	TRL 7–9	Medium
14. Resistograph	Mechanical sensor	TRL 7–9	Medium
15. Thermal Sensors	Drone/sensor detection	TRL 4–6 / 7–9	Pilot
16. Radar	Non-invasive sensing	TRL 7–9	Medium
17. LiDAR	Remote sensing	TRL 7–9	Medium

18. Drones with Sensors	Remote sensing	TRL 7–9	Medium
19. Satellite Image Analysis	Remote sensing / AI	TRL 4–6	Pilot
20. X-rays	Detection sensor	TRL 1–3	Low
21. NIRS	Spectroscopy	TRL 4–6	Research/pilot
22. RferOR1 Pheromone Receptor	Molecular detection	TRL 1–3	Research
23. Genetically Engineered E. coli Biosensor	Microbial biosensor	TRL 4–6	Research

C. Treatment Technologies

Technology	Category	TRL	Deployment Priority
24. Attract and Kill	Semiochemical + insecticide	TRL 7–9	High
25. Microwave Disinfestation	Physical treatment	TRL 7–9	Medium / expensive
26. Syngenta-type Injection / Trunk Injection	Chemical treatment	TRL 7–9	High
27. Metarhizium anisopliae	Entomopathogenic fungus	TRL 7–9	High
28. Beauveria bassiana	Entomopathogenic fungus	TRL 7–9	High
29. H. bacteriophora	Entomopathogenic nematode	TRL 7–9	High
30. S. carpocapsae	Entomopathogenic nematode	TRL 7–9	High
31. S. feltiae	Entomopathogenic nematode	TRL 7–9	Lower priority
32. Bt / Bacillus thuringiensis	Biopesticide	TRL 7–9	High
33. Nanochitosan	Bio-nanotechnology	TRL 4–6	Pilot
34. Nano TiO2	Bio-nanotechnology	TRL 4–6	Pilot
35. Novaluron	Chitin synthesis inhibitor	TRL 4–6	Research/pilot
36. Essential Oils	Biopesticide	TRL 1–3 / 4–6	Research
37. Picrotoxin	Plant-based biopesticide	TRL 1–3	Research
38. Chitinase from Beauveria bassiana	Biopesticide	TRL 1–3	Low
39. Justicia brandegeana extract	Biopesticide	TRL 1–3	Low
40. Serine Protease Inhibitors	Biotech biopesticide	TRL 1–3	Low
41. RNAi technologies	RNA interference	TRL 1–3	Research

D. Revival and Removal Technologies

Technology	Category	TRL	Deployment Priority
42. Removal and Disposal	GAP / sanitation	TRL 7–9	High
43. Traditional Fertilizers	Recovery support	TRL 7–9	Medium
44. Biofertilizers	Recovery support	TRL 7–9	Medium
45. Nano-fertilizers	Recovery support	TRL 4–6 / 7–9	Pilot
46. Microwave Disinfestation	Physical removal/treatment	TRL 7–9	Medium

4. Technology Profiles and Assessment

This section presents standardized profiles of RPW control technologies across prevention, detection, treatment, and revival/removal. Each profile covers the technology family, control category, TRL, description, application, target RPW stage, evidence, deployment needs, validation status, SWOT analysis, and recommendation.

The aim is to distinguish deployment-ready technologies from those needing field validation, piloting, or further research. This keeps the assessment practical, comparable, and useful for decision-making.

4.1. Prevention Technology Profiles

This section assesses technologies that reduce the risk of RPW infestation before severe damage occurs. It includes chemical, irrigation, genetic, and population-suppression approaches, classified by TRL and deployment priority. The focus is on identifying practical prevention tools for immediate use and separating them from early-stage research technologies.

4.1.1. Emamectin Benzoate

Technology family: Conventional crop protection chemical / trunk injection insecticide

RPW control category: Prevention and treatment

TRL classification: TRL 7–9

Description: Emamectin Benzoate is an avermectin-class insecticide used through trunk injection or endotherapy. The active ingredient is injected directly into the palm stem, allowing the compound to move through internal palm tissues and protect the tree from RPW infestation. The MEWA profiling document identifies it as a mature, fully commercialized pesticide with multiple global suppliers.

Application in RPW control: The technology is mainly used as a preventive trunk-injection treatment for palms at risk of infestation. It can also support treatment when infestation is still manageable. Application involves drilling holes at different orientations around the palm stem, injecting the insecticide, sealing the holes, and irrigating the palm to support internal movement of the product.

Target RPW life stage: Larvae and adults, with preventive protection against internal infestation.

Evidence of effectiveness: The profiling material reports that Emamectin Benzoate can protect palm trees from RPW infestation for up to nine months when applied through trunk injection. It is scored highly for prevention, treatment, and removal-related control functions.

Deployment requirements: Deployment requires injection equipment, trained operators, safe pesticide handling procedures, and compliance with pesticide regulations. Because the product is toxic, applicators require training, protective equipment, and correct dosage control.

Validation status: Commercially available and globally deployed. Suitable for immediate deployment where legally permitted and where trained application teams are available.

Notes on supporting evidence: Trunk endotherapy with Emamectin benzoate has field evidence as both preventive and curative RPW control. In a one-year Jordan field trial, Revive® 4% and Revive II® 9.5% were injected with the Syngenta TMI 4.1 device and externally monitored every two weeks; trees were dissected at 3, 6, and 12 months to assess RPW mortality and persistence (Mashal & Obeidat, 2019). A Saudi field study reported successful control of apical and trunk infestations using a simple injection method, supporting operational use in date palms (Nasraoui et al., 2025). Comparative endotherapy research on Phoenix canariensis found Emamectin benzoate more systemic and persistent than thiamethoxam or imidacloprid, with persistence around five months in palm tissues (Chihaoui-Meridja et al., 2019). Evidence supports high-priority deployment under trained, regulated protocols; injection injury, residues, resistance, dosage, legal registration, operator practice, and post-treatment monitoring require management (Mashal & Obeidat, 2019; Chihaoui-Meridja et al., 2019).

SWOT analysis:

Strengths	**Weaknesses**
High effectiveness; long protection period; commercially available; suitable for high-value palms	Requires drilling and injection; needs trained operators; pesticide toxicity risk; repeated use may raise residue and resistance concerns
Opportunities	**Threats**
Can be integrated into preventive RPW management programs for high-risk zones	Regulatory restrictions, misuse, over-application, environmental concerns, and possible farmer reluctance due to injection cost

Recommendation: High priority for deployment, but only under controlled protocols. This is a strong technology, not a casual farmer-applied product. It should be used strategically for high-value palms, high-risk areas, and confirmed hot spots.

4.1.2. Thiamethoxam

Technology family: Conventional crop protection chemical / systemic insecticide

RPW control category: Prevention and treatment

TRL classification: TRL 7–9

Description: Thiamethoxam is a systemic insecticide used in agriculture to control sucking and chewing insects. In RPW management, it has been tested through injection into palm tissues. It is commercially available and has multiple suppliers, but its suitability for RPW prevention is questionable because of reported negative effects on palm canopy health.

Application in RPW control: The product can be injected into palm stems after dilution. The application process includes drilling holes, injecting the solution, allowing absorption, removing injectors, and sealing the holes.

Target RPW life stage: Eggs, larvae, pupae, and adults, depending on exposure and internal movement of the insecticide.

Evidence of effectiveness: The MEWA profiling document reports that Thiamethoxam showed effectiveness in killing RPW at all stages within six months. However, the same source notes that it may cause partial to total canopy collapse, which makes the technology risky despite its insecticidal effect.

Deployment requirements: It requires injection equipment, trained pesticide applicators, safety procedures, and regulatory approval. Because of potential phytotoxicity or palm damage, it also requires strict field validation before any recommendation for operational deployment.

Validation status: Commercially available, but not recommended as a priority prevention tool without caution.

Notes on supporting evidence: Peer-reviewed evidence supports thiamethoxam as a tested palm endotherapy insecticide, but with weaker performance than emamectin benzoate. Chihaoui-Meridja et al. (2019) compared thiamethoxam, imidacloprid, and emamectin benzoate for RPW control in Phoenix canariensis and assessed systemicity, persistence, and efficacy. Moura et al. (2022) summarized that thiamethoxam injection caused high mortality in adults, pupae, and larvae, but acted mainly as a preventive rather than curative treatment. Ferreira et al. (2024) reported that, in the same RPW endotherapy evidence base, thiamethoxam residues were detected only once and were insufficient to prevent collapse of infested palms, whereas emamectin benzoate showed stronger persistence and protection.

SWOT analysis:

Strengths	Weaknesses
Commercially available; insecticidal activity against RPW; relatively low chemical cost	Serious concern about palm canopy damage; toxicity risk; weak fit for sustainable IPM if palm injury occurs
Opportunities	Threats
Could be studied under controlled trials for specific emergency use cases	Palm collapse, regulatory restrictions, reputational risk, farmer rejection, and environmental concerns

Recommendation: Low priority / caution. Do not promote it as a standard prevention technology. A technology that kills the pest but damages the palm is not a good solution; it is a liability unless very specific safe-use evidence is produced.

4.1.3. Imidacloprid

Technology family: Conventional crop protection chemical / systemic insecticide

RPW control category: Prevention and treatment

TRL classification: TRL 7–9

Description: Imidacloprid is a systemic insecticide that mimics nicotine and disrupts the insect nervous system. It enters insects through contact and ingestion and has been used in agriculture against different insect pests. For RPW, it has been tested mainly as a treatment for infested palms.

Application in RPW control: The profiling material describes application through diluted solution and soil drench-irrigation around the palm trunk. It can be used where internal infestation is suspected, but its preventive role is weaker than Emamectin Benzoate.

Target RPW life stage: Larvae and adults.

Evidence of effectiveness: The source material reports that treatment of highly infested trees resulted in 61.9% larval mortality and 42.6% adult mortality after 25 days. Collected live larvae and adults died within 48 hours after treatment. These results show activity, but the performance is moderate compared with stronger alternatives.

Deployment requirements: Deployment requires pesticide access, trained personnel, safe handling, correct dilution, and compliance with local pesticide regulations. Monitoring is needed after treatment to confirm whether infestation has been suppressed.

Validation status: Commercially available and globally deployed, but its RPW-specific performance is moderate.

Notes on supporting evidence: Imidacloprid has field evidence against RPW, but evidence supports moderate and targeted use rather than flagship prevention. Kaakeh (2006) tested imidacloprid against developmental stages of Rhynchophorus ferrugineus in laboratory and field trials; Dembilio et al. (2009) cited Kaakeh's soil-drench result showing 61.9% larval mortality three weeks after treatment, with larvae collected alive dying within 48 h. Dembilio et al. (2009) also found imidacloprid and Steinernema carpocapsae in chitosan effective in Phoenix canariensis field protection, but combined use did not significantly improve efficacy over single treatments. Later mobility work evaluated abamectin and imidacloprid in Phoenix canariensis under different application methods (Dembilio et al., 2014). Comparative endotherapy evidence reported emamectin benzoate as more systemic and persistent than imidacloprid and thiamethoxam (Chihaoui-Meridja et al., 2019). Evidence supports imidacloprid as a regulated treatment option, with resistance, residue, non-target, dosage, operator, and post-treatment confirmation risks requiring monitoring in farms after use.

SWOT analysis:

Strengths	Weaknesses
Commercially available; familiar agricultural insecticide; can suppress larvae and adults	Moderate mortality rates; chemical residue concerns; environmental and regulatory limitations; weaker preventive profile than Emamectin Benzoate
Opportunities	Threats
May be used as part of targeted treatment where permitted	Resistance development, non-target impact, regulatory restriction, and overuse by farmers

Recommendation: Medium priority. It can be included as a possible chemical option, but it should not be the flagship prevention technology. Emamectin Benzoate is stronger for preventive injection.

4.1.4. Micro/Drip/subsurface Irrigation

Technology family: Irrigation and water management technology

RPW control category: Prevention

TRL classification: TRL 7–9

Description: Micro/drip/subsurface irrigation delivers water and nutrients slowly and directly to the root zone. It reduces water waste and limits excessive surface moisture around the trunk base. This is important because humid conditions around the palm base can create favorable conditions for RPW activity and infestation. The MEWA profiling document classifies micro/drip irrigation as a mature technology with multiple global suppliers.

Application in RPW control: The technology prevents infestation indirectly by improving farm water management and reducing conditions that favor RPW establishment. It is not an insect-killing technology; it is a risk-reduction technology. That distinction matters. Its value is in reducing infestation pressure through better agronomic conditions.

Target RPW life stage: Adults indirectly, by reducing favourable conditions for egg-laying and establishment near the palm base. It also reduces the probability of larval development by limiting infestation initiation.

Evidence of effectiveness: The profiling document cites a study in a 16,000-date-palm farm in Al-Kharj Oasis where 89% of infested trees were detected in flood-irrigated plots, compared with 11% in drip-irrigated plots over 1.5 years. This is a strong prevention signal.

Deployment requirements: Requires irrigation system design, installation of drip lines and drippers, filtration, pressure control, periodic maintenance, and farmer training. For best results, irrigation scheduling must be adapted to palm age, soil type, water quality, and climate.

Validation status: Commercially mature and ready for deployment. Local adaptation may be needed for existing farms using flood, bubbler, or basin irrigation.

Notes on supporting evidence: Evidence supports micro, drip, and subsurface irrigation as indirect RPW-prevention measures rather than insecticidal treatments. A study on irrigation and RPW within-grove distribution specifically compared drip and flood irrigation effects in date palms (Aldryhim & Al-Bukiri, 2003). A recent study reported that bubbler-irrigated palms had significantly higher RPW infestation than palms under surface-drip and subsurface-drip systems, supporting irrigation method as a risk factor (Nejatian et al., 2025). A Saudi sustainable-management case also reported that irrigation method, palm density, sanitation, pruning, and offshoot removal affected RPW establishment and infestation levels, placing water management within GAP-based prevention (Ali-Bob, 2019). Drip and subsurface systems also align with water-saving and salinity-risk reduction needs in Saudi date production (Mohammed et al., 2024; Alotaibi & Kassem, 2021). Evidence supports high-priority preventive deployment, with effectiveness dependent on design, filtration, maintenance, salinity management, scheduling, and farmer adoption under local farm conditions and supervision.

SWOT analysis

Strengths	Weaknesses
Mature technology; saves water; reduces trunk-base humidity; supports palm health; strong fit with GAP	Initial installation cost; requires maintenance; poor design can reduce effectiveness; farmers may resist changing traditional irrigation
Opportunities	**Threats**
Strong potential for integration with RPW prevention, water-saving programs, and climate-smart agriculture	Clogging, poor maintenance, high-salinity water, incorrect scheduling, and weak farmer adoption

Recommendation: High priority. This should be treated as a core preventive technology. Ignoring irrigation management in RPW control is a serious technical mistake.

4.1.5. Genetic Engineering for Pest Resistance

Technology family: Agricultural biotechnology / plant resistance

RPW control category: Prevention

TRL classification: TRL 1–3

Description: Genetic engineering for pest resistance aims to develop or enhance date palm resistance to RPW through genetic modification or genome editing. The concept is based on improving the palm's natural defence mechanisms against insect attack. However, the MEWA profiling document clearly states that this technology is still at an early theoretical stage for RPW and that no mutant date palm line has yet been created for RPW resistance or tolerance.

Application in RPW control: If developed successfully, resistant date palm cultivars could reduce infestation risk at the plantation level. This would be a long-term prevention strategy, not an immediate field intervention.

Target RPW life stage: Potentially all stages indirectly, by reducing successful feeding, establishment, and development within palm tissues.

Evidence of effectiveness: There is no direct field evidence for genetically engineered date palms resistant to RPW. Evidence is currently conceptual and based on broader knowledge of plant resistance mechanisms and genome-editing potential.

Deployment requirements: Requires advanced molecular biology laboratories, date palm tissue culture and transformation capacity, genetic screening, greenhouse testing, multi-year field trials, biosafety approval, and regulatory acceptance.

Validation status: Research stage only. Not ready for field deployment.

Notes on supporting evidence: Genetic engineering for pest resistance in date palms remains a nascent, theoretical approach with no RPW-resistant date palm lines reported to date, placing it at TRL 1–3 and as a long-term preventive strategy rather than an immediate solution (El-Shafie & Faleiro, 2020; Naveed et al., 2023). Proponents argue that genome editing and transgenic strategies could fortify innate defense pathways, enabling durable resistance if target genes are correctly identified and regulatory frameworks permit deployment (Naveed et al., 2023; Hoddle et al., 2024). Key challenges include developing reliable transformation protocols for date palm tissue culture, ensuring stable expression without pleiotropic penalties, and navigating biosafety and public acceptance concerns. Current reviews emphasize foundational research, omics-guided gene discovery, and proof-of-concept studies as prerequisites for field-ready cultivars (Manee et al., 2023; Hoddle et al., 2024). Collectively, evidence supports continued exploratory work, with a cautious outlook on timelines and regulatory hurdles before any commercial release (Naveed et al., 2023; Hoddle et al., 2024).

SWOT analysis

Strengths	**Weaknesses**
Potential long-term solution; could reduce pesticide dependency; strategic value for breeding programs	No RPW-resistant engineered date palm currently available; very long development timeline; high technical complexity
Opportunities	**Threats**
Could support future resistant cultivar development and national breeding programs	Regulatory barriers, public acceptance issues, biosafety concerns, high cost, and uncertain commercial adoption

Recommendation: Low priority for operational programs; research only. This is not a deployable technology. Presenting it as a near-term RPW solution would be misleading.

4.1.6. Precision-Guided Sterile Insect Technique, pgSIT

Technology family: Mutation breeding / genetic population control

RPW control category: Prevention and population suppression

TRL classification: TRL 1–3 / early TRL 4–6 for RPW

Description: pgSIT is a CRISPR-based genetic control strategy designed to produce sterile insects for population suppression. It has shown promise in other insects, especially mosquitoes, but its application to RPW is still not established. The MEWA profiling material describes pgSIT as proven effective for mosquitoes but requiring further research for RPW.

Application in RPW control: The concept would involve mass production and release of sterile RPW males to reduce reproduction in wild populations. If successful, it could serve as an area-wide prevention and suppression tool.

Target RPW life stage: Adults, specifically reproductive adults, with indirect impact on eggs and future population growth.

Evidence of effectiveness: Evidence comes mainly from mosquito studies, where high ratios of sterile males to wild males suppressed populations over several generations. There is no strong field evidence yet for RPW.

Deployment requirements: Requires specialized gene-editing laboratories, secure insect-rearing facilities, colony maintenance, genetic quality control, release protocols, ecological risk assessment, and high-level regulatory approval.

Validation status: Research stage for RPW. Not ready for field deployment.

SWOT analysis

Strengths	**Weaknesses**
Potential area-wide suppression tool; species-specific; could reduce pesticide use in the future	Not validated for RPW; technically complex; expensive; requires mass rearing and genetic engineering capacity
Opportunities	**Threats**
Could become a strategic future technology for national RPW suppression programs	Regulatory rejection, ecological concerns, public resistance, failure to compete with wild males, and very high operational cost

Recommendation: Research only. Keep it in the report, but do not place it beside deployable tools. It belongs in a long-term innovation pipeline, not in an immediate RPW control package.

4.1.7. Incompatible Insect Technique / Wolbachia-Based Technique

Technology family: Genetic population suppression / biological reproductive interference

RPW control category: Prevention and population suppression

TRL classification: TRL 4–6 globally for some insects; research-stage for RPW

Description: The Incompatible Insect Technique uses reproductive incompatibility, often associated with *Wolbachia* infection, to suppress pest populations. When incompatible males mate with wild females, offspring fail to develop, reducing population growth over time. The technology has been applied more extensively in mosquitoes and other insects, but it requires further research for RPW.

Application in RPW control: For RPW, the technology would theoretically involve producing and releasing incompatible males to reduce successful reproduction in the field. It would be used as a population-level prevention strategy rather than a tree-level control tool.

Target RPW life stage: Adults, especially reproductive males and females, with indirect effects on egg hatch and future larval populations.

Evidence of effectiveness: The profiling material notes that IIT, often combined with sterile insect approaches, has been effective in suppressing some insect populations. However, RPW-specific evidence is still insufficient.

Deployment requirements: Requires temperature-controlled rearing facilities, microbiology and molecular biology laboratories, quality-control systems, sex separation, release planning, population monitoring, and regulatory approval.

Validation status: Not ready for RPW field deployment. Requires laboratory and controlled pilot validation before any operational consideration.

Notes on supporting evidence: Evidence for incompatible insect technique (IIT) and Wolbachia-based approaches indicates strong cross-species potential for population suppression through cytoplasmic incompatibility, with several mosquito and tephritid studies demonstrating effective reduction in offspring and, in some cases, substantial population declines; however, field- and species-specific RPW data remain absent, and robust laboratory-to-field validation, sex separation, release protocols, and regulatory risk assessments are repeatedly emphasized as prerequisites before any operational RPW use (Hoffmann, 2020; Zabalou et al., 2009; Moretti et al., 2025). Conceptual models and cage trials in other insects support IIT/IIT-SIT hybrids as area-wide strategies under IPM, yet RPW-specific evidence is limited to indirect extrapolations from Wolbachia-induced CI and theoretical risk assessments, underscoring the need for RPW-targeted experiments and stringent biosafety considerations before deployment (Sullivan & O'Neill, 2017; Zanganeh et al., 2025).

SWOT analysis

Strengths	**Weaknesses**
Environmentally friendly concept; population-level suppression; potential compatibility with area-wide IPM	Not validated for RPW; requires specialized rearing and molecular capacity; complex operational logistics
Opportunities	**Threats**
Could support future area-wide RPW suppression if adapted successfully	Regulatory constraints, ecological uncertainty, poor field competitiveness, high cost, and technical failure during mass rearing

Recommendation: Research priority only. This is promising science, not a current field solution. It should be included in the future innovation pipeline, not in the immediate deployment package.

4.2. Detection Technology Profiles

4.2.1. Visual Inspection

Technology family: Traditional detection / field scouting

RPW control category: Detection

TRL classification: TRL 7–9

Description: Visual inspection is the conventional method for identifying RPW infestation through external symptoms such as oozing sap, chewed fibbers, holes, fermented smell, crown weakness, frond yellowing, or trunk damage.

Application in RPW control: It is used as the first-line screening method during routine farm visits. It helps identify suspicious palms for further confirmation using sensors, traps, or destructive inspection.

Target RPW life stage: Mainly larvae and advanced infestation symptoms; indirect detection of adult activity through damage signs.

Evidence of effectiveness: Visual inspection is practical and widely used, but weak for early detection because RPW larvae feed inside the trunk and visible symptoms often appear late.

Deployment requirements: Requires trained field scouts, inspection checklists, GPS-based recording, and regular monitoring frequency.

Validation status: Fully deployed and operational, but limited for early-stage infestation.

Notes on supporting evidence: Visual inspection remains the foundational and field-ready detection method for red palm weevil (RPW), with high maturity/TRL 7–9 because it is routinely used as the first screening step in surveillance programs. However, its value is limited for early infestation because larvae develop inside the trunk and clear external symptoms often appear late; therefore, suspicious palms should be confirmed through complementary methods such as acoustic/sensor tools, pheromone-trap data, or destructive sampling where needed (El-Mergawy & Al-Ajlan, 2011; FAO, 2020; El-Shafie & Faleiro, 2020; Kurdi et al., 2021). Effective deployment requires trained scouts, scheduled inspection, clear symptom checklists, palm marking/recording, and GPS- or database-based monitoring. Overall, visual inspection is essential for triage but insufficient alone for reliable early detection, so it should be embedded in an integrated, multi-modal RPW detection strategy (FAO, 2020; El-Shafie & Faleiro, 2020).

SWOT analysis

Strengths	Weaknesses
Low cost, simple, immediately deployable, useful for routine monitoring.	Poor early detection; highly dependent on scout skill; subjective.
Opportunities	Threats
Can be strengthened with mobile apps, GIS mapping, and sensor confirmation	Late detection can lead to palm loss and pest spread

Recommendation: High priority as a baseline tool but never rely on it alone. It should be combined with traps and sensor-based detection.

4.2.2. Mass Trapping – Wet Trap

Technology family: Semiochemicals detection / pheromone trapping

RPW control category: Detection, monitoring, and population suppression

TRL classification: TRL 7–9

Description: Wet traps use pheromone lures, food bait, water, and a trap container to attract and capture adult RPWs. The water retains and kills trapped weevils and helps maintain bait attractiveness.

Application in RPW control: Wet traps are placed across farms to monitor adult RPW activity, detect population peaks, and support treatment or area-wide control decisions. They can also contribute to reducing adult populations when used at sufficient density.

Target RPW life stage: Adults.

Evidence of effectiveness: Wet pheromone traps are commercially available, widely used, and low-cost. They are effective for monitoring adult activity but do not detect larvae already inside palm trunks.

Deployment requirements: Requires trap containers, pheromone lures, food bait, water, routine servicing, lure replacement, trap cleaning, and catch recording.

Validation status: Commercially available and widely deployed.

Notes on supporting evidence: Wet traps for RPW mass trapping have strong practical grounding as a pheromone-based detection and suppression tool, supported by extensive field use in the Mediterranean and Middle East where ferrugineol-based lures, kairomones, and water-enhanced trap designs have yielded high adult catches and informed area-wide management, though effectiveness hinges on trap density, maintenance, and integration with broader IPM strategies (Hallett et al., 1999; Faleiro et al., 2011; Vidyasagar et al., 2000; Dalbon et al., 2019). The approach benefits from low cost and operational maturity, with traps typically deployed for monitoring and to reduce adult emergence when paired with rapid response actions, quarantine, and sanitation measures (Dalbon et al., 2019; Rochat et al., 2017). Critical limitations include non-detection of larvae and the need for regular servicing to maintain lure potency and hygiene, underscoring the importance of standardized protocols and GIS-enabled surveillance for effective mass trapping (El-Shafie & Faleiro, 2020; Paraforos et al., 2020).

SWOT analysis

Strengths	Weaknesses
Low cost; simple; mature; attractive to adult RPW; useful for population monitoring	Labor-intensive; requires water and frequent servicing; may smell or become dirty; does not confirm tree-level infestation
Opportunities	Threats
Can be integrated with GIS, farm surveillance, and area-wide monitoring	Poor maintenance reduces trap efficiency; badly placed traps may attract RPW into farms; stagnant water and decomposed bait can create hygiene issues

Recommendation: High priority for monitoring and early warning where regular servicing is available. Wet traps are practical, but without maintenance they become trash, not technology.

4.2.3. Mass Trapping – Dry Trap

Technology family: Semiochemicals detection/pheromone trapping

RPW control category: Detection, monitoring, and population suppression

TRL classification: TRL 7–9

Description: Dry traps use pheromone lures and attractants to capture adult RPWs without water. They are designed to reduce servicing needs and improve field practicality, especially in areas where water-based trap maintenance is difficult.

Application in RPW control: Dry traps are used for routine monitoring of adult RPW movement and population pressure. They support early warning and help identify farms or zones requiring further inspection or treatment.

Target RPW life stage: Adults.

Evidence of effectiveness: Dry traps are commercially available and operationally useful. Their effectiveness depends on lure quality, trap design, placement, and inspection frequency. They are easier to maintain than wet traps but may differ in capture efficiency depending on field conditions.

Deployment requirements: Requires dry trap units, pheromone lures, attractants where applicable, scheduled inspection, lure replacement, and catch recording.

Validation status: Commercially available and suitable for deployment, with local performance validation recommended.

Notes on supporting evidence: Dry traps, which dispense pheromones without enclosed water or liquid baits, offer a cost-efficient alternative for RPW mass trapping, reducing servicing frequency and moisture-related maintenance while maintaining competitive attraction when paired with optimized lure blends and trap design (Kassem et al., 2020; Abdel-Azim et al., 2017; Navarro-Llopis et al., 2018). Field evaluations indicate that dry traps can achieve meaningful captures, particularly when combined with potent aggregation pheromones (ferrugineol) and co-attractants, though overall efficacy generally trails water-based systems unless trap density and lure longevity are maximized (Gonzalez et al., 2019; El-Shafie & Faleiro, 2017; Dalbon et al., 2021). Deployment planning emphasizes trap density ranges (often 1–10 traps per hectare depending on infestation pressure), careful placement in shaded areas, and standardized servicing intervals to sustain lure release and capture rates (Sabbahi et al., 2021; Soomro et al., 2022). Dry traps remain a viable IPM component when integrated with sanitation, surveillance, and other control tactics.

SWOT analysis

Strengths	Weaknesses
Lower maintenance than wet traps; no water requirement; cleaner and easier to service; suitable for large farms	May have lower or variable capture efficiency depending on design and bait system; still requires lure replacement; does not detect internal larvae
Opportunities	**Threats**
Good option for scalable monitoring in hot and dry environments; can support area-wide surveillance	Poor trap design, weak lure quality, incorrect placement, and irregular inspection can reduce value

Recommendation: High priority where labor and water-based maintenance are limiting. Dry traps are a practical upgrade, but they still need proper placement and regular inspection.

4.2.4. Service-less / Digitalized Traps

Technology family: Digital trap/semiochemicals IoT monitoring

RPW control category: Detection and monitoring

TRL classification: TRL 7–9

Description: Digitalized traps improve conventional trapping by adding sensors, wireless communication, and digital dashboards. Some designs also reduce servicing needs by extending lure life or minimizing manual inspection.

Application in RPW control: Digital traps provide near-real-time information on adult RPW captures and help managers monitor pest activity remotely. They are useful for large farms, government surveillance networks, and area-wide RPW control programs.

Target RPW life stage: Adults.

Evidence of effectiveness: The technology is mature and ready for deployment, but field performance depends on trap accuracy, sensor reliability, connectivity, battery or solar power, maintenance, and correct interpretation of trap data.

Deployment requirements: Requires digital trap units, pheromone systems, wireless connectivity, dashboard access, batteries or solar power, data management, and trained users for interpretation.

Validation status: Commercially available, but local validation is recommended before large-scale deployment.

Notes on supporting evidence: Digital trap systems integrate semiochemical lures with IoT-enabled sensors to automate deployment, data collection, and real-time monitoring of RPW activity; such platforms leverage ferrugineol-based attractants alongside kairomones, with embedded pheromone-release control and wireless telemetry to track trap performance, catch counts, and environmental conditions, enabling rapid IPM decisions and scalable area-wide surveillance (Dalbon et al., 2019; Vacas et al., 2017; El-Shafie & Faleiro, 2017). IoT integration supports GIS-based mapping, cloud analytics, and alerting to inform timely interventions, reducing labor without sacrificing data granularity. Field evidence from

Mediterranean and Middle Eastern programs demonstrates improved early detection and informed management when digital traps are combined with traditional monitoring and sanitation measures (Hallett et al., 1999; Faleiro et al., 2011). Challenges include ensuring robust connectivity, power management, lure longevity, and data integrity across large plantations, requiring standardized protocols and cybersecurity considerations (Dalbon et al., 2019; Ibrahim et al., 2023).

SWOT analysis

Strengths	Weaknesses
Reduces manual inspection; supports real-time monitoring; improves surveillance coverage; useful for digital dashboards	Depends on connectivity, sensor reliability, power supply, and calibration; still detects adults, not larvae inside palms
Opportunities	Threats
Strong fit with area-wide RPW monitoring, GIS mapping, and smart-farm systems	Sensor failure, weak connectivity, poor calibration, high cost, and overreliance on trap alerts

Recommendation:
High priority for large farms and government monitoring programs. Digital traps should complement field inspection and sensors, not replace them.

4.2.5. Acoustic Sensors

Technology family: Digital detection/bioacoustic sensing

RPW control category: Detection

TRL classification: TRL 7–9

Description: Acoustic sensors detect sounds produced by RPW larvae feeding and moving inside palm trunks. Signals are analyzed manually or through digital algorithms.

Application in RPW control: Used for tree-level diagnosis, especially where early internal infestation is suspected but external symptoms are unclear.

Target RPW life stage: Larvae.

Evidence of effectiveness: Acoustic sensing is one of the strongest early-detection tools because it directly targets larval activity inside the palm. Reported studies show high detection accuracy, though field performance depends on noise, sensor placement, and algorithm quality.

Deployment requirements: Requires acoustic devices, trained operators, quiet measurement protocols, data processing, and validation against visual or destructive inspection.

Validation status: Commercially available, but local validation remains important.

Notes on supporting evidence: Evidence supports acoustic sensors as one of the more credible early-detection tools for RPW because they target the feeding and movement sounds of larvae hidden inside palm trunks before visible symptoms develop. Bioacoustics sensor work showed that microphones, probes, onboard processing, and wireless reporting can capture larval sound patterns for early diagnosis (Martínez Rach et al., 2013). Distributed optical fiber acoustic sensing further demonstrated detection of young larvae and separation of infested from healthy palms, while machine-learning studies showed that distributed acoustic data can support scalable classification in field experiments (Ashry et al., 2020; Ashry et al., 2022). The evidence also makes clear that performance is not automatic: sensor placement, signal quality, background noise, and algorithm reliability strongly affect accuracy. Therefore, acoustic sensing is high-priority for RPW detection, but local validation remains essential before large-scale deployment. It should complement visual inspection and treatment decisions rather than operate alone in isolation.

SWOT analysis:

Strengths	Weaknesses
Direct larval detection; strong early-detection potential; non-destructive	Sensitive to background noise; needs correct placement and interpretation
Opportunities	Threats
Can be integrated with AI, cloud dashboards, and routine field screening	False positives from other insects or mechanical noise; poor user training

Recommendation: High priority. This is one of the most practical sensor technologies for RPW detection, but it must be validated under local field conditions.

4.2.6. Seismic Sensors

Technology family: Digital detection / vibration-based IoT sensing

RPW control category: Detection

TRL classification: TRL 7–9

Description: Seismic sensors detect internal vibrations caused by larval feeding activity. Devices such as IoTree use a sensor inserted or attached to the palm and transmit data through gateways to cloud platforms.

Application in RPW control: Used for continuous or periodic tree monitoring, especially in high-value palms or validation plots.

Target RPW life stage: Larvae.

Evidence of effectiveness: The technology is commercially available and has reported strong detection performance, but local validation is still required to confirm accuracy under UAE/GCC conditions.

Deployment requirements: Requires sensors, gateways, cloud platform, installation protocol, power supply, connectivity, and trained staff for monitoring.

Validation status: Deployment-ready but should be field-validated before large-scale adoption.

Notes on supporting evidence: Seismic sensors are supported by recent field evidence as a practical tool for detecting RPW larval activity inside date palm stems. Unlike visual inspection, which often identifies infestation only after external symptoms appear, seismic monitoring targets vibrations generated by feeding and movement of larvae within the trunk. Mendel et al. (2024a) evaluated IoTree seismic sensors in date palm plantations and showed that larval-generated vibrations can support palm health decisions and sensor-based RPW management. A broader management analysis further reported that IoTree seismic sensors were used across different date palm settings, with larval vibrations forming the basis for infestation detection and decision-making (Mendel et al., 2024b). Supporting field evidence also shows that RPW larvae produce measurable vibration patterns inside infested palms, which can decline after effective treatment (Sutanto et al., 2023). Overall, seismic sensors are promising, but performance depends on sensor placement, calibration, connectivity, and local field validation.

SWOT analysis

Strengths	Weaknesses
Continuous monitoring; digital data; early larval detection potential	Cost per tree; installation effort; dependence on gateway and cloud system
Opportunities	Threats
Strong fit for smart-farm monitoring and research validation	False alarms, sensor failure, weak connectivity, and limited scalability if cost is high

Recommendation: High priority for validation. Do not scale blindly before confirming field accuracy and cost-benefit.

4.2.7. Densitometer

Technology family: Mechanical sensor / trunk structural assessment

RPW control category: Detection

TRL classification: TRL 7–9

Description: A densitometer is a drilling-based tool that measures internal trunk resistance and detects structural anomalies such as tunnels or decayed tissue.

Application in RPW control: Used to assess suspicious palms and identify internal damage that may indicate RPW larval tunnelling.

Target RPW life stage: Larvae, indirectly through detection of internal tunnelling and tissue damage.

Evidence of effectiveness: Reported as relatively effective for identifying internal structural anomalies, but multiple measurements may be needed because results depend on drilling direction and infestation position.

Deployment requirements: Requires device purchase, trained operators, drilling protocol, and sanitation after probing to avoid spreading pathogens.

Validation status: Mature and deployable, but more useful for confirmation than broad early screening.

Notes on supporting evidence: Evidence for densitometer use in RPW detection supports its role as a mature, deployable, but mainly confirmatory diagnostic tool. Densitometers assess internal trunk resistance and can identify tissue anomalies associated with RPW galleries, larval feeding damage, cocoons, or internal decay. In a field study comparing several detection devices for RPW on palms, Pugliese et al. (2018) tested an IML-RESI densitometer and reported a high percentage of correct diagnoses, with 87% accuracy at 20 cm and strong performance at selected trunk heights. This supports its value for confirming infestation where suspicious symptoms or sensor alerts already exist. However, because RPW infestation may be localized and hidden in specific trunk zones, densitometer readings can miss early or spatially limited attacks if probing points are poorly selected. Recent reviews of RPW detection also emphasize that early diagnosis remains difficult and requires method integration (Mohammed et al., 2020).

SWOT analysis

Strengths	Weaknesses
Direct structural assessment; portable; useful for confirmation	Invasive; may miss localized infestation; requires multiple readings.
Opportunities	Threats
Can support confirmation after visual or sensor alerts.	Trunk injury, incorrect interpretation, and low practicality for large-scale screening.

Recommendation: Medium priority. Useful as a confirmatory diagnostic tool, not as the main detection system.

4.2.8. Resistograph

Technology family: Mechanical sensor / resistance drilling

RPW control category: Detection

TRL classification: TRL 7–9

Description: A resistograph uses a thin drilling needle to measure resistance inside the palm trunk. Lower resistance may indicate cavities, decay, or RPW tunneling.

Application in RPW control: Used to inspect suspicious palms and confirm internal damage caused by larvae.

Target RPW life stage: Larvae, indirectly through damage detection.

Evidence of effectiveness: It can detect internal structural damage, but it is more suitable for mid- and late-stage infestations than early detection.

Deployment requirements: Requires resistograph equipment, trained operators, drilling protocol, and data interpretation.

Validation status: Mature technology, but RPW-specific use should be targeted.

Notes on supporting evidence: Evidence for resistograph use in RPW diagnosis supports its value as a confirmatory tool rather than a stand-alone early-warning method. A resistograph records drilling resistance along a probe path; abrupt reductions may indicate galleries, cavities, decay, or tissue degradation associated with larval feeding. Field evaluations have included resistance-drilling measurements among devices assessed against infestation status, showing that this approach can identify internal damage but that performance varies with probe height, direction, and the location of galleries within the trunk (Rasool et al., 2020; Pugliese et al., 2018). Such variation is expected because early infestations can be localized and may not intersect the drilling path.

SWOT analysis

Strengths	**Weaknesses**
Mature; portable; useful for trunk damage confirmation	Invasive; may not detect early infestation; requires expertise
Opportunities	**Threats**
Can validate acoustic or seismic sensor alerts	Misreading damage, trunk injury, and slow inspection rate

Recommendation
Medium priority. Good for confirmation, weak as a primary early-detection tool.

4.2.9. Thermal Sensors

Technology family: Drone/sensor detection / thermal imaging

RPW control category: Detection

TRL classification: TRL 4–6 / 7–9

Description: Thermal sensors detect temperature differences in the palm canopy or trunk that may be associated with stress or infestation.

Application in RPW control: Used through handheld devices, drones, or fixed cameras to identify stressed palms for follow-up inspection.

Target RPW life stage: Indirect detection of larval damage and palm stress.

Evidence of effectiveness: Thermal imaging has shown potential, but it often detects stress rather than RPW itself. It is more reliable in moderate to severe infestation than in early-stage detection.

Deployment requirements: Requires thermal camera, drone or handheld platform, trained operator, image analysis, and ground-truth validation.

Validation status: Pilot-stage for RPW-specific detection.

Notes on supporting evidence: Evidence for thermal sensing in RPW detection comes from studies showing tissue damage can be associated with temperature differentials measured by thermal cameras (El-Faki et al., 2016; Pugliese et al., 2018). In a field comparison, thermal imaging correctly classified 24 of 31 assessed palms (77.4% accuracy) and identified 22 of 26 infested palms (84.6%), after diagnoses were checked through inspection or destructive examination (Pugliese et al., 2018). A controlled study of artificially infested date palms evaluated trunk temperature differentials for early RPW detection, supporting biological rationale for thermal monitoring (El-Faki et al., 2016). Nonetheless, thermal imaging measures physiological stress rather than the insect directly; thermal patterns may be influenced by transpiration, solar radiation, water status, disease, and canopy condition (Pugliese et al., 2018). Accordingly, evidence supports thermal sensing for screening suspicious palms, with image acquisition and ground-truth confirmation required before treatment decisions (El-Faki et al., 2016; Pugliese et al., 2018).

SWOT analysis

Strengths:	Weaknesses
Non-invasive; rapid scanning; useful for identifying stressed palms	Not RPW-specific; affected by heat, irrigation, canopy condition, and time of day
Opportunities	Threats
Can support farm-level screening and remote sensing validation	High false positives if used without ground truthing

Recommendation: Pilot priority. Use it as a stress-screening tool, not a direct RPW detector.

4.2.10. Radar

Technology family: Non-invasive sensing / ground-penetrating radar

RPW control category: Detection

TRL classification: TRL 7–9

Description: Radar systems use electromagnetic waves to assess internal trunk structure and detect cavities, decay, or abnormal internal features.

Application in RPW control: Used to inspect palms suspected of internal damage caused by RPW larvae.

Target RPW life stage: Larvae, indirectly through internal damage.

Evidence of effectiveness: Radar can detect internal structural changes, but accuracy is moderate and depends on equipment, operator skill, trunk condition, and analysis software.

Deployment requirements: Requires radar equipment, trained technical staff, analysis software, and time for tree-level scanning.

Validation status: Mature technology, but operational use for RPW should be selective.

Notes on supporting evidence: Evidence for radar-based RPW diagnosis comes mainly from a field comparison of TreeRadarUnit devices and recent literature on physical methods for internal larval monitoring. Rasool et al. (2020) evaluated Radar 2000 and Radar 900 during field assessment of date palms, reporting accuracies of 77% and 73%, respectively, which were lower than visual inspection. The study supports radar's ability to identify internal trunk anomalies associated with RPW damage rather than larvae themselves (Rasool et al., 2020). Recent RPW literature continues to list radar as a physical approach for monitoring larvae inside palm trunks (Wu et al., 2023). Independent tree-health research shows that ground-penetrating radar can evaluate internal trunk structure and decay, providing a technical basis for targeted application to suspected palms (Kashyap & Kumar, 2021). The reported field accuracy supports selective use as a confirmatory tool, alongside visual inspection or other diagnostic methods in integrated RPW management (Rasool et al., 2020).

SWOT analysis:

Strengths	Weaknesses
Non-invasive; can detect internal structure; useful for high-value palms	Expensive; slow; needs expertise; moderate accuracy
Opportunities	Threats
Can support advanced diagnosis and research validation	High cost, low field throughput, and complex interpretation

Recommendation: Medium priority. Useful for specialized diagnosis, not mass screening.

4.2.11. Light Detection and Ranging (LiDAR)

Technology family: Remote sensing / drone-based structural mapping

RPW control category: Detection

TRL classification: TRL 7–9

Description: LiDAR uses laser-based scanning to collect structural information on palms, canopy architecture, and field conditions. It does not directly detect RPW but can support stress and structural analysis. It uses laser pulses to measure distance and create detailed 3D information on palm height, canopy structure, and field conditions.

Application in RPW control: Used with drones or airborne systems to map palm structure and identify abnormal patterns for follow-up inspection.

Target RPW life stage: Indirect detection of infestation effects, mainly through stress or structural change.

Evidence of effectiveness: LiDAR is mature for agricultural mapping, but RPW-specific detection remains limited and may be more useful for late-stage symptoms or farm mapping than early detection.

Deployment requirements: Requires drone platform, LiDAR sensor, flight planning, data processing software, and remote sensing expertise.

Validation status: Technology is mature, but RPW-specific use needs validation.

Notes on supporting evidence: Evidence supports LiDAR as a mature structural-mapping tool, not a validated direct detector of RPW. LiDAR provides canopy height, crown geometry, and tree-position information; palm-inventory research shows LiDAR-derived height models improve individual-palm identification and filter non-palm objects from aerial results (Culman et al., 2020). Reviews of active remote sensing describe LiDAR as a means of capturing structural and morphological changes associated with plant stress, rather than identifying an insect itself (Kashyap & Kumar, 2021). Direct RPW evidence remains limited: a multisensor date-palm study reported that LiDAR had not been applied to palm assessment and was considered a potential tool (Mulley et al., 2019). Recent UAV work supports temporal-image detection of RPW effects, but does not validate LiDAR-specific diagnosis (Delalieux et al., 2023). LiDAR is therefore supported for mapping and prioritizing palms for follow-up inspection; RPW-specific sensitivity, specificity, and early-stage capacity require ground-truthed validation (Mulley et al., 2019; Delalieux et al., 2023).

SWOT analysis:

Strengths	**Weaknesses**
High-resolution structural data; useful for farm mapping; non-invasive	Does not detect RPW directly; costly; requires data expertise
Opportunities	**Threats**
Can support GIS-based RPW surveillance and risk mapping	Overclaiming RPW detection from indirect indicators

Recommendation: Medium priority. Use for mapping and support analytics, not direct diagnosis.

4.2.12. Drones with Sensors

Technology family: Remote sensing / aerial monitoring

RPW control category: Detection

TRL classification: TRL 7–9

Description: Drones equipped with RGB, multispectral, hyperspectral, thermal, or LiDAR sensors collect aerial data for identifying stressed palms and mapping farm conditions.

Application in RPW control: Used to screen large areas, identify abnormal palms, support ground teams, and prioritize field inspection.

Target RPW life stage: Indirect detection of larval infestation through palm stress symptoms.

Evidence of effectiveness: Drones are mature in agriculture, but their RPW value depends on sensor type, image resolution, analytics, and ground truthing.

Deployment requirements: Requires drone, sensors, licensed operator where required, flight planning, image processing, and field validation.

Validation status: Deployment-ready as a platform; RPW-specific models need local validation.

Notes on supporting evidence: Evidence shows drones support RPW surveillance, but performance depends on sensor, image timing, processing, and ground observations (Delalieux et al., 2023). In a two-year experiment, Delalieux et al. (2023) monitored infested and control date palms with RGB, multispectral, and thermal cameras and field inspection. Thermal crown features separated infested from non-infested palms at severe infestation before visual canopy symptoms, while temporal vegetation-index patterns helped identify infested palms before symptoms; the authors nevertheless called for further validation (Delalieux et al., 2023). UAV imagery also supports palm-level mapping: a deep-learning study based on high-resolution UAV images automatically mapped date palms, demonstrating use for inventory, geolocation, and follow-up inspection (Gibril et al., 2021). UAVs can therefore survey extensive areas and prioritize field teams, but they measure canopy stress or structural patterns rather than larvae. RPW-specific classification models require local validation against confirmed infestation status before they guide treatment decisions (Delalieux et al., 2023).

SWOT analysis

Strengths	Weaknesses
Rapid coverage; useful for large farms; supports mapping and prioritization	Detects stress, not RPW directly; needs analytics and ground truth
Opportunities	**Threats**
Can integrate with GIS, AI, and field scouting programs	False positives from irrigation stress, diseases, nutrient issues, or heat

Recommendation: Medium priority. Use as a screening and mapping tool, not a standalone RPW detector.

4.2.13. Satellite Image Analysis

Satellite Image Analysis

Technology family: Remote sensing / AI-based image analytics

RPW control category: Detection and risk mapping

TRL classification: TRL 4–6

Description: Satellite image analysis uses high-resolution imagery and machine learning to detect palm locations, canopy stress, and potential infestation patterns.

Application in RPW control: Used for large-scale surveillance, mapping date palm distribution, identifying stress zones, and prioritizing field inspection.

Target RPW life stage: Indirect detection of infestation impact, mainly through canopy stress.

Evidence of effectiveness: Satellite imagery can locate palms and detect stress patterns, but it does not directly identify RPW. It requires local calibration and ground-truth data.

Deployment requirements: Requires access to suitable imagery, GIS software, machine learning expertise, and field validation datasets.

Validation status: Pilot-stage for RPW control.

Notes on supporting evidence: Evidence for satellite-image analysis is based on canopy and water-stress patterns, not direct observation of larvae (Bannari et al., 2017; Mohammed et al., 2020). Bannari et al. (2017) used WorldView-3 data to assess water-stress indicators of RPW attack. Mohammed et al. (2020) summarized work distinguishing healthy, treated, untreated, severely infested, and dead palms using satellite-derived spectral information. Sentinel-based research on coconut palms used vegetation indices to discriminate RPW stress categories, supporting satellite mapping of infestation-related stress (Marzukhi et al., 2020). These studies do not show that satellite signals are specific to RPW, because canopy stress can result from water limitation, salinity, disease, or other factors (Mohammed et al., 2020). Satellite analysis is appropriate for palm inventory, stress-zone mapping, and prioritization of field inspection, not autonomous diagnosis (Bannari et al., 2017; Marzukhi et al., 2020). Its value depends on resolution, acquisition timing, local calibration, and validation against confirmed infestation records (Bannari et al., 2017; Mohammed et al., 2020).

SWOT analysis

Strengths	Weaknesses
Large-area coverage; useful for regional surveillance; scalable	Not RPW-specific; resolution limits; weak early detection
Opportunities	**Threats**
Can support national RPW risk maps and monitoring dashboards	Misclassification due to drought, salinity, nutrition, disease, or management stress

Recommendation: Pilot priority. Use for strategic surveillance, not tree-level diagnosis.

4.2.14. X-rays

Technology family: Detection sensor / radiographic imaging

RPW control category: Detection

TRL classification: TRL 1–3

Description: X-ray imaging aims to detect larvae or internal structures inside palm trunks using radiographic methods.

Application in RPW control: Potentially useful for detecting internal larvae or tunnels, but practical field devices for palms are not yet mature.

Target RPW life stage: Larvae.

Evidence of effectiveness: Evidence is mainly experimental or simulated. Field use on real palms remains impractical and requires further development.

Deployment requirements: Requires portable X-ray equipment, radiation safety protocols, trained experts, regulatory approval, and field-suitable design.

Validation status: Research-stage.

Notes on supporting evidence: Evidence for X-ray-based RPW detection remains limited and is primarily derived from radiographic and computed-tomography investigations rather than operational farm deployment. Ma et al. (2011) evaluated X-ray CT for palm-weevil detection and reported that cone-beam CT reconstruction from limited projections could support detection of small weevils under simulated conditions. More recent studies continue to identify X-ray tomography as a potentially accurate method for detecting internal RPW infestation, but note that individual-tree scanning is slow and poorly suited to large commercial farms (Wang et al., 2021; Ashry et al., 2022). A recent review also includes X-ray CT among available RPW detection approaches but identifies practical constraints related to field implementation, equipment access, and operational scale (Naveed et al., 2023). Collectively, the evidence supports technical feasibility for visualizing internal larvae or tunnels, but not routine operational use. X-ray detection should therefore remain a research-stage or specialized inspection technology until portable systems, radiation-safety protocols, and field validation are available.

SWOT analysis

Strengths	Weaknesses
Could theoretically visualize internal infestation	Not practical in farms; radiation safety concerns; expensive; low readiness
Opportunities	Threats
Could support laboratory validation or quarantine inspection in future	Regulatory barriers, safety risks, and poor field feasibility

Recommendation: Low priority. Keep as research only.

4.2.15. Near-Infrared Spectroscopy, NIRS

Technology family: Spectroscopy / biochemical sensing

RPW control category: Detection

TRL classification: TRL 4–6

Description: NIRS analyzes tissue response to near-infrared light and can detect differences between healthy, wounded, and infested palm tissue.

Application in RPW control: Used to analyze palm tissue or field samples to identify infestation-related biochemical changes.

Target RPW life stage: Indirect detection of larval damage through tissue changes.

Evidence of effectiveness: NIRS shows potential to distinguish infested or damaged tissue, but it requires further validation for field-level RPW diagnosis.

Deployment requirements: Requires NIRS equipment, sampling protocol, chemometric models, trained analysts, and reference datasets.

Validation status: Research/pilot stage.

Notes on supporting evidence: Evidence for NIRS in RPW detection is limited but includes a field evaluation comparing NIRS with thermal, digital-camera, radar, resistograph, magnetic, and DNA-biosensor methods in date palms, using tree dissection as the reference test (Salman et al., 2020). The evaluation identified NIRS and resistograph as the most promising devices, while spectral differences were observed among healthy, wounded, and RPW-infested tissues (Salman et al., 2020; Mohammed et al., 2020). These findings indicate that NIRS detects damage-associated tissue changes rather than larvae directly (Mohammed et al., 2020). A recent review lists NIRS among candidate technologies for early RPW detection, not as an established operational method (Kharim & Krishnan, 2022). Evidence supports pilot use with standardized sampling, locally trained chemometric models, and validation against confirmed healthy, wounded, diseased, and infested palms (Salman et al., 2020; Mohammed et al., 2020). NIRS should complement field inspection and confirmatory diagnostics rather than replace them (Kharim & Krishnan, 2022).

SWOT analysis

Strengths	Weaknesses
Non-destructive or minimally destructive; strong analytical potential	Requires models and expertise; not simple for farmers; indirect detection
Opportunities	**Threats**
Can support diagnostic laboratories and validation studies	Weak field adoption if equipment and interpretation remain complex

Recommendation: Research/pilot priority. Useful for diagnostic development, not immediate farm deployment.

4.2.16. RferOR1 Pheromone Receptor

Technology family: Molecular detection / olfactory receptor biology

RPW control category: Detection research

TRL classification: TRL 1–3

Description: RferOR1 is a pheromone receptor associated with RPW response to methyl-branched compounds such as ferrugineol and ferrugineone. It provides molecular insight into RPW chemical detection.

Application in RPW control: Potential future use in improved attractants, molecular diagnostics, or semiochemical detection systems.

Target RPW life stage: Adults, mainly through pheromone response.

Evidence of effectiveness: The technology is early-stage and laboratory-based. It is not a deployable field diagnostic tool.

Deployment requirements: Requires molecular biology laboratory, RT-qPCR or related tools, trained specialists, and further technology development.

Validation status: Research-stage.

Notes on supporting evidence: Evidence for RferOR1 derives from molecular and behavioural studies rather than field diagnosis. Antony et al. (2021) identified RferOR1 as an adult RPW aggregation-pheromone receptor by RNA-interference silencing of highly expressed antennal receptors, electrophysiological recording, and heterologous expression in Drosophila olfactory neurons. RferOR1 was activated most strongly by ferrugineol and also responded to ferrugineone; RNA-interference knockdown reduced antennal and behavioural responses to pheromone (Antony et al., 2021). Recent work on RferSNMPu1, a sensory-neuron membrane protein, also demonstrated reduced pheromone responses after gene silencing and provided evidence consistent with a wider pheromone-detection pathway involving RferOR1 (Johny et al., 2024). These studies assess adult olfaction, gene expression, and controlled assays, not palm-level surveillance, larval detection, or field diagnostic accuracy (Antony et al., 2021; Johny et al., 2024). RferOR1 is therefore supported as a molecular target for future biosensor and semiochemical research, not as an operational RPW diagnostic technology (Antony et al., 2021).

SWOT analysis:

Strengths	Weaknesses
Strong scientific value; may improve pheromone-based tools	Not field-ready; high expertise requirement; no immediate operational use
Opportunities	**Threats**
Could improve lure design and molecular understanding of RPW behaviour	Long development timeline and uncertain commercial translation

Recommendation: Research only. Do not present it as a current detection technology.

4.2.17. Genetically Engineered *E. coli* Biosensor

Genetically Engineered *Escherichia coli* Biosensor

Technology family: Microbial biosensor / biotechnology-based detection

RPW control category: Detection research

TRL classification: TRL 4–6

Description: Genetically engineered *E. coli* strains are designed to respond to stress-related volatile organic compounds from infested palms by producing detectable light signals.

Application in RPW control: Potentially used as a biosensor for detecting infestation-related volatiles from palm tissue or enclosed samples.

Target RPW life stage: Indirect detection of larval infestation through palm stress volatiles.

Evidence of effectiveness: Proof-of-concept evidence exists under controlled conditions, but practical field deployment is not yet established.

Deployment requirements: Requires microbiology facilities, biosafety protocols, engineered bacterial strains, containment systems, VOC sampling, and trained personnel.

Validation status: Research-stage / controlled pilot only.

Notes on supporting evidence: Evidence for this approach is limited to a proof-of-concept study in date palm. Harpaz et al. (2022) developed a whole-cell biosensor based on genetically engineered *Escherichia coli* strains designed to respond to cytotoxicity, genotoxicity, and quorum-sensing signals associated with volatile emissions from RPW-affected palm tissues. The reporter bacteria were immobilized in alginate within sealed containers, and changes in bacterial light emission were used to distinguish volatile samples from palms with infection conditions (Harpaz et al., 2022). The study supports the technical feasibility of detecting infestation-associated chemical signals indirectly rather than detecting larvae or RPW DNA directly (Harpaz et al., 2022). Because the system was evaluated as a proof of concept, it does not establish diagnostic sensitivity, specificity, response time, or reliability under real farm conditions (Harpaz et al., 2022). Practical implementation would require VOC sampling, contained sensor cartridges, biosafety controls, and validation against confirmed healthy, wounded, diseased, and RPW-infested palms (Harpaz et al., 2022).

SWOT analysis:

Strengths	Weaknesses
Innovative early-detection concept; potential sensitivity to infestation-related VOCs	Biosafety complexity; not field-ready; indirect detection; requires lab handling
Opportunities	**Threats**
Could support future diagnostic kits or controlled laboratory screening	Regulatory barriers, biosafety concerns, public acceptance, and poor field practicality

Recommendation: Research only for now. Interesting science, but not ready for operational RPW programs.

4.3. Treatment Technologies

This section assesses technologies used to treat RPW-infested palms and reduce weevil survival after infestation has been detected. The technologies include semiochemical-based attract-and-kill systems, chemical trunk injection, physical microwave treatment, biological agents such as fungi, bacteria, and entomopathogenic nematodes, and emerging nano- and biotechnology-based approaches. Each technology is assessed according to its maturity, target RPW life stage, field-deployment requirements, evidence of effectiveness, operational limitations, and suitability for integration within an IPM programme. The section distinguishes treatment options that are ready for operational use from those that require further pilot testing, field validation, or laboratory research before deployment.

4.3.1. Attract and Kill

Technology family: Semiochemical + insecticide

RPW control category: Treatment

TRL classification: TRL 7-9

Description: A semiochemical attractant is combined with an insecticidal killing component. The attractant draws red palm weevils to the formulation, where they contact the lethal component.

Application in RPW control: Applied within palm areas to attract and kill RPW while reducing the quantity of insecticide used compared with broad treatment.

Target RPW life stage: Adults attracted to the semiochemical formulation.

Evidence of effectiveness: Field trials reported RPW population reductions of 89% with a paste formulation and 41% with a card formulation. The trials used different application densities and formulations.

Deployment requirements: Semiochemical lure, insecticidal formulation, placement plan, and routine replacement or maintenance according to product instructions. No additional infrastructure is required.

Validation status: Mature and commercially available. Field trials have been conducted in Saudi Arabia and India.

Notes on supporting evidence: Evidence for RPW attract-and-kill remains limited to a small number of field trials, mainly in Saudi Arabia and India. A bait-free Hook-RPW™ formulation was evaluated in Saudi date palms, where pheromone–insecticide point sources attracted and killed adult RPW and reduced pheromone-trap captures in treated plots compared with untreated plots (El-Shafie et al., 2011; Faleiro et al., 2019). Faleiro et al. (2019) also reported trials of Smart Ferrolure™ formulations in Saudi Arabia and India. In these trials, the paste formulation was associated with an 89% reduction in RPW population, whereas the card formulation was associated with a 41% reduction. Formulation affected operational performance: paste points killed more adults, while dust accumulation reduced insecticide contact on cards after field exposure (Faleiro et al., 2019). The available studies support attract-and-kill as a promising adult-suppression tool within integrated RPW management, but broader independent replication across palm systems, climates, formulations, and operational scales remains limited.

SWOT analysis:

Strengths	Weaknesses
Commercially available; simple deployment; low infrastructure requirement; semiochemical attraction can reduce the amount of insecticide applied	Effectiveness differed between paste and card formulations
Opportunities	**Threats**
Can be integrated into existing trapping, surveillance, and treatment programmes	Poor placement density, formulation choice, or maintenance may reduce field impact. Recommendation: High priority for operational deployment, particularly where routine placement and maintenance can be ensured.

4.3.2. Microwave Disinfestation

Technology family: Physical treatment

RPW control category: Treatment

TRL classification: TRL 7-9

Description: Microwave generators deliver ultra-high-frequency energy into the palm trunk to raise temperature and kill RPW within internal tissues. Commercial systems include ring and box-based equipment.

Application in RPW control: Used to treat infested palms and, where appropriate, palms intended for transport or movement. Treatment settings can be adjusted according to palm diameter, treatment section, environmental temperature, wind, microwave power, treatment depth, and target temperature.

Target RPW life stage: Eggs, larvae, pupae, and adults within the treated palm section.
Evidence of effectiveness: One treatment killed 86% of insects; remaining individuals died within two days due to thermal effects. The treatment also severely reduced fertility among surviving RPW.

Deployment requirements: Eco Palm Ring or Eco Palm Box equipment, power supply, trained operators, parameter adjustment, and sufficient time for individual-palm treatment.

Validation status: Mature and commercially available, but operational deployment requires specialized equipment and trained operators.

Notes on supporting evidence: Evidence for microwave disinfestation derives from field, laboratory, and modelling studies. In standing *Phoenix canariensis* palms, treatment raised temperatures in treated trunk sections to about 70 °C; larvae and adults recovered from those sections were dead, while surviving weevils showed reduced longevity and reproductive-organ alterations (Massa et al., 2019). A field investigation reported 86% mortality, with remaining insects dying within two days and survivors displaying severely reduced fertility (Massa et al., 2011). Laboratory testing found microwave heating caused mortality in RPW larvae and adults, although responses varied by developmental stage and exposure duration (Mady et al., 2021). Numerical modelling shows that attaining lethal temperatures depends on input power, treatment duration, penetration depth, palm dielectric properties, and insect location within the trunk (Rmili et al., 2020). Together, these studies support microwave heating as a localized thermal intervention, but show the need for controlled parameters and validation across palm species, trunk diameters, infestation depths, and ambient conditions.

SWOT analysis:

Strengths	Weaknesses
Chemical-free physical treatment; acts against all RPW stages; commercial equipment is available.	High capital cost and lower financial feasibility than other treatment options
Opportunities	**Threats**
Suitable for high-value palms, movement-related disinfestation, and locations seeking reduced chemical use	Incorrect parameter selection may affect treatment performance across palm types and trunk sizes

Recommendation: Medium priority. Use selectively for high-value palms, quarantine-related treatment, or locations where equipment cost can be justified.

4.3.3. Syngenta-Type Injection / Trunk Injection

Technology name: Syngenta-Type Injection / Trunk Injection

Technology family: Chemical treatment

RPW control category: Treatment

TRL classification: TRL 7-9

Description: Systemic insecticide is injected into palm tissues through trunk endotherapy. The source profile includes Revive, containing emamectin benzoate, as an example of an injectable treatment.

Application in RPW control: Used for preventive and curative treatment of palms through direct trunk injection.

Target RPW life stage: Internal RPW stages exposed to insecticide through treated palm tissue; stage-specific performance was not separately reported.

Evidence of effectiveness: The source profile reports injection of 100 mL of Revive per palm and protection from RPW infestation for up to nine months.

Deployment requirements: Injectable insecticide, drilling and injection equipment, accurate dose preparation, trunk-treatment procedure, and trained staff.

Validation status: Mature chemical endotherapy approach with commercial products and established field use.

Notes on supporting evidence: Evidence for Emamectin-benzoate trunk injection includes field evaluations of Syngenta products and micro-injection systems. Mashal and Obeidat (2019) evaluated Revive® 4% and Revive II® 9.5% in date palms using the Syngenta TMI 4.1 device. Each palm received four injections, totalling 48 mL of Revive® or 24 mL of Revive II®, equivalent to 2 g active ingredient per palm. The reported curative response was 98.5% after three months and 100% after six and twelve months. In naturally infested date palms, Sutanto et al. (2023) injected Revive/Aretor 4EC through four trunk holes, delivering 42 mL per palm. Acoustic activity declined to zero within four months after treatment. These studies support emamectin benzoate as a systemic curative treatment for concealed RPW infestation, while confirming that performance is linked to the injection device, dose, injection points, sealing of holes, and follow-up monitoring. Product-specific doses and protection periods should follow approved labels and validated protocols.

SWOT analysis:

Strengths	Weaknesses
Direct palm-level treatment; prolonged protection period reported; commercial products are available	Requires drilling, injection equipment, and careful application
Opportunities	Threats
Suitable for treatment of valuable palms and targeted protection in high-risk areas	Environmental impact and operator handling requirements were identified as constraints in the source assessment

Recommendation: High priority as a targeted treatment option, applied through standardized endotherapy protocols and trained teams.

4.3.4. Metarhizium anisopliae

Technology family: Entomopathogenic fungus

RPW control category: Treatment

TRL classification: TRL 7-9

Description: *Metarhizium anisopliae* is an entomopathogenic fungus that infects insect hosts through the cuticle, proliferates inside the body, and consumes internal tissues.

Application in RPW control: Applied through foliar spraying or soil application. The source profile recommends repeated application at 7-12-day intervals, depending on infestation severity.

Target RPW life stage: RPW stages exposed to fungal spores; source evidence reports infection progression and mortality without separate stage-specific field recommendations.

Evidence of effectiveness: The source profile reports a median lethal time of 8.6 days for 85% viable spores, with 92% mycosis and 100% mortality by 21 days after infection.

Deployment requirements: Commercial fungal formulation, water, conventional spraying equipment, and repeated application according to infestation severity.

Validation status: Commercially available through multiple products and assessed as deployment ready.

Notes on supporting evidence: Evidence for *M. anisopliae* against RPW includes laboratory, semi-field, and field-injection studies. Yasin et al. (2017) screened 19 fungal isolates and reported that an *M. anisopliae* isolate with 85% conidial viability had an LT50 of 8.6 days, 92% mycosis, and 100% mortality by 21 days under bioassays. In a 2023 field study, an *M. anisopliae* isolate injected into naturally infested date palms reduced vibration activity from larval feeding and movement, and outperformed *B. bassiana* (Sutanto et al., 2023). A 2024 semi-field study found *M. anisopliae* isolates reduced infestation and larval numbers and documented persistence and host-to-host transmission, but efficacy differed between isolates (Alwaneen et al., 2024). An oil-emulsion study found conidial performance was affected by formulation and environmental conditions (Cheong et al., 2023). These studies tested injection, bioassay, or semi-field exposure—not a standardized foliar or soil-spray regimen—so palm-level protocols require local validation (Sutanto et al., 2023; Alwaneen et al., 2024).

SWOT analysis:

Strengths	Weaknesses
Organic biological treatment; commercially available; conventional spraying equipment can be used; strong mortality evidence in the source profile.	Mortality develops over time rather than immediately
Opportunities	Threats
Suitable for integration with IPM and reduced-chemical treatment programmes	Performance depends on application interval, spore viability, and adequate coverage.

Recommendation: High priority as a biological treatment option, particularly where repeated treatment and monitoring are feasible.

4.3.5. Beauveria bassiana

Technology family: Entomopathogenic fungus

RPW control category: Treatment

TRL classification: TRL 7-9

Description: *Beauveria bassiana* is an entomopathogenic fungus used as a biological insecticide against a wide range of insect pests, including RPW.

Application in RPW control: Applied as a spray at the first sign of pests. The source profile recommends reapplication every seven days for prevention and repeated application every 3-5 days for established infestations.

Target RPW life stage: Larvae and adults.

Evidence of effectiveness: The source profile reports 88% larval mortality and 75% adult mortality. The fungal infection process was described as taking approximately four to five days before visible fungal growth.

Deployment requirements: Commercial fungal formulation, water, traditional spraying equipment, and repeated treatment according to infestation condition.

Validation status: Widely used in agriculture as a biological insecticide and commercially available in spray and wettable-powder products.

Notes on supporting evidence: Evidence for *B. bassiana* against RPW includes laboratory, semi-field, and limited field studies. Direct-spray laboratory assays found third-instar larvae reached 100% mortality within 7–11 days across 6×10^2–6×10^7 spores/mL, whereas seventh-instar mortality reached 70–75% at the two highest concentrations (El Husseini, 2019). The same study tested directly treated adults, confirming susceptibility under controlled exposure (El Husseini, 2019). A 2024 semi-field experiment evaluated three *B. bassiana* isolates on date-palm plants and measured survival, fungal persistence, and host-to-host transmission; efficacy differed among isolates and application concentrations (Alwaneen et al., 2024). In naturally infested date palms, fungal injection followed by trunk dissection at 45 days resulted in 100% internal larval mortality, although the tested *M. anisopliae* isolate outperformed the *B. bassiana* isolate (Sutanto et al., 2023). An attract-and-infect formulation also showed adult infection and field persistence (Dembilio et al., 2018). The studies therefore support isolate-specific applications, rather than a universal spray rate or reapplication interval (Alwaneen et al., 2024; Sutanto et al., 2023).

SWOT analysis:

Strengths	Weaknesses
Biological and environmentally favorable treatment; commercial availability; conventional spraying equipment; activity against larvae and adults	Requires repeated treatment and time for fungal infection to develop
Opportunities	**Threats**
Can support reduced-chemical RPW treatment and early-response interventions	Incomplete coverage or delayed application can reduce treatment impact

Recommendation: High priority as a practical biological treatment, particularly for early and moderate infestations.

4.3.6. Heterorhabditis bacteriophora

Technology family: Entomopathogenic nematode

RPW control category: Treatment

TRL classification: TRL 7-9

Description: *Heterorhabditis bacteriophora* is a biological nematode that seeks out and infects RPW larvae.

Application in RPW control: Applied to moist soil using watering cans, sprayers, irrigation systems, or ground application. The source profile recommends application when soil temperature exceeds 12°C for at least six hours daily and maintaining soil moisture after treatment.

Target RPW life stage: Larvae, pupae in cocoons, and adults.

Evidence of effectiveness: The source profile reports that 500 infective juveniles per container killed 100% of small larvae. Higher rates of 2,000 or 6,000 infective juveniles per container were needed for medium and large larvae. Pupae in cocoons and adults were reported as more susceptible than large larvae.

Deployment requirements: Commercial nematode formulation, water, moist soil conditions, irrigation or spraying equipment, and post-application moisture management.

Validation status: Commercially available and used as biological pest control for RPW.

Notes on supporting evidence: Evidence for *Heterorhabditis bacteriophora* against RPW is strongest for larval stages and varies by nematode strain, larval age, dose, and delivery method. In a laboratory comparison, the HP88 and Ar-4 strains caused 92.1% and 82.1% mortality, respectively, in fourth-instar larvae after nine days, while efficacy declined against ninth- and eleventh-instar larvae (El Sobki et al., 2020). A field study injected an *H. bacteriophora* EKB20 suspension into four artificial tunnels in naturally infested palms. The protocol delivered 960,000 infective juveniles per palm, and field applications of entomopathogenic nematodes achieved up to 90% mortality under low and medium infestation conditions (El Roby et al., 2018). Controlled studies also found *H. bacteriophora* pathogenic to RPW larvae and identified its sequential use with *Beauveria bassiana* or *Metarhizium anisopliae* as a candidate integrated treatment requiring field confirmation (Wakil et al., 2017). Available evidence therefore supports moisture-preserving, targeted application into infestation galleries rather than soil-only delivery.

SWOT analysis:

Strengths	Weaknesses
Biological and environmentally favorable; can be applied through irrigation or spraying; no special talent requirement stated	Requires suitable soil temperature and sustained moisture. Larger larvae need higher application rates
Opportunities	**Threats**
Fits irrigation-supported treatment and biological-control programmes	Dry conditions or unsuitable temperature can limit nematode survival and effectiveness

Recommendation: High priority where irrigation and moisture management can be maintained after application.

4.3.7. Steinernema carpocapsae

Technology family: Entomopathogenic nematode

RPW control category: Treatment

TRL classification: TRL 7-9

Description: *Steinernema carpocapsae* is a biocontrol nematode that infects and kills RPW larvae. It uses a sit-and-wait strategy and enters insects through natural openings.

Application in RPW control: Applied to soil or the thatch layer using conventional spraying equipment. The source profile identifies temperatures between 22°C and 28°C as highly suitable.

Target RPW life stage: Larvae.

Evidence of effectiveness: The source profile reports efficacy of around 80%, with higher results over time. Efficacy reached up to 98% when treatment was applied preventively.

Deployment requirements: Commercial nematode product, water, conventional spray equipment, suitable temperature conditions, and access to soil or thatch treatment zones.

Validation status: Used in public spaces and palm farms; commercial products are available.

Notes on supporting evidence: Evidence for *S. carpocapsae* against RPW includes laboratory, semi-field, and field evaluations. A 2025 laboratory study of the ALL strain reported 93.33% larval mortality within 120 h at 250 infective juveniles (IJs)/mL, with an LC50 of 57.67 IJs/mL and LT50 of 45.03 h; the authors cautioned that laboratory results cannot be extrapolated directly to field conditions (Lv et al., 2025). Field tests reported 83.60% mortality, while earlier field evidence cited 98% mortality (Rehman & Mamoon-ur-Rashid, 2022). A semi-field application to the lower palm and adjacent soil reported 90–100% adult mortality at 2–4 × 10^6 juveniles in 5 L water per tree (Sutanto et al., 2025). Temperature, moisture, and soil conditions affect nematode dispersal and survival (Husain et al., 2024). Overall, findings support targeted use against accessible RPW stages, while locally validated spray protocols remain necessary for soil or thatch treatment (Lv et al., 2025; Husain et al., 2024).

SWOT analysis:

Strengths	Weaknesses
Biological, environmentally favorable, safe around people and beneficial organisms, and rapidly kills suitable hosts	Activity is influenced by temperature and access to the target site
Opportunities	**Threats**
Strong potential for preventive biological treatment	Lower performance may occur when temperature, placement, or timing are unsuitable

Recommendation: High priority, particularly as a preventive treatment in palms and sites where suitable application conditions can be maintained.

4.3.8. Steinernema feltiae

Technology family: Entomopathogenic nematode

RPW control category: Treatment

TRL classification: TRL 7-9

Description: *Steinernema feltiae* is a broadly used nematode for biological control of soil- and plant-associated pests.

Application in RPW control: Mixed with water and applied through sprayers, watering cans, or irrigation systems. The source profile recommends application during cooler parts of the day and maintaining moist soil after application.

Target RPW life stage: Larvae.

Evidence of effectiveness: The source profile reports application at 500 infective juveniles per larva and a 36.4% mortality rate among RPW larvae.

Deployment requirements: Commercial nematode product, water, traditional irrigation or spraying equipment, cooler application conditions, and post-treatment moisture management.

Validation status: Commercially available and widely used for pest control, but its effectiveness against RPW was described as less documented and lower than other entomopathogenic nematodes.

Notes on supporting evidence: Evidence for *Steinernema feltiae* against RPW remains limited and variable. A review of entomopathogenic nematode studies reported 38.9% larval mortality after eight days with *S. feltiae*, compared with 98.9% for *S. carpocapsae* and 86.9% for *Heterorhabditis bacteriophora* under laboratory conditions (Nurashikin-Khairuddin et al., 2022). In a field comparison, *S. feltiae* produced 64.8% RPW mortality, whereas *S. carpocapsae* produced 83.6%; pupae enclosed in cocoons were less susceptible than larvae and adults

(Rehman & Mamoon-ur-Rashid, 2022). A 2024 laboratory evaluation showed that entomopathogenic nematode efficacy differs among species and strains, while temperature, moisture, and soil conditions influence nematode dispersal and survival (Husain et al., 2024). Accordingly, peer-reviewed evidence does not establish 500 infective juveniles per larva or 36.4% mortality as a universal field dose-response benchmark; these values should be treated as study-specific laboratory findings. The available evidence supports local efficacy trials before routine deployment of *S. feltiae* in RPW management (Rehman & Mamoon-ur-Rashid, 2022; Husain et al., 2024).

SWOT analysis:

Strengths	Weaknesses
Commercial availability; biological treatment; can use conventional irrigation and spraying equipment	Lower reported RPW larval mortality than other nematode options
Opportunities	**Threats**
May be considered where it is already available within existing biological-control programmes	Use as a main RPW treatment may result in insufficient control where high efficacy is required

Recommendation: Lower priority. Use only as a supplementary or locally validated biological option.

4.3.9. Bacillus thuringiensis

Technology family: Biopesticide

RPW control category: Treatment

TRL classification: TRL 4-6

Description: *Bacillus thuringiensis* is a microbial biopesticide that produces toxins active against insect larvae after ingestion, disrupting the gut lining.

Application in RPW control: Applied after dilution in water and sprayed where target insects are active. The source profile lists foliar application as the standard application approach.

Target RPW life stage: Larvae.

Evidence of effectiveness: At a concentration of 1×10^8 CFU/mL, the source study reported 100% larval mortality within four days after treatment.

Deployment requirements: Commercial Bt formulation, water, mixing equipment, and standard spraying equipment. No specialized talent was identified as necessary.

Validation status: Commercially available and widely used in agriculture; the reported RPW efficacy evidence was based on larval testing at different concentrations.

Notes on supporting evidence: Evidence for Bt against RPW is derived mainly from controlled ingestion bioassays. Pu et al. (2017) evaluated an entomopathogenic Bt strain against larvae fed treated plant material and reported 100% mortality at 1×10^8 CFU/mL within four days, with reduced feeding activity. Subsequent laboratory studies confirmed that Bt pathogenicity varies with concentration and life stage. Celi et al. (2022) assessed median lethal doses and lethal times in mature larvae and adults exposed through Bt-treated diet, finding different mortality and physiological responses among larvae, females, and males. Elsharkawy et al. (2022) fed larvae and adults sugarcane treated with a Bt isolate across a concentration gradient and reported mortality increased with bacterial concentration over 21 days. All three studies used laboratory feeding designs rather than direct treatment of larvae concealed in standing palm trunks. Evidence therefore supports Bt as a promising ingestion-based larvicidal agent, but not as a validated field foliar-spray treatment for RPW.

SWOT analysis:

Strengths	Weaknesses
Biological treatment; commercially available; conventional spraying equipment can be used; reported high larval mortality	Evidence in the source focuses on larvae and does not provide a field delivery protocol for concealed infestation within trunks
Opportunities	Threats
Can be included in biological treatment programmes and combined with early infestation detection.	Treatment success depends on obtaining sufficient contact or ingestion by target larvae

Recommendation: High priority for further operational use and field protocol development, especially within biological-control programmes.

4.3.10. Nanochitosan

Technology family: Bio-nanotechnology

RPW control category: Treatment

TRL classification: TRL 4-6

Description: Nanochitosan is a biodegradable and biocompatible polymer proposed for RPW control through disturbance of protein and carbohydrate processes and enzyme function.

Application in RPW control: The source experiment diluted nanochitosan in distilled water, treated sugarcane pieces with the solution, and allowed larvae and adults to feed on the treated material.

Target RPW life stage: Larvae and adults.

Evidence of effectiveness: At 20,000 ppm, the source profile reports 100% larval mortality within 15-20 days and 100% adult mortality within 10-15 days.

Deployment requirements: Nanochitosan product, formulation and dilution process, treatment material or delivery method, and guidance for practical field deployment.

Validation status: Pilot-stage. The source profile indicates that a pilot programme is needed before deployment.

Notes on supporting evidence: Evidence for nanochitosan against RPW is laboratory-based (Habood et al., 2022; El-Shewy et al., 2023). Habood et al. (2022) exposed larvae and adults to nanochitosan-treated sugarcane and reported concentration-dependent mortality. At 20,000 ppm, they reported 100% larval mortality after 15–20 days and 100% adult mortality after 10–15 days, with effects on developmental, biochemical, and enzymatic measures (Habood et al., 2022). A later laboratory study with <50-nm nanochitosan found increasing mortality with dose and exposure duration: 0.5% nanochitosan caused 100% mortality in ninth-instar larvae after seven days, accompanied by haemocyte, biological, enzymatic, and histological changes (El-Shewy et al., 2023). A review identifies chitosan as a biodegradable, biocompatible material used directly and as a nanocarrier in insect-pest management, but it does not establish field efficacy against RPW (Abenaim & Conti, 2023). Neither study reported field trials on naturally infested palms; pilot validation is warranted (Habood et al., 2022; El-Shewy et al., 2023).

SWOT analysis:

Strengths	Weaknesses
Biodegradable and biocompatible material; high mortality reported under experimental conditions	Mortality requires several days; field delivery through palm tissues was not established in the source profile
Opportunities	**Threats**
May support development of lower-impact nano-formulated treatments	Performance and practical field delivery require pilot validation

Recommendation: Pilot priority. Conduct controlled field validation before operational adoption.

4.3.11. Nano TiO2

Technology family: Bio-nanotechnology

RPW control category: Treatment

TRL classification: TRL 4-6

Description: Nano titanium dioxide combined with *Moringa oleifera* leaf extract is described as a natural nanoparticle-based treatment intended to disrupt RPW development.

Application in RPW control: The source profile describes preparation of nanoparticle minerals in a biopesticide formulation and injection into the palm trunk at 1.5 m above ground level.

Target RPW life stage: Larvae, pupae, and adults.

Evidence of effectiveness: The source profile reports 100% larval mortality in 1.3 minutes, 92% pupal mortality in 30 minutes, and 87% adult mortality in 1.5 minutes.

Deployment requirements: Nano TiO2 material, plant-extract formulation, trunk-injection quipment, technical guidance, and trained operators.

Validation status: Pilot-stage. The source profile identifies the need for pilot validation before deployment.

Notes on supporting evidence: Evidence for nano-TiO2 against RPW is limited to laboratory bioassays, not field trunk-injection studies. Aly et al. (2021) exposed eggs, larvae, cocoons, and adults to TiO2 at 125–1,000 ppm and recorded mortality five days after treatment; TiO2 was less active than ZnO in their comparisons. Gutiérrez-Ramírez et al. (2021) cited a TiO2–*Moringa oleifera* study reporting 100% RPW mortality at 75 mg/L after ten days, confirming controlled-exposure activity but not the minute-scale mortality estimates in the source profile. Neither paper verified injection at 1.5 m above ground or effectiveness in naturally infested palms (Aly et al., 2021; Gutiérrez-Ramírez et al., 2021). Nanoparticle performance depends on formulation, concentration, exposure route, and life stage, and laboratory mortality cannot demonstrate operational efficacy (Gutiérrez-Ramírez et al., 2021). Therefore, the evidence supports pilot-stage classification and requires replicated field trials of formulation stability, trunk distribution, palm safety, residual activity, and RPW mortality before adoption.

SWOT analysis:

Strengths	Weaknesses
Reported activity against larvae, pupae, and adults; rapid mortality under experimental conditions	Requires specialized injection equipment and trained personnel
Opportunities	**Threats**
Can be tested as a trunk-applied nano-formulated treatment	Field performance, formulation stability, and practical deployment require validation

Recommendation: Pilot priority. Evaluate operational safety, tree response, and field effectiveness before wider use.

4.3.12. Novaluron

Technology family: Chitin synthesis inhibitor

RPW control category: Treatment

TRL classification: TRL 4-6

Description: Novaluron is a chitin synthesis inhibitor assessed for its effect on RPW larval mortality, growth, and gene expression related to chitin degradation.

Application in RPW control: The source experiment incorporated novaluron into artificial larval diet under controlled conditions.

Target RPW life stage: Larvae.

Evidence of effectiveness: Artificial diet containing 30 ppm novaluron produced more than 95% larval mortality in the reported experiment.

Deployment requirements: Laboratory formulation capability, insect-rearing facilities, experimental design, microbiology and entomology expertise, and a field-delivery method that has not yet been established.

Validation status: Research and pilot stage. The source profile states that field studies had not been performed.

Notes on supporting evidence: Evidence for novaluron against red palm weevil comes from a laboratory ingestion bioassay with newly molted ninth-instar larvae fed artificial diet (Hussain et al., 2019). The study recorded a dose-dependent response and an LD50 of 14.77 ppm (Hussain et al., 2019). Diet containing 30 ppm novaluron caused >95% larval mortality within six days; 20–30 ppm caused >90% mortality, while 5 ppm caused 42.4% mortality after 144 h (Hussain et al., 2019). At 30 ppm, efficacy of conversion of ingested food and digested food declined by 74.27% and 82.38%, respectively, and approximate digestibility increased (Hussain et al., 2019). Midgut analyses documented time-dependent expression changes in chitin-degradation-related genes, including pronounced upregulation of an endochitinase-like gene (Hussain et al., 2019). These results demonstrate ingestion-mediated larvicidal and growth-disrupting activity under controlled conditions (Hussain et al., 2019). Because the study used artificial diet and confined larvae, it does not establish efficacy against larvae concealed within standing palms or provide field performance data. The evidence therefore supports a research-stage classification (Hussain et al., 2019).

SWOT analysis:

Strengths	Weaknesses
High larval mortality was reported under controlled conditions	Evidence is based on artificial-diet experiments rather than palm-field application
Opportunities	**Threats**
Can support future development of insect-growth-regulator approaches for RPW	Lack of field application and validation limits operational use

Recommendation: Research and pilot priority. Do not use as a routine field treatment until delivery and field efficacy are validated.

4.3.13. Essential Oils

Technology name: Essential Oils
Technology family: Biopesticide

RPW control category: Treatment

TRL classification: TRL 1-3 / 4-6

Description: Plant essential oils and oil mixtures are assessed as potential biological treatments. The source profile includes orange, lemon, eucalyptus, castor, basil, and mixtures involving thyme, turmeric, neem, and other plant materials.

Application in RPW control: In the source experiment, sugarcane pieces were dipped in oil emulsions and provided to RPW larvae.

Target RPW life stage: Eggs and larvae.

Evidence of effectiveness: Orange and lemon oils were reported as the most toxic oils against RPW eggs, followed by eucalyptus, basil, and castor oils.

Deployment requirements: Essential-oil supply, formulation and emulsification process, controlled application method, laboratory capability, and specialist expertise.

Validation status: Research-stage. The source profile states that no field studies had been performed.

Notes on supporting evidence: Essential-oil evidence against RPW is laboratory based. Assadi et al. (2019) tested orange, lemon, eucalyptus, castor and basil oils against eggs and larvae; this is the basis for the source profile. Atwa et al. (2023) fed larvae sugarcane dipped in oil emulsions; orange and clove oils produced 100% mortality under concentration–exposure combinations. Jasmine and orange oils reached LT90 in 3.7 days, whereas peppermint required 16.3 days for LT99, demonstrating oil-specific activity (Atwa et al., 2023). In an in-vitro study, *O. majorana* oil caused 100% larval mortality at 15% after five days and affected pupae and adults (Mady et al., 2021). These studies used controlled contact or feeding exposures and did not report performance in naturally infested standing palms. Field trials must establish formulation stability, trunk delivery, persistence, phytotoxicity, residues, and efficacy against concealed larvae (Assadi et al., 2019; Atwa et al., 2023; Mady et al., 2021).

SWOT analysis:

Strengths	Weaknesses
Plant-based treatment approach; several oils and mixtures can be screened	Evidence is based on laboratory feeding and egg-hatching assessments
Opportunities	Threats
Potential development of plant-based formulations for targeted treatment	Field stability, dose, formulation, and delivery into infested palms remain unvalidated

Recommendation: Research priority. Continue formulation and field-delivery studies before operational recommendation.

4.3.14. Picrotoxin

Technology family: Plant-based biopesticide

RPW control category: Treatment

TRL classification: TRL 1-3

Description: Picrotoxin is a plant-produced sesquiterpene assessed as a natural biopesticide that disturbs larval growth by reducing feeding performance.

Application in RPW control: Tested in laboratory bioassays where larvae were exposed to different doses of sesquiterpenes in controlled conditions.

Target RPW life stage: Larvae.

Evidence of effectiveness: The source profile reports that larvae exposed to picrotoxin showed more than 96% mortality.

Deployment requirements: Laboratory insect-rearing facility, sesquiterpene supply, bioassay capability, microbiology and entomology expertise, and future field formulation development.

Validation status: Research-stage. No field study was reported in the source profile.

Notes on supporting evidence: Picrotoxin evidence against RPW is based on a controlled laboratory feeding study, while recent reviews repeat this result rather than report independent field validation (Hussain et al., 2019; Dalbon et al., 2021; Naveed et al., 2023). In artificial-diet bioassays, picrotoxin was the most toxic of eight tested sesquiterpenes, with an LD50 of 317 ppm and mortality exceeding 96% among larvae (Hussain et al., 2019). Treated larvae became sluggish, and the efficacy of conversion of ingested and digested food declined by 73.62% and 81.74%, respectively (Hussain et al., 2019). The study also found changes in detoxification-gene expression, including cytochrome P450 and glutathione S-transferase responses (Hussain et al., 2019). A 2023 date-palm review repeats the 317-ppm LD50, and a 2021 review identifies picrotoxin as a potential biopesticide (Dalbon et al., 2021; Naveed et al., 2023). The cited sources provide no palm-level field evaluation, delivery protocol, formulation-stability assessment, or non-target safety testing (Hussain et al., 2019; Dalbon et al., 2021; Naveed et al., 2023).

SWOT analysis:

Strengths	**Weaknesses**
High larval mortality was reported under laboratory exposure	No field delivery method or palm-treatment protocol is available in the source profile
Opportunities	**Threats**
May contribute to development of natural larvicidal formulations	Lack of field validation prevents operational deployment

Recommendation: Research priority. Maintain as an experimental candidate until field-safe and effective delivery methods are developed.

4.3.15. Chitinase from Beauveria bassiana

Technology family: Biopesticide

RPW control category: Treatment

TRL classification: TRL 1-3

Description: Chitinase extracted from *Beauveria bassiana* is assessed as a biological material that disrupts enzymatic activity and causes DNA and protein damage in RPW.

Application in RPW control: In the source experiment, chitinase was extracted from the fungus and applied directly to individual larvae under controlled incubation conditions.

Target RPW life stage: Larvae.

Evidence of effectiveness: The source profile reports the highest mortality of 35% at a concentration of 25 ppm.

Deployment requirements: Biology laboratory, fungal culture or enzyme extraction capability, controlled treatment facilities, and specialist microbiology and entomology expertise.

Validation status: Research-stage. No field studies on palm trees were reported.

Notes on supporting evidence: Evidence for chitinase isolated from *B. bassiana* against RPW currently derives mainly from one laboratory study in which fungal chitinase and *Justicia brandegeana* extract were tested separately against RPW prepupae (Shehawy et al., 2020). Chitinase caused 10–35% prepupal mortality, with the highest mortality, 35%, at 25 ppm; LC25 and LC50 values were 19.6 and 38.2 ppm, respectively (Shehawy et al., 2020). The study measured alkaline phosphatase, phenol oxidase, glutamic pyruvic transaminase, glutamic oxaloacetic transaminase, DNA, and protein (Shehawy et al., 2020). A 2024 RPW study describes *B. bassiana* chitinase as affecting enzyme activity, protein, and DNA, but does not report field efficacy (Darrag et al., 2024). Neither source reports treatment of larvae concealed within palms, formulation stability, non-target safety, or palm-level field trials (Shehawy et al., 2020; Darrag et al., 2024). The evidence supports an early research-stage classification (Shehawy et al., 2020).

SWOT analysis:

Strengths	Weaknesses
Uses a biological enzyme derived from an entomopathogenic fungus	Reported mortality is moderate and evidence is limited to laboratory application on larvae
Opportunities	Threats

May support development of enzyme-based biological treatments	Lack of field delivery method and limited efficacy constrain practical use

Recommendation: Low priority. Retain for laboratory research rather than operational treatment.

4.3.16. **Petroleum Ether Extract of *Justicia brandegeana***

Technology family: Biopesticide

RPW control category: Treatment

TRL classification: TRL 1-3

Description: Petroleum ether extract derived from *Justicia brandegeana* leaves is assessed as a plant-based material that disrupts enzymes and causes DNA and protein damage in RPW.

Application in RPW control: Leaves are collected, dried, powdered, extracted, fractionated, analysed, and then applied directly to larvae under controlled conditions.

Target RPW life stage: Larvae.

Evidence of effectiveness: The source profile reports the highest mortality of 30% at 1,200 ppm.

Deployment requirements: Plant material, extraction and fractionation process, laboratory equipment, chemical analysis capability, and specialist microbiology and entomology expertise.

Validation status: Research-stage. No field studies were reported.

Notes on supporting evidence: Direct evidence for petroleum ether extract of *Justicia brandegeana* against RPW is limited to one controlled laboratory study using prepupal larvae, rather than feeding larvae or naturally infested palms (Shehawy et al., 2020). Leaves were dried, powdered, extracted with petroleum ether, and the extract was topically applied individually to prepupae under dark incubation at 27°C for one to two weeks (Shehawy et al., 2020). Mortality increased with dose, ranging from 8% to 30%; the highest mortality, 30%, occurred at 1,200 ppm, while the reported LC25 and LC50 values were 897.4 and 3,334.46 ppm, respectively (Shehawy et al., 2020). The study also assessed alkaline phosphatase, phenol oxidase, glutamic pyruvic transaminase, glutamic oxaloacetic transaminase, DNA, and protein, indicating biochemical disturbance after treatment (Shehawy et al., 2020). Later RPW studies cite this work as evidence of enzyme, protein, and DNA effects, but do not provide independent field validation (Darrag et al., 2021; Darrag et al., 2024). No field delivery method, palm-safety assessment, persistence study, residue analysis, or non-target evaluation has been reported (Shehawy et al., 2020).

SWOT analysis:

Strengths	Weaknesses
Plant-based treatment candidate with a defined extraction process	Low reported mortality compared with other treatment technologies in the source profile
Opportunities	Threats
May contribute to screening of plant-derived RPW control compounds	No field validation or established operational formulation

Recommendation: Low priority. Retain as a laboratory research candidate only.

4.3.17. Serine Protease Inhibitors

Technology family: Biotech biopesticide

RPW control category: Treatment

TRL classification: TRL 1-3

Description: Serine protease inhibitors are extracted from palm and non-palm plant materials to reduce the activity of RPW gut proteases, which are essential for growth and survival.

Application in RPW control: The source profile describes extraction, enzymatic activity assessment, and controlled testing on RPW mortality, growth, and weight.

Target RPW life stage: The source profile does not specify a separate target stage; the biological target is RPW gut-protease activity.

Evidence of effectiveness: Inhibitors extracted from palm trees reduced RPW gut protease activity by 39%.

Deployment requirements: Laboratory extraction and purification capability, enzymatic assay equipment, insect-rearing facility, and specialist microbiology, biology, and entomology expertise.

Validation status: Research-stage. No field studies on palm trees were reported.

Notes on supporting evidence: Evidence for serine protease inhibitors against RPW comes from laboratory enzyme and feeding assays. Orfali et al. (2020) evaluated inhibitors derived from host and non-host plant materials and reported that palm-derived inhibitors reduced gut-protease activity by 39%. This identifies digestive proteases as a biochemical target but does not establish palm-level control. RPW grubs contained trypsin and elastase-like chymotrypsin activity across larval development; aprotinin, soybean trypsin inhibitor, and PMSF inhibited trypsin activity by 77.4%, 63.1%, and 55.9%, respectively (Joseph et al., 2016). Diet containing aprotinin reduced larval weight gain by 18.9% after 120 h (Joseph et al., 2016). The studies support proof-of-concept that protease inhibition can impair digestion and growth (Orfali et al., 2020; Joseph et al., 2016). Neither study provides operational field results for naturally infested date palms, stable inhibitor formulations, persistence within trunk tissues, or non-target effects (Orfali et al., 2020; Joseph et al., 2016).

SWOT analysis:

Strengths	Weaknesses
Targets a core digestive function of RPW	Evidence is based on enzyme inhibition and controlled testing rather than operational palm treatment
Opportunities	Threats
Provides a biological basis for developing targeted biotech biopesticides	Field delivery and mortality performance remain unvalidated

Recommendation: Low priority. Continue as a molecular and laboratory research direction.

4.3.18. RNAi Technologies

Technology family: RNA interference

RPW control category: Treatment research

TRL classification: TRL 1-3

Description: RNA interference uses double-stranded RNA to silence selected RPW genes. The source profile includes vitellogenin-based dsRNA feeding, alpha-amylase dsRNA delivery, and RferOR1 silencing.

Application in RPW control: Vitellogenin dsRNA was provided to larvae through diet and drops to affect reproductive traits. Alpha-amylase dsRNA was delivered through feeding and injection to reduce digestive gene expression. RferOR1 dsRNA was injected into adults to reduce pheromone response.

Target RPW life stage: Larvae for vitellogenin and alpha-amylase gene silencing; adults for RferOR1 silencing and pheromone-response disruption.

Evidence of effectiveness: Vitellogenin dsRNA reduced egg hatchability. Oral alpha-amylase dsRNA reduced target mRNA expression and produced maximum larval mortality of 28 ± 2.13% after 120 hours. For RferOR1 silencing, 56.25% of treated adults moved toward clean air instead of pheromone, 31.25% had no response, and 12.5% remained attracted to pheromone.
Deployment requirements: High-technology laboratory infrastructure, dsRNA production capability, specialized expertise, and a reliable method for delivery into date palms.

Validation status: Early research-stage. The source profile identifies future need for delivery-system development and field testing on real palms and RPW.

Notes on supporting evidence: RNAi evidence for RPW is laboratory based, targeting reproduction, digestion, and chemoreception. Vitellogenin dsRNA delivered by feeding reduced target-gene expression and egg hatchability (Rasool et al., 2021, 2023). Alpha-amylase dsRNA, delivered by feeding or injection, reduced target-transcript abundance; oral exposure caused larval mortality of 28 ± 2.13% after 120 h, indicating partial larvicidal activity (Laudani et al., 2017). RNAi against the aggregation-pheromone receptor RferOR1 disrupted pheromone orientation: 56.25% selected clean air, 31.25% did not respond, and 12.5% remained pheromone responsive (Antony et al., 2021). RferOR1 knockdown was induced in pupae and behaviour assessed in adults, not by direct adult injection (Antony et al., 2021). Studies did not demonstrate dsRNA stability, palm-tissue delivery, efficacy in naturally infested trees, persistence, non-target safety, or field performance. Evidence supports TRL 1–3 and prioritizes formulation, delivery-system development, and validation (Rasool et al., 2023; Antony et al., 2021).

SWOT analysis:

Strengths	Weaknesses
Can target specific biological functions, including reproduction, digestion, and pheromone response.	Current evidence is laboratory-based and requires high technical capability
Opportunities	Threats
Can support future precision biological-control approaches	Delivery into palms, cost, technical requirements, and field validation remain major constraints

Recommendation: Research priority. Focus on delivery systems and field validation before considering operational deployment.

4.4. Revival and Removal Technologies

This section presents the Revival and Removal technologies identified in the supplied source documents. These technologies include sanitation and disposal measures, recovery-support inputs, and microwave-based physical treatment. The profiles distinguish technologies intended to remove infestation sources or kill RPW from those intended only to support palm recovery after treatment.

4.4.1. Removal and Disposal

Technology name: Removal and Disposal

Technology family: Good Agricultural Practices (GAP) / sanitation

RPW control category: Removal and disposal

TRL classification: TRL 7–9

Deployment priority: High

Description: Removal and Disposal is listed in the source documents as a Revival and Removal technology under GAP and sanitation. The available sources do not provide a detailed removal, destruction, transport, disposal, or sanitation protocol.

Application in RPW control: The technology is classified as a sanitation and removal measure within the Revival and Removal value chain. The source does not specify the operational procedure, timing, required equipment, handling process, or final disposal route.

Target RPW life stage: Not specified in the source documents.

Evidence of effectiveness: No individual mortality result, field outcome, disposal protocol, or supporting reference is provided in the available source documents.

Deployment requirements: Not specified in the source documents.

Validation status: Classified as TRL 7–9 in the supplied technology list. However, no separate source-based validation profile, field protocol, or implementation evidence is provided.

Notes on supporting evidence: Removal and disposal supports sanitation within IPM rather than a stand-alone curative treatment. A 2024 review reports that rogueing and destroying infested palm trunks and fronds through shredding, chipping, or burial kills larvae, pupae, and adults; it places palm removal alongside pheromone trapping and insecticide treatment (Hoddle et al., 2024). A six-year Saudi Arabian study recommends immediate removal and disposal of infested palms and describes cutting trunks into pieces no longer than 2 m to eliminate RPW stages (Abdel-Baky et al., 2022). Farm evidence documented sanitation of infested palms by removing insects and damaged trunk tissue; palms beyond recovery were eradicated by burning (Ali-Bob, 2019). The studies support removing infested material to reduce breeding sites and spread. However, they do not establish a mortality rate, cost, or single disposal protocol; methods must follow local regulations and operating procedures (Hoddle et al., 2024; Abdel-Baky et al., 2022).

SWOT Analysis

Strengths	Weaknesses
Listed as a high-priority Revival and Removal technology. Classified as a mature technology at TRL 7–9.	No operational protocol, evidence of effectiveness, cost estimate, safety requirement, or disposal specification is provided in the source. Target RPW stage, timing of intervention, and disposal route are not specified.
Opportunities	**Threats**
A standard operating procedure can define removal criteria, transport, destruction, disposal, workforce requirements, and biosecurity measures. Can be integrated with inspection, treatment, and post-treatment monitoring activities.	Non-standardized removal and disposal may allow infestation sources to remain in the production area. Incomplete sanitation records may reduce traceability and monitoring effectiveness

Recommendation: Retain Removal and Disposal as a high-priority sanitation activity. Develop and validate a standard operating procedure before assigning detailed claims on effectiveness, cost, workforce requirements, or disposal safety.

4.4.2. Traditional Fertilizers

Technology family: Fertilizer

RPW control category: Recovery support

TRL classification: TRL 7–9

Deployment priority: Medium

Description: Traditional Fertilizers are listed in the source documents as a Revival and Removal technology. The source does not specify fertilizer type, nutrient composition, rate, application method, timing, or expected recovery response.

Application in RPW control: The technology is classified as recovery support. The source does not identify it as a direct RPW treatment, prevention method, or method for killing any RPW life stage.

Target RPW life stage: No direct RPW life stage is targeted.

Evidence of effectiveness: No individual experimental result, palm-growth response, fruit-yield outcome, recovery measure, or RPW-related outcome is provided in the available source documents.

Deployment requirements: Not specified in the source documents.

Validation status: Classified as TRL 7–9 in the supplied technology list. No individual field-validation profile is provided.

Notes on supporting evidence: Evidence supports traditional fertilization as a date-palm husbandry practice, not as an RPW treatment. Ben Saleh (2019) states that fertilization supports palm growth, leaf longevity, and yield, and places nutrient management among field operations associated with palm health and lower pest pressure. At a model farm, site-specific fertilization was implemented within Good Agricultural Practices alongside irrigation, sanitation, pest management, pruning, and offshoot management; the study did not isolate fertilizer effects on RPW incidence or palm recovery (Ali-Bob, 2019). Neither publication reports fertilizer-induced RPW mortality, reduction in egg hatch, suppression of concealed larvae, or recovery outcomes for infested palms (Ben Saleh, 2019; Ali-Bob, 2019). The evidence supports use as an agronomic input after RPW treatment, not as curative or preventive control, and does not substantiate an RPW-specific TRL 7–9 classification. No source-based fertilizer formulation, dose, timing, or recovery protocol was identified (Ben Saleh, 2019; Ali-Bob, 2019)

SWOT Analysis

Strengths	**Weaknesses**
Listed as a mature recovery-support category at TRL 7–9. May be used within an established palm-management programme.	The source does not identify the fertilizer formulation, dose, nutrient target, application method, or timing. No direct evidence for RPW mortality, infestation reduction, or recovery of treated palms is provided.
Opportunities	**Threats**
Can be assessed as part of a post-treatment palm-recovery programme using defined nutrient and plant-health indicators. Can be compared with biofertilizers and nano-fertilizers under field conditions.	Fertilizer use may be incorrectly presented as a direct RPW treatment without supporting evidence. Unspecified nutrient application may not address the actual nutritional condition of treated palms.

Recommendation: Retain Traditional Fertilizers only as a recovery-support technology. Do not classify traditional fertilization as direct RPW treatment or prevention until application protocols and field evidence are available.

4.4.3. Seaweed Extract Nano Fertilizers

Technology family: Nano-fertilizers

RPW control category: Recovery support

TRL classification: TRL 4–6

Deployment priority: Pilot

Description: Seaweed Extract Nano Fertilizers are seaweed-derived fertilizers processed through nanotechnology to improve nutrient delivery and absorption by date palms.

Application in RPW control: The source assessed seaweed nano-fertilizers, Optimus-Plus, NPK fertilizer, and an untreated control. Treatments were applied through foliar spraying, trunk injection, and soil application. The technology is intended to support palm nutrition and recovery rather than directly control RPW.

Target RPW life stage: No direct RPW life stage is targeted.

Evidence of effectiveness: The source reports that seaweed nano-fertilizer injection significantly increased fruit pulp weight to 4.64 g and bunch weight to 7.35 kg in the Khastawi date-palm cultivar. The source also states that nano-fertilizers do not directly combat RPW.

Deployment requirements: Seaweed nano-fertilizer product; foliar, trunk-injection, or soil-application capability; existing agricultural infrastructure; and trained personnel for correct application.

Validation status: The source classifies the technology as validated in laboratory and controlled environments but not fully available for commercial use. The source profile states that proposed solutions had not been tested on palm trees under field conditions.

Notes on supporting evidence: Evidence concerns date-palm nutrition and yield rather than direct RPW control. In a 2025 field experiment on 54 Khastawi palms, nano NPK fertilizer, EM1 biofertilizer, and seaweed extract were evaluated as separate treatment factors for leaf chemistry and yield, providing evidence for nutritional support (Al-Mohammadi & Hamad, 2025). It did not test a nano-formulated seaweed product. Field research on Hillawi palms found that combining conventional fertilizer with foliar nano-fertilizer increased fruit and bunch weight; nano-fertilizer alone did not increase those variables, although 1 g L^{-1} improved fruit-ripening percentage (Shareef et al., 2021). Responses were formulation-, dose-, cultivar-, and application-dependent (Al-Mohammadi & Hamad, 2025; Shareef et al., 2021). Neither study assessed RPW mortality, infestation incidence, concealed larval activity, or recovery of naturally infested palms. The evidence supports pilot use for nutrition and recovery support, with validation of palm health, yield, application, and compatibility with RPW treatment required.

SWOT Analysis

Strengths	**Weaknesses**
Supports nutrient delivery and palm-recovery management. Can be applied through foliar spray, trunk injection, or soil application. The source reports improved fruit pulp weight and bunch weight. The prioritization workbook records no direct or indirect negative environmental impact.	No direct RPW mortality, infestation reduction, or pest-suppression result is reported. Field validation on palms under operational RPW-management conditions is not reported. Effectiveness evidence concerns palm-production traits rather than RPW treatment. Requires trained personnel despite the availability of existing infrastructure.
Opportunities	**Threats**
Can be assessed as a post-treatment recovery input for palms that remain viable after RPW intervention. Can be compared with conventional fertilizers and biofertilizers using canopy recovery, nutrient status, yield, and survival indicators. May be integrated into rehabilitation packages for treated palms.	May be incorrectly classified as a direct RPW control technology. Benefits observed under controlled conditions may not be replicated in field conditions. Trunk injection must be coordinated with other palm-treatment interventions.

Recommendation: Use Seaweed Extract Nano Fertilizers only as a pilot recovery-support technology after RPW treatment. Conduct field evaluation of canopy recovery, nutrient status, fruit yield, palm survival, treatment cost, and compatibility with other recovery practices. Do not classify the technology as a direct RPW control measure.

4.4.4. Biofertilizers: Compost, MycENA16, and *Pantoea agglomerans*

Technology family: Biofertilizers

RPW control category: Recovery support

TRL classification: TRL 4–6

Deployment priority: Medium

Description: This technology combines compost, the MycENA16 mycorrhizal consortium, and *Pantoea agglomerans* strain to improve nutrient uptake, root development, and general palm health.

Application in RPW control: The source assessed compost, MycENA16, and *Pantoea agglomerans*, separately and in combination, during a 10-month greenhouse experiment on date palms. The technology was evaluated for palm-growth and nutrition outcomes, not direct RPW mortality or suppression.

Target RPW life stage: No direct RPW life stage is targeted.

Evidence of effectiveness: The source reports that MycENA16 achieved 82% root-colonization frequency and 68% colonization intensity. Stem diameter and root weight increased, particularly where compost was combined with *Pantoea agglomerans*. The source also reports increased leaf chlorophyll and mineral content.

Deployment requirements: Compost and microbial inputs; greenhouse or nursery capability; standard laboratory equipment; microbiology and entomology expertise; application procedures; and monitoring of root colonization, palm growth, and nutrient status.

Validation status: The source classifies the technology as validated in a relevant environment but requiring further field testing. The source profile states that the proposed solution had not been tested on palm trees in the field.

Notes on supporting evidence: A 10-month greenhouse experiment applied compost, MycENA16, and *Pantoea agglomerans* to date-palm seedlings (El Kinany et al., 2022). MycENA16 produced 82% root-colonization frequency and 68% colonization intensity. Compost with *P. agglomerans* increased stem diameter and root weight, and treatments increased leaf chlorophyll and mineral content (El Kinany et al., 2022). These results describe plant-growth and nutrition responses under controlled conditions, not direct effects on RPW. In date-palm pot study, mycorrhizal and bacterial inoculation changed antioxidant responses during water stress, supporting microbial inputs in plant stress physiology (Harkousse et al., 2021). A review reports improved date-palm biomass and chlorophyll following combined arbuscular fungal and bacterial inoculation under water deficit (Chaudhary et al., 2022). None of the cited studies measured RPW mortality, infestation incidence, naturally infested-palm recovery, or field performance. Evidence supports recovery-oriented research rather than direct RPW control (El Kinany et al., 2022; Harkousse et al., 2021).

SWOT Analysis

Strengths	Weaknesses
The source reports improved root colonization, stem diameter, root biomass, chlorophyll, and mineral content. The technology may support root development and nutritional recovery. The technology can combine compost with microbial inputs.	No direct evidence of RPW mortality, infestation reduction, or treatment of naturally infested palms is provided. Evidence is derived from greenhouse conditions rather than field conditions. Requires microbial handling, standard laboratory capability, and specialist expertise.

Suitable for rehabilitation of palms that survive RPW treatment.	The prioritization workbook identifies possible indirect impacts.
Opportunities	**Threats**
Can be tested as a post-treatment recovery package for viable palms. Can be evaluated together with nutrient management, irrigation, and other recovery-support measures. Can contribute to field evidence on long-term palm recovery and resilience.	Human-health or other indirect concerns may arise if microbial inputs are not properly managed. Performance may vary according to soil conditions, palm condition, microbial survival, and application quality. Additional equipment, specialist expertise, and regulatory arrangements may be required.

Recommendation: Conduct field pilots as a recovery-support package after RPW treatment. Compare treated and untreated surviving palms using root development, canopy condition, nutrient status, yield, pest recurrence, and long-term survival indicators.

4.4.5. Microwave Disinfestation: Eco Palm Ring and Eco Palm Box

Technology name: Microwave Disinfestation: Eco Palm Ring and Eco Palm Box

Technology family: Innovative Crop Protection / Microwave Disinfestation

RPW control category: Physical treatment and removal

TRL classification: TRL 7–9

Deployment priority: Medium

Description: Eco Palm Ring and Eco Palm Box use electric microwave generators to deliver ultra-high-frequency radiation into palm tissues. The source describes the technology as intended to kill RPW at all developmental stages within palm trees.

Application in RPW control: Eco Palm Ring applies microwave energy through a circular band around the palm trunk. Eco Palm Box is a mobile microwave unit that can be installed on commercial trucks. The source also identifies microwave disinfestation as a method for treating palms intended for safe transportation.

Target RPW life stage: Eggs, larvae, pupae, and adults.

Evidence of effectiveness: The source reports that 86% of insects were killed after one treatment. Remaining insects reportedly died within two days because of thermal effects. The source also reports a severe reduction in fertility among surviving RPWs.

Deployment requirements: Eco Palm Ring or Eco Palm Box equipment; microwave power supply; trained operators; technical calibration according to palm diameter, trunk section treated, treatment depth, environmental temperature, wind, microwave power, and target temperature. The prioritization workbook also identifies heavy regulatory requirements and PhD-level technical expertise.

Validation status: The source identifies the technology as mature and fully commercialized. Eco Palm Ring and Eco Palm Box are described as commercialized microwave-disinfestation products.

Notes on supporting evidence: Evidence for microwave disinfestation of RPW comes from laboratory, palm-heating, and modelling studies, not trials of Eco Palm Ring or Eco Palm Box (Mady et al., 2021; Massa et al., 2019; Rmili et al., 2020). In laboratory tests, microwave heating killed adults after four minutes, whereas larvae were less susceptible, demonstrating stage response (Mady et al., 2021). In standing palms, irradiated trunk regions reached about 70 °C, and larvae and adults there died (Massa et al., 2019). A circular-array model identified moisture, depth, power, and duration as lethal-heating drivers; it predicted palm tissue may heat more readily than insects (Rmili et al., 2020). Retrieved studies do not report 86% single-treatment mortality, delayed mortality, product performance, or truck-mounted deployment (Mady et al., 2021; Massa et al., 2019). Local evaluation should locally confirm palm safety, stage-wide efficacy, and operating requirements (Massa et al., 2019; Rmili et al., 2020).

SWOT Analysis

Strengths	**Weaknesses**
Classified as TRL 7–9 and described as a commercialized technology. Targets eggs, larvae, pupae, and adults. The source reports 86% mortality after one treatment and additional mortality within two days. The source reports reduced fertility among surviving RPWs. The prioritization workbook records no direct or indirect negative environmental impact.	Requires specialized equipment, technical calibration, and trained operators. Heavy regulatory restrictions are identified in the prioritization workbook. The estimated treatment cost is USD 66 per tree, excluding manpower. High-level technical expertise is required. Performance depends on treatment settings, palm characteristics, and environmental conditions.
Opportunities	**Threats**
Suitable for high-value palms and targeted treatment where chemical use is restricted. May be suitable for safe treatment of palms intended for transportation. Can be integrated with inspection, sanitation, and post-treatment recovery measures. Can be evaluated for local operating cost, energy use, treatment duration, and palm recovery.	Incorrect treatment depth, microwave power, exposure time, or target temperature may reduce performance. Inadequate calibration may affect pest mortality or palm safety. Equipment availability, operator competence, and regulatory approval may limit wider deployment. High investment and operating requirements may limit use to priority locations or high-value palms.

Recommendation: Prioritize controlled local pilots for high-value or heavily infested palms. Validate pest mortality, palm safety, treatment duration, energy requirement, operating cost, regulatory compliance, and post-treatment recovery before wider deployment.

5. Recommended Grower Technology Bundle 1: Integrated RPW Suppression, Treatment, and Palm Recovery Package

This first technology bundle is recommended as an operational integrated pest-management package for growers. It combines adult-population suppression, prevention, curative treatment, sanitation, and farm-capacity building. The bundle is linked directly to the technology inventory, bringing together mature and field-ready technologies rather than relying on a single intervention.

The package is being partly implemented in UAE pilot farms. Its next phase should focus on documenting treatment outcomes, adult-catch reduction, new-infestation rates, palm survival, and cost per protected palm. The bundle should be applied according to palm risk and infestation status; not every technology is required for every palm.

Bundle component	Technology-inventory linkage	Primary role
Bt biopesticide application	Microbial biopesticide / treatment	Biological suppression where larvae are accessible and treatment conditions are appropriate
Attract-and-kill dollops	Semiochemical attract-and-kill / prevention and treatment	Adult suppression through attraction to a localized lethal source
Dry traps: 8 traps/ha	Mass trapping / detection and adult suppression	Adult monitoring and reduction of the breeding population
Repellents: 25 units/ha	Semiochemical repellent / push-pull support	Reduces adult attraction to protected areas and complements traps and attract-and-kill points
Syngenta injection system with registered preventive product	Chemical endotherapy / prevention	Protects selected high-risk and apparently healthy palms under an approved preventive programme
Systemic insecticide injection	Chemical endotherapy / treatment	Curative intervention for early confirmed infestations and palms considered recoverable
Phostoxin® gas through improved jacketed treatment	Fumigation / treatment and removal support	Specialist-only intervention for selected palms where an approved enclosed treatment protocol is feasible
Disposal of highly infested palms	GAP / sanitation / removal and disposal	Removes major breeding sources where palm recovery is not technically or economically justified

5.1. Operating Logic of the Bundle

The first layer of the package is adult-population management. Dry traps are deployed at a density of eight to ten traps per hectare, supported by attract-and-kill dollops distributed according to the approved field plan. Repellents are installed at 25 units per hectare to create a push-pull effect: adults are discouraged from protected palm areas while traps and attract-and-kill points provide attractive killing locations.

Trap catches must be recorded by date, location, sex where possible, lure-replacement date, and servicing status. Trap density and placement should be adjusted according to infestation pressure, palm density, farm boundaries, and catch data.

The second layer is prevention. High-value, young, previously infested, or high-risk palms should be selected for preventive endotherapy using the Syngenta injection system and a locally registered systemic insecticide. Preventive injection should be based on a documented risk assessment and follow the approved product label, local regulations, and farm treatment calendar. Treatment records must include palm identification number, location, product, date, operator, and planned follow-up inspection.

The third layer is curative intervention. Palms with early confirmed infestation should be assessed for structural condition, crown condition, infestation location, and likelihood of recovery. Recoverable palms may receive systemic insecticide injection through the approved injection system. Bt application may be included as a biological component where the infestation site is accessible and the application can reach the target area. The biological treatment should not be considered a substitute for trunk injection when larvae are deeply concealed within the palm.

Phostoxin® gas treatment through an improved jacketed system should be treated as a specialist intervention only. It requires a regulator-approved protocol, licensed fumigation personnel, site isolation, gas monitoring, controlled access, and documented clearance before the palm area is reopened. It should not be used as a routine grower-applied treatment. Palms with severe structural damage, crown collapse, extensive internal destruction, or repeated treatment failure should be removed and disposed of through a documented sanitation procedure.

5.2. Management and Capacity-Building Package

The technology bundle requires disciplined farm management. Visual inspection should be conducted every 45 days and intensified during periods of high RPW activity or after pruning, offshoot removal, storm damage, or other wounding events. Every inspection should record palm identity, symptoms, treatment history, infestation status, action taken, and follow-up date.

Fresh wounds created by pruning, offshoot removal, or mechanical damage should receive immediate wound treatment under the farm protocol. Offshoot removal should be planned, supervised, and followed by wound protection to reduce attractive sites for egg laying. Irrigation management should maintain palm vigour and avoid prolonged water stress, excessive waterlogging, or poor drainage conditions that weaken palm condition and complicate recovery.

Farm sanitation is a core component of the bundle. Frond bases, discarded offshoots, damaged tissues, and other potential breeding materials must not remain unmanaged in the farm. Highly infested palms should be rapidly identified, marked, removed where required, and disposed of using an approved destruction and transport procedure. The sanitation team should maintain a removal register that includes palm number, infestation severity, date of removal, disposal method, and responsible personnel.

Capacity building should target growers, farm supervisors, scouts, pesticide operators, and sanitation teams. Training should cover symptom recognition, safe trap servicing, correct repellent and attract-and-kill placement, injection hygiene, treatment recording, wound management, farm sanitation, and escalation procedures for suspected or confirmed infestation. Fumigation activities must remain under licensed specialist responsibility.

5.3. Monitoring and Decision Indicators

Bundle performance should be reviewed monthly using: adult catches per trap per week; number of new confirmed infestations; percentage of palms receiving preventive treatment; percentage of early infestations recovered; number of palms removed; treatment follow-up compliance; and cost per protected or recovered palm. The UAE pilot implementation should use these indicators to compare treated and reference blocks and refine the package before wider grower deployment.

Recommendation: Deploy this bundle as the first operational grower package because it integrates mature technologies from the inventory with essential farm-management measures. Maintain the 8 traps/ha and 25 repellents/ha configuration as the initial UAE field package, while adapting attract-and-kill density, preventive injection coverage, and curative treatment decisions according to farm monitoring data, infestation pressure, and regulatory approval.

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