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# Non destructive detection and localization of internal pests in agricultural hosts using microwave imaging with application to red palm weevil

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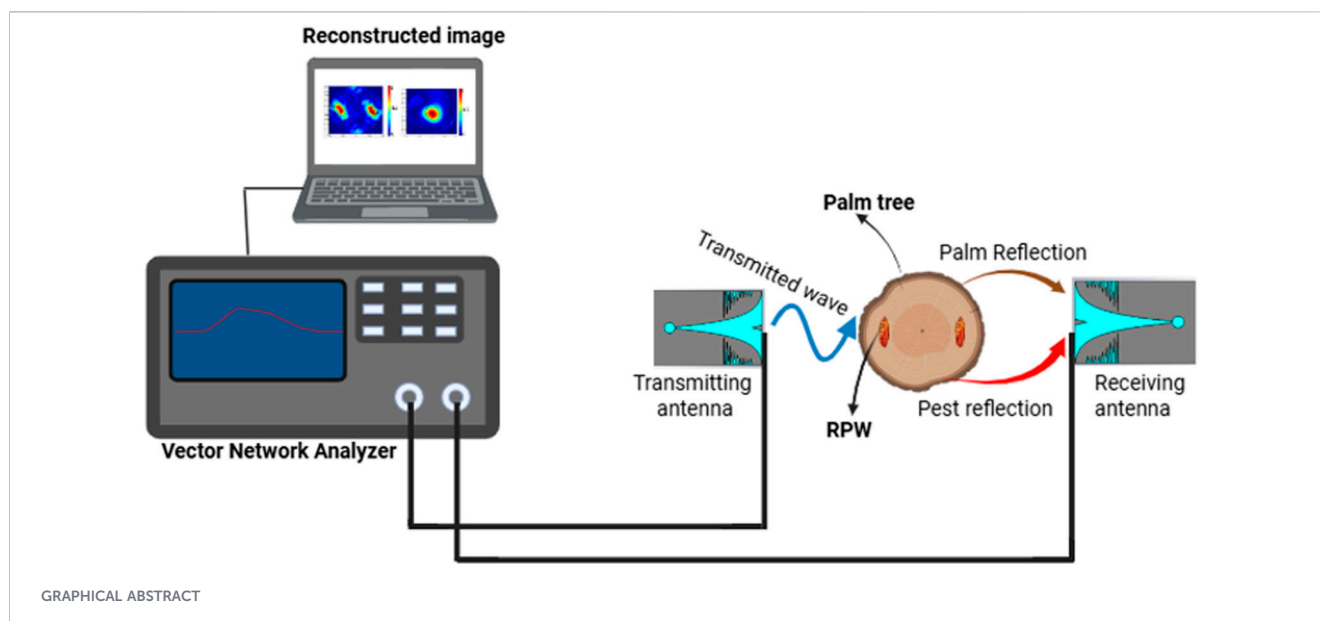
Red Palm Weevil (RPW) infestations present a major threat to global palm agriculture, causing substantial economic losses and lacking reliable early stage detection tools. Microwave imaging (MWI) is a well-established non-invasive technique in medical diagnostics; however, its application in pest detection remains largely unexplored. This study investigates the use of MWI for RPW detection through a controlled experimental setup in which a biologically realistic phantom replicating the pupal stage of RPW in terms of geometry and dielectric properties was embedded within a natural palm trunk. Electromagnetic simulations and experimental validation using a rotating antenna platform were performed. The results demonstrate that MWI can accurately detect and localize internal RPW infestations, including challenging scenarios involving multiple hidden pupae. These findings highlight MWI as a powerful non-destructive technique for pest detection, offering advanced capabilities for early diagnosis and supporting more effective integrated pest management strategies.

**KEYWORDS**

antenna, microwave imaging, pest detection, red palm weevil infestation, rhynchophorus ferrugineus, integrated pest management

## Introduction

The Red Palm Weevil (RPW) (*Rhynchophorus Ferrugineus*) (Coleoptera: Curculionidae), commonly known as the Asian palm weevil, is an aggressive pest that infests palm species worldwide (Hamadttu Abdel Farag and Romeno Faleiro, 2020). Classified as a Category one pest by the FAO in the Middle East and North Africa, it represents a major threat to date palm growers (Hamadttu Abdel Farag and Romeno Faleiro, 2020). First documented in the Gulf region in the mid-1980s, RPW rapidly expanded its range in North Africa and later into Eu- rope, where it was first identified on *Phoenix canariensis* in Spain in 1995 (Faleiro, 2006). Originally native to South and Southeast Asia (Faleiro, 2006), the pest now affects over 40 palm species globally, although it was first described on coconut in 1906 and date palm in 1917 (El Bouhssini and Faleiro, 2018).



The spread of RPW has caused considerable economic, ecological, and ornamental losses in palm-based systems. It threatens agricultural production (e.g., date palm plantations), degrades the aesthetic value of landscape and urban palms, including unmanaged populations such as UNESCO World Heritage palm groves, and endangers natural ecosystems such as palm oases and endemic palm species (Hamadttu Abdel Farag and Romeno Faleiro, 2020) (Faleiro, 2006). Date palms are grown on approximately one million hectares, with over 100 million date palms worldwide. Around 60% of these palms are cultivated in the Arab world, mainly in the Middle East and North Africa (El Bouhssini and Faleiro, 2018). In the Gulf region, the annual loss due to the eradication of severely infested palms has been estimated at between 5.18 and 25.92 million US dollars for infestation levels of 1% and 5%, respectively (El Bouhssini and Faleiro, 2018). *Rhynchophorus Ferrugineus* is a fatal pest of palms, and given the economic importance of date palm cultivation, if the pest is not detected and treated at an early stage of attack, infested palms will die (El Bouhssini and Faleiro, 2018).

Currently, visual inspection is widely adopted to locate infested palms. However, a qualified inspector is expected to examine only about 200–300 palms per day, depending on field conditions, palm density, and sanitation practices (Hamadttu Abdel Farag and Romeno Faleiro, 2020). For this reason, research efforts have increasingly focused on advanced detection techniques, including infrared cameras, thermal imaging, microwave sensing, and IoT-based solutions (Hamadttu Abdel Farag and Romeno Faleiro, 2020) (Bait-Suwailam et al., 2022). Thermal imaging, a well-established tool in agricultural sciences for detecting plant stress, has shown effectiveness as a non-invasive method for identifying RPW infestations (Bait-Suwailam et al., 2022) (Stephen et al., 2025). Under uniform climatic and solar conditions, an infested palm generally exhibits a higher surface temperature than a healthy one.

More recently, multispectral and hyperspectral imaging techniques have been explored for early detection of pest infestations by analyzing spectral reflectance variations associated

with physiological stress in plants. These methods enable the identification of subtle biochemical changes caused by pest activity before visible symptoms appear, making them promising tools for large-scale and early pest monitoring (Trends in Plant Disease, 2016) (Zhang et al., 2012). However, despite their usefulness, these techniques remain limited to surface-level analysis and are highly dependent on environmental conditions. Most importantly, they do not provide precise information about the internal location of the pest.

Accurate localization is a critical parameter for selecting optimal treatment strategies, both for determining the appropriate frequency when microwave heating is employed and for optimizing chemical applications by adjusting insecticide dosage and timing. These limitations have motivated the exploration of alternative technologies, particularly microwave-based methods. Microwave technology has been applied for pest detection using antennas and complementary split-ring resonator (CSRR) sensors that emit electromagnetic waves capable of penetrating deeply into palm trunks. The presence of RPW alters the dielectric properties of the palm tissue (Trends in Plant Disease, 2016), resulting in measurable changes in the scattering response of microwave sensors (Bait-Suwailam et al., 2022), this contrast enables healthy palm trees to be distinguished from infested ones. In addition to detection, microwave technology has also been employed for pest control, showing promising results in the management of RPW without adversely affecting palm quality (Bait-suwail and am, 2021). This approach has been extended to pests infesting wood materials (Massa, 2017), storage environments (Patrascu et al., 2018), and field pests such as wild cochineal (El Arroud et al., 2024). In this study, we propose a novel application of a multistatic Microwave Imaging (MWI) system for the non-invasive detection of RPW pupae inside palm trunks, supported by experimental validation. The precise localization provided by MWI enables optimization of treatment strategies, particularly when microwave heating is used, as it allows the selection of appropriate operating frequencies according to the required penetration depth.

MWI is a safe and non-invasive technique that utilizes low-power, non-ionizing electromagnetic radiation (Zahrae et al., 2024), with energy levels comparable to those emitted by common radiofrequency devices such as mobile phones and Wi-Fi routers (Brian et al., 2022). MWI methods are generally categorized into passive, active, and hybrid approaches (Zhang, 2020). In this work, an active configuration is adopted, where transmitted signals are captured and processed using a microwave radar-based imaging algorithm to reconstruct an image and estimate target position (Hekal et al., 2023). The underlying principle of MWI is the dielectric contrast between the target and the surrounding medium (Zhang, 2020). The significant difference in dielectric properties between RPW and palm tissue motivates the use of MWI for pest detection (Patrascu et al., 2018).

In a typical radar-based MWI system, low-power electromagnetic waves are transmitted into the object (O'Loughlin, 2018), and the backscattered signals are collected by either a single antenna (monostatic) or multiple antennas (multistatic), depending on system configuration (Ghavami et al., 2022). These reflections contain information about the internal structure of the object, as variations in permittivity lead to specific scattering patterns (Zhang, 2020). Computer-based processing of this data enables the detection and localization of embedded targets (Brian et al., 2022).

Microwave Imaging has also shown strong potential as a non-destructive method for detecting contaminants and assessing internal quality in food products. Previous studies have demonstrated its use for fruit ripeness classification and internal defect detection (Alagee and Assalem, 2020; Ghavami et al., 2019). For example, a circular ultra-wideband antenna array was used to image entire watermelons and correlate microwave images with sugar content and internal structural anomalies (Zidane et al., 2020). In the egg industry, a waveguide-based MWI system was developed to screen eggs based on albumen volume, enabling non-invasive discrimination between healthy and compromised eggs (Garvin et al., 2023).

Similarly, MWI has been applied to detect internal contamination in packaged food products by exploiting dielectric contrasts between foreign materials and host food. Feasibility studies have investigated the use of MWI for real-time food inspection, providing insights into detection limits, imaging resolution, and system integration challenges (Tai et al., 2020; Ricci et al., 2022; Ricci, 2023). In another study, a microwave tomography system was developed to inspect packaged foods on a production line, successfully detecting millimeter-sized plastic or glass fragments inside jars of cream (Bellizzi et al., 2024). These findings support the extension of MWI to agricultural pest detection applications.

The structure of the paper is as follows: Initially, both numerical and physical models of an infested palm trunk are developed. The numerical model is then employed to simulate the MWI system and evaluate its capability in identifying internal pest infestations. Following this, an experimental study is conducted using the physical model to validate the simulation results. A rotary scanning system, chosen as a low cost alternative to conventional switch matrices, is implemented in the experimental setup for the proposed lab scale system. Finally, the paper concludes with a summary of key findings and directions for future research.

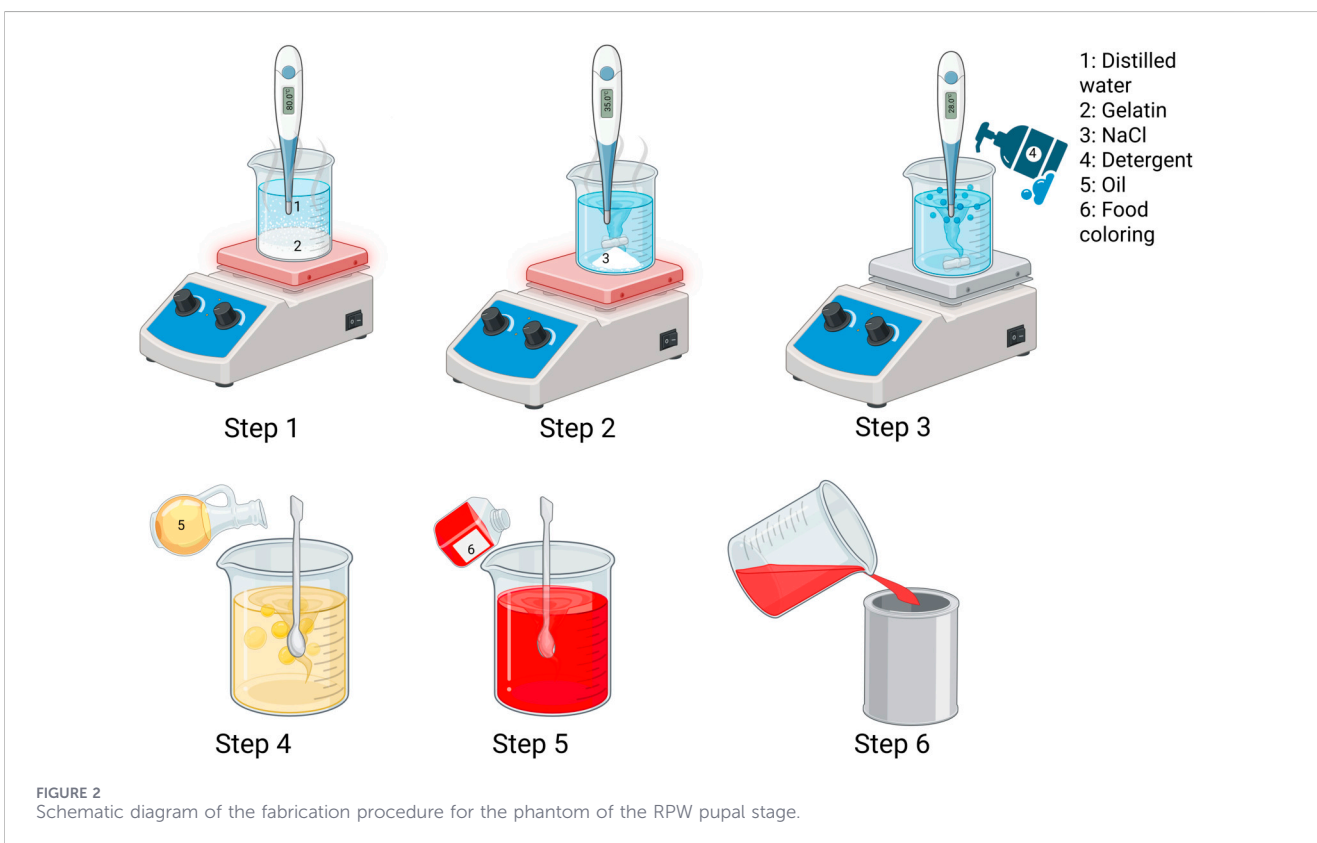
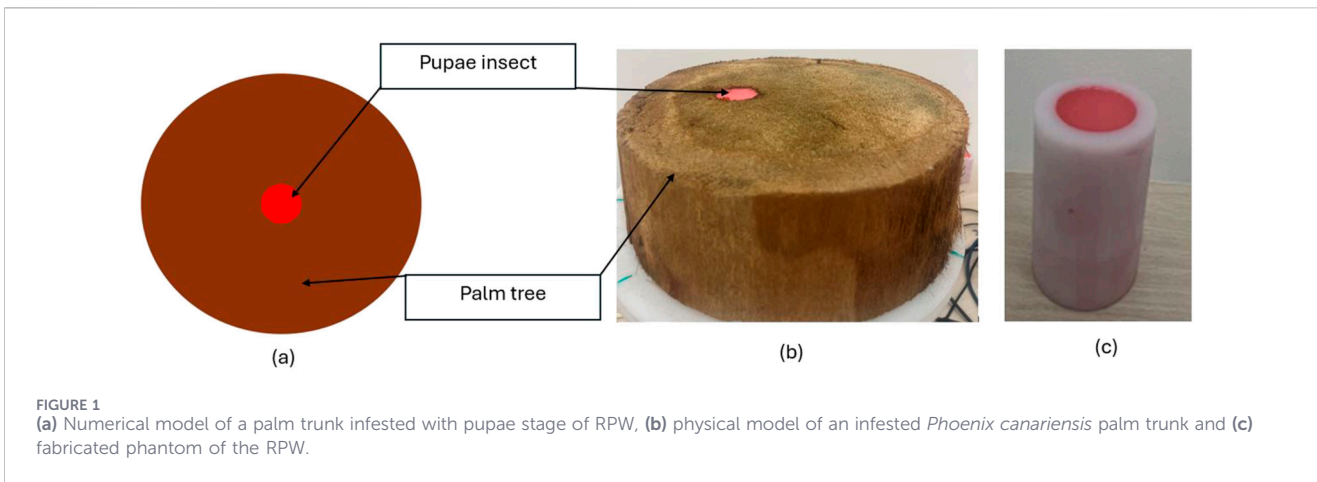
## Materials and methods

### Dielectric modeling of infested palm tree trunk

MWI for detecting RPW infestations can be conducted through the utilization of phantom models that mimic the dielectric characteristics of infested palm trees. This section focuses on both simulated and fabricated models developed based on the dielectric properties reported in (Tobon Vasquez et al., 2020). Two distinct numerical models have been reported in the literature to analyze the electromagnetic behavior of the palm tree and the RPW. In (Bait-Suwailam et al., 2022), a compact numerical model was created, the palm trunk was modeled as a cylinder with dimensions of 44.7 mm in height and 80 mm in diameter, while the RPW was represented as a cylindrical inclusion measuring 2 mm in height and 6 mm in diameter. Alternatively, a more realistic model was developed in (Massa et al., 2014), where the palm trunk was represented as a cylinder with a diameter of 26.6 cm and height of 10 cm. The weevil was modeled as a cylindrical object with dimensions of 3 cm in height and 0.5 cm in diameter, reflecting either a larva or small adult. In the present work, a realistic dimension for the pupal stage of the RPW is used. It is represented as a cylinder measuring 2 cm in diameter and 4 cm in height, following morphological data reported in (Rmili et al., 2020). The palm dimensions are chosen to be compact, with a diameter of 20 cm and a height of 10 cm, to manage the intensive memory requirements associated with 3D simulations using the finite element method in HFSS (Figure 1a). The dielectric properties of both the *Phoenix canariensis* (*P. canariensis*) palm tree and the RPW, which were used to develop the Multipole Debye Model in HFSS, are sourced from (Tobon Vasquez et al., 2020).

### Development and fabrication of the RPW phantom model

To validate the numerical model experimentally, a real *P. canariensis* palm trunk with dimensions identical to those of the simulated structure was used (a diameter of 20 cm and a height of 10 cm). The fresh palm trunk used in the experimental study was obtained from the experimental farm of Mohammed VI Polytechnic University, Benguerir, Morocco. The trunk was characterized by a moisture content of 138%, measured using an analytical balance, to mimic realistic field conditions. Moisture content was monitored throughout the measurements to ensure consistent results. All measurements were conducted at controlled ambient laboratory temperature (~22 °C). A physical phantom was developed to mimic the RPW in its pupal stage, mimicking both its dielectric properties (Tobon Vasquez et al., 2020) and the geo-metric characteristics of the numerical model (Figure 1a). Semi solid phantoms are widely adopted in imaging applications due to their simplicity and stability. In this work, an oil in gelatin dispersion phantom was synthesized using readily available components, in accordance with the methodology proposed in (Life and Palm, 2014), to simulate RPW. The fabrication protocol follows the next steps and it is schematically represented in Figure 2.



Step 1: A measured amount of distilled water was mixed with gelatin in a beaker, then heated to 80 °C while monitoring the temperature.

Step 2: The mixture was cool to 35 °C before slowly adding NaCl while continuing to stir.

Step 3, 4, and 5: Room temperature dishwashing detergent was added, followed by slow stir-ring. When the mixture reached 28 °C, room temperature oil was added and stirring continued until the mixture became white and homogeneous. Food coloring was then added to match the color of the target pest.

Step 6: The final mixture was filled into a 3D printed cylindrical mold and left to solidify overnight. Figure 2 presents the various materials utilized throughout the fabrication process, and outlines the sequential steps followed to construct the breast phantom. The completed structure of the fabricated RPW phantom is shown in Figure 1c.

Dielectric properties were measured using the open ended coaxial probe technique, a simple and widely used method for dielectric characterization (El Arroud et al., 2024). A Keysight

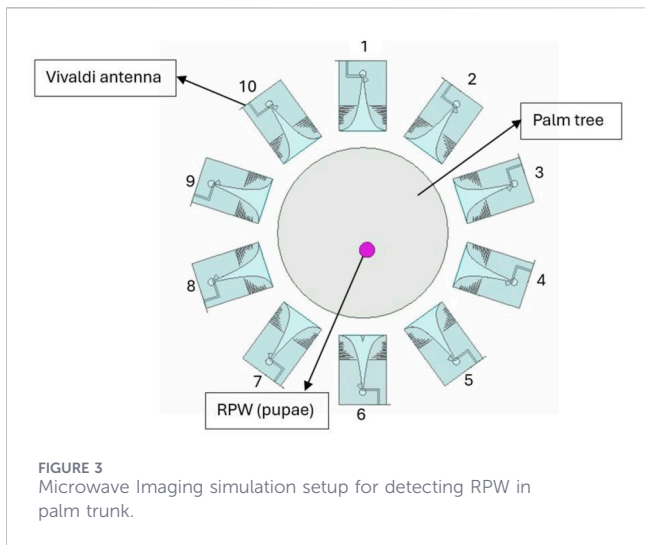


FIGURE 3 Microwave Imaging simulation setup for detecting RPW in palm trunk.

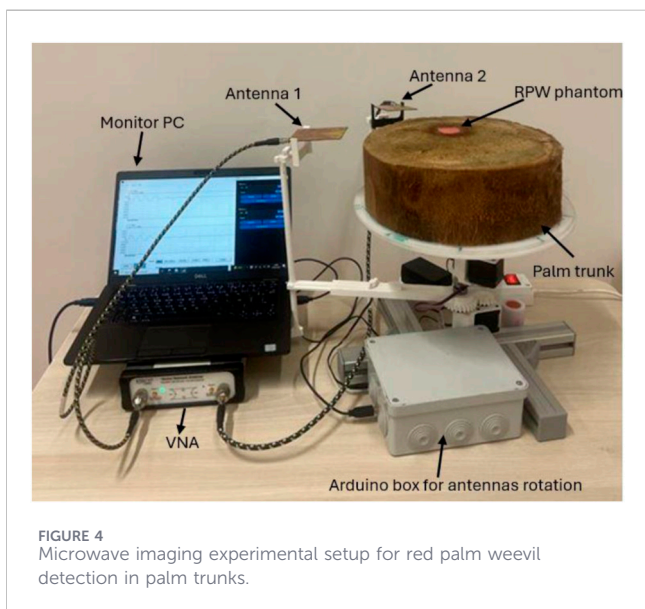


FIGURE 4 Microwave imaging experimental setup for red palm weevil detection in palm trunks.

85070E dielectric probe kit (Agilent Technologies, Bayan Lepas, Penang, Malaysia) was placed in direct contact with the RPW phantom and connected to a Keysight N5235B PNA L network analyzer to measure the permittivity of the RPW phantom in the 0.5–6 GHz frequency range. Reflection coefficient measurements at the probe material interface were carried out using a short air water calibration procedure. Relative permittivity and conductivity were extracted using Keysight Materials Measurement Suite software, version 20.0.22083101.

### Simulation study of MWI for detecting RPW infestation in palm trunks

MWI based on radar techniques begins by illuminating the infested palm tree with electromagnetic waves. Incident microwave

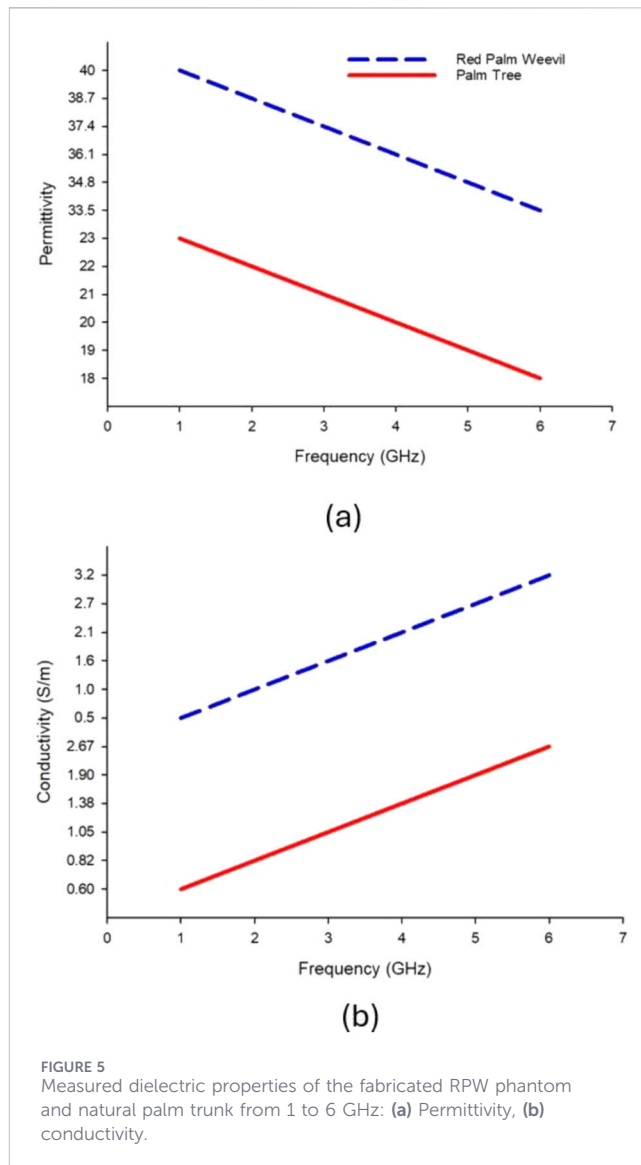


FIGURE 5 Measured dielectric properties of the fabricated RPW phantom and natural palm trunk from 1 to 6 GHz: (a) Permittivity, (b) conductivity.

signals interact with the internal structure of the tree, where the presence of Red Palm Weevil infestation causes variations in dielectric properties. In the next step, the backscattered signals are captured and processed to reconstruct an image of the internal structure (Kuwahara, 2021). In this study, Images were reconstructed by applying the delay-and-sum (DAS) and delay-multiply-and-sum (DMAS) methods (Sami et al., 2020). By enabling clear visualization of anomalies within the trunk, this approach enhances the ability to detect and localize RPW infestations in a non-invasive manner (Lalith et al., 2022; Alsawafah et al., 2022).

### Simulation setup

Ultra wideband (UWB) antennas are well suited to MWI due to their wide frequency coverage, which improves image resolution (Casu et al., 2017; Ren et al., 2022). In this study, a broadband Vivaldi antenna operating in the 1.6–5.9 GHz band was used for imaging RPW infestations in palm trunks, a frequency range chosen

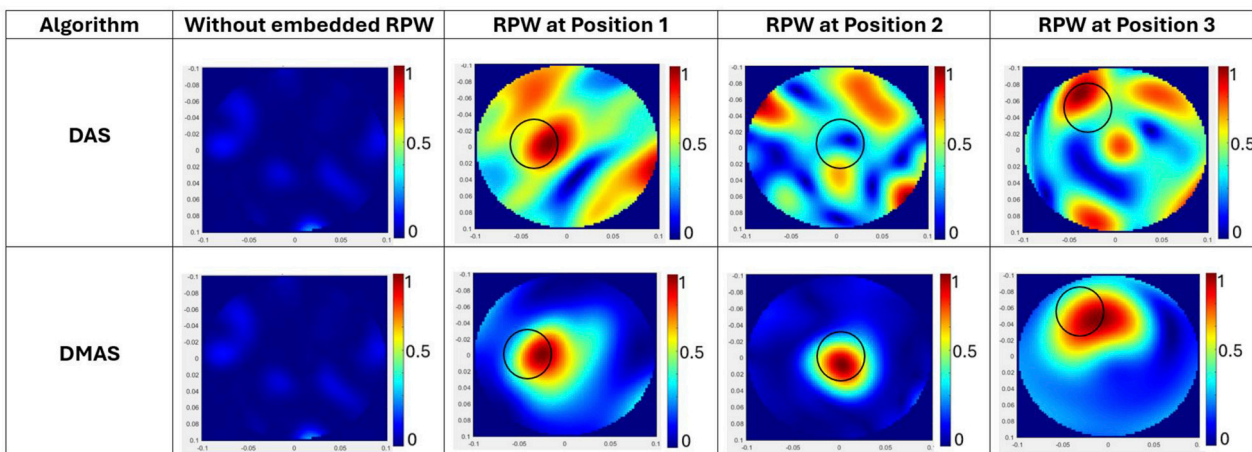


FIGURE 6 Comparative analysis of DAS and DMAS algorithms for large scale RPW detection at different locations in palm trunks: real positions Indicated by black circles.

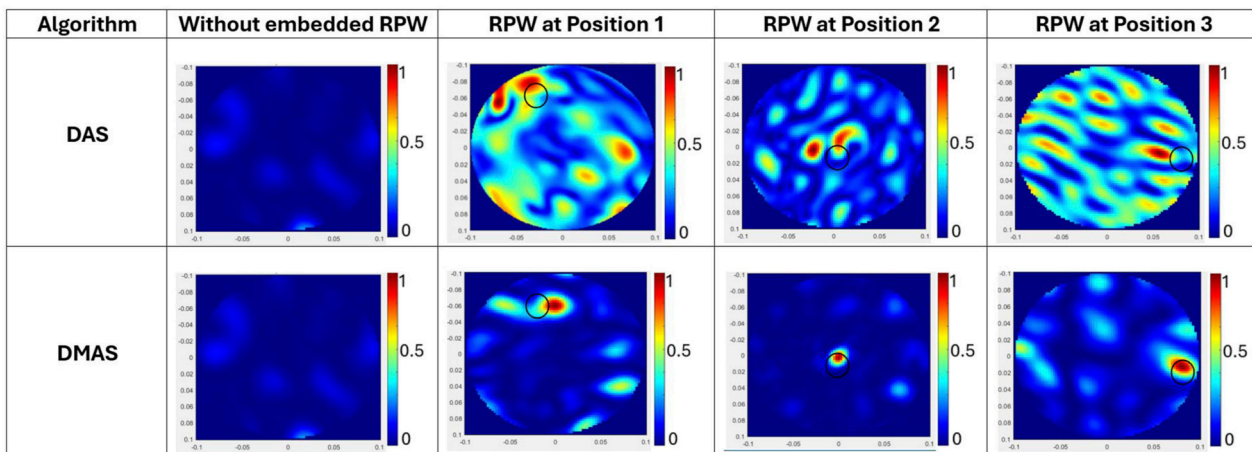


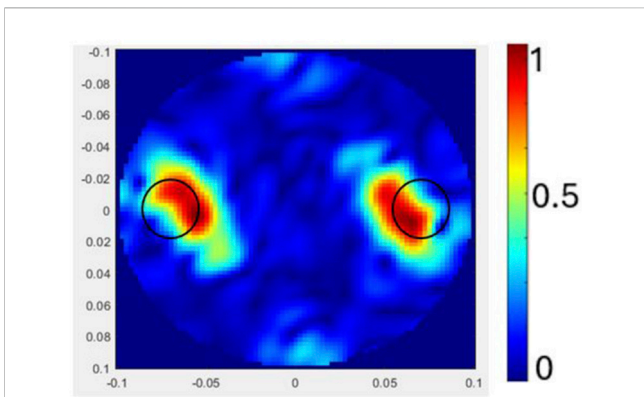
FIGURE 7 Comparative analysis of DAS and DMAS algorithms for small scale RPW detection at different locations in palm trunks: real positions Indicated by black circles.

as a compromise between penetration depth and spatial resolution for Microwave Imaging of palm tissue.

The spatial resolution achievable in a MWI system is strongly influenced by several factors, including the number of antennas, their distance from the material under test and the operating frequency range. In this study, the numerical model of the palm tree trunk is surrounded by an array of ten identical, uniformly distributed Vivaldi antennas positioned 30 mm from the surface of the palm (Figure 3). This configuration was chosen as optimal for ensuring high image accuracy, as it offers a good compromise between impedance matching at the antenna interface and efficient coupling of electromagnetic energy into the trunk.

### Experimental configuration

To evaluate the effectiveness of MWI in detecting internal infestations in palm trunks, an experimental setup was developed. The system employed antennas identical to those used in the simulation phase, fabricated on a 1.6 mm thick FR4 substrate using standard printed circuit board (PCB) technique. In this experimental configuration, two fabricated antennas were used, one as a transmitter and the other as a receiver, to eliminate the need for a switch, thereby reducing system complexity. Each antenna was mechanically coupled to a Nema 17 stepper motor via a support rod made from polylactic acid (PLA) to ensure minimal impact on electromagnetic performance. The motors



**FIGURE 8**  
Detection of palm trunk infestation by two large RPW pupae using the DMAS algorithm: real positions Indicated by black circles.

were driven by TB6560 motor drivers, with an Arduino Uno microcontroller coordinating the rotational movement of the antennas around an infested palm trunk containing the pupae stage of the RPW.

The experimental investigations focus exclusively on the pupal stage of RPW, using a developed artificial phantom to mimic the dielectric properties of real pupae. All measurements were performed on a cut, static palm trunk section under controlled laboratory conditions. Therefore, the proposed system is not intended to represent immediate field readiness, but rather to demonstrate the fundamental feasibility of MWI for internal pest

detection. Validation under realistic field conditions, including experiments on live palms and mobile life stages, will be addressed in future work.

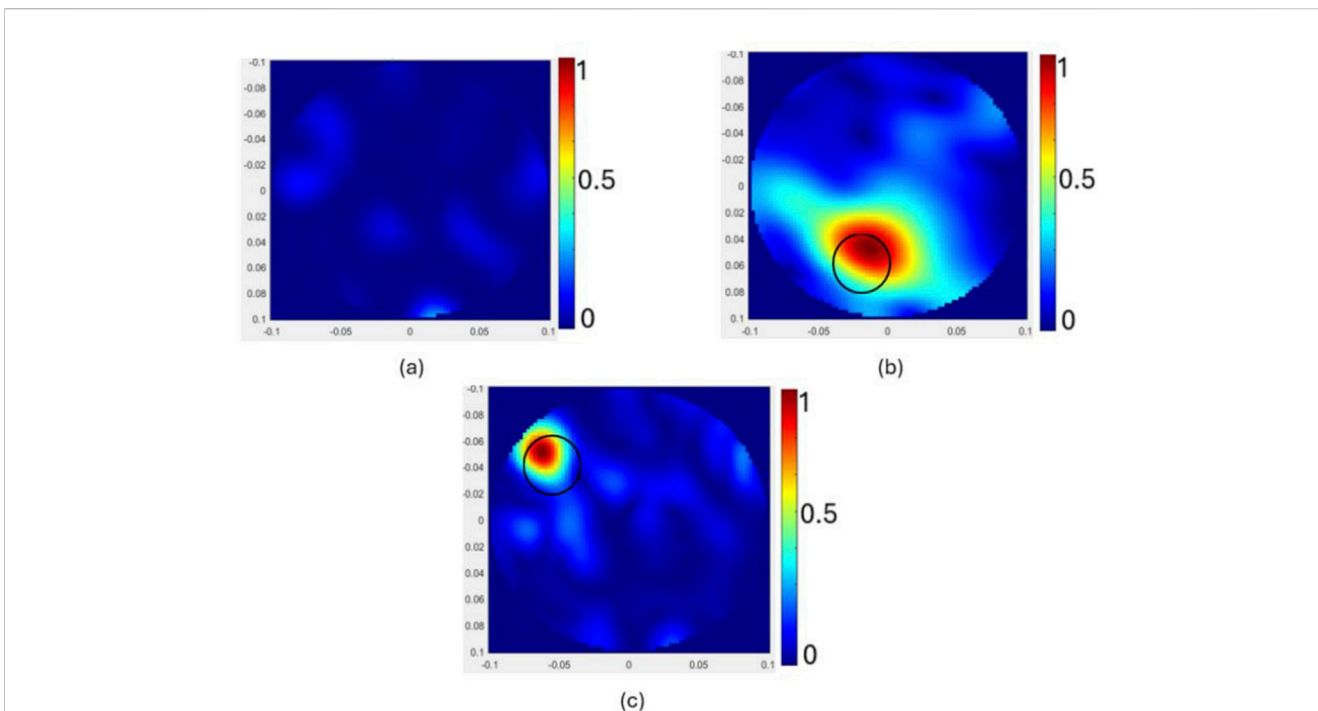
Three palm trunk segments from different trees were tested to evaluate the repeatability of the measurements. All samples were characterized by the same moisture content during the measurements.

Scattering parameters (S parameters) were measured using a PicoVNA 108 vector network analyzer, operating in a frequency range from 300 kHz to 8.5 GHz. The pupal stage was selected for this study because it is immobile, allowing reliable Microwave Imaging measurements with the rotating experimental setup.

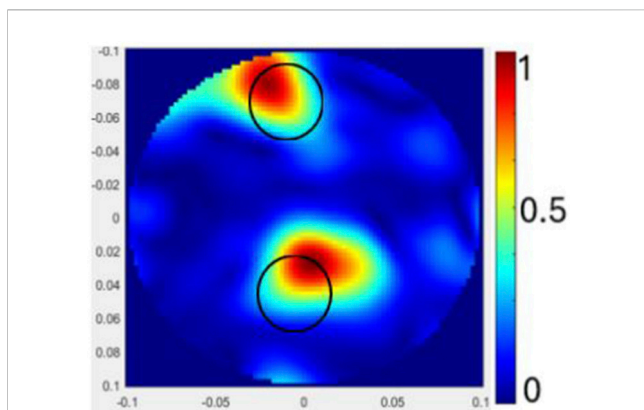
The transmitting antenna rotated around the infested trunk **Figure 1b** in fixed angular steps, while at each transmitter position, the receiving antenna continuously rotated around the trunk until reaching its maximum angular range. The angular step ( $\Delta\phi$ ) for the transmitter’s rotation was determined using the following relationship:

$$\Delta\phi = \frac{360}{p}$$

Where  $p$  represents the number of discrete transmitter positions. In this study, 10 transmitter positions were used, corresponding to an angular step of  $36^\circ$ . At each transmitter position, the receiving antenna swept over nine discrete positions, yielding nine receiver measurements per transmitter. This configuration effectively mimics a circular array composed of  $p$  transmitters, facilitating the scattering matrix measurement via the PicoVNA device connected to the antennas **Figure 4**.



**FIGURE 9**  
Experimental results using the DMAS algorithm: comparative analysis of (a) an uninfested palm trunk, (b) a palm trunk infested with a large RPW pupa at position 1, and (c) a palm trunk infested with a large RPW pupa at position 2: real positions Indicated by black circles.



**FIGURE 10**  
Radar based MWI for detecting two large RPW infestation sites in palm trunks using the DMAS algorithm: real Positions Indicated by black circles.

S-parameter measurements were acquired only over the frequency range of interest (1.6–5.9 GHz), using 401 discrete frequency points, resulting in a frequency step of approximately 10 MHz. An integration time of 1 m per frequency point was used, with 16 averages to improve the signal-to-noise ratio. The PicoVNA vector network analyzer was calibrated using the standard open-short-load (OSL) procedure, and the antennas were calibrated in free space before being positioned around the palm trunk. Once the measurement procedure was complete, the resulting CSV files were compiled and analyzed using the DMAS algorithm for image reconstruction.

## Results and discussion

### Validation data: permittivity of the RPW pupal phantom and host palm trunk

Results over the measured frequency range are shown in Figure 5. The phantom developed to represent the RPW in its pupal stage had a dielectric constant ranging from 40 to 33.5 and an electrical conductivity between 0.5 and 3.2 S/m. The real world palm trunk used in the experimental study showed dielectric constant values ranging from 23 to 17 and an electrical conductivity between 0.6 and 2.67 S/m. The observed permittivity and conductivity trends for both the phantom and the palm trunk are consistent with the typical dispersive behavior of biological tissues, where the dielectric constant decreases with increasing frequency due to dipolar relaxation phenomena. The measured properties of the phantom and real palm tree closely match the *in vivo* dielectric characteristics of RPW pupae and palm trunks reported in the literature (Tobon Vasquez et al., 2020). This close agreement confirms that the fabricated phantom is a valid substitute for real infestations and is suitable for use in controlled MWI studies, providing reliable field truth for evaluating the detection and localization capabilities of the imaging system. The pupal stage was selected for this study because it is immobile, allowing reliable Microwave Imaging measurements with the rotating experimental setup.

### Simulation findings on RPW detection

The MWI system for RPW detection was numerically simulated using Ansoft HFSS. As shown in Figure 3, a model of a palm trunk containing a large pupae stage of the Red Palm Weevil (external width of 2 cm) was used to evaluate the performance of MWI technology in detecting the embedded RPW.

The MWI technique demonstrated reliable performance in identifying the pupal stage across different positions and sizes, as illustrated in Figure 6, the technique successfully identified pupae located at different depths within the palm trunk, while Figure 7 shows its ability to detect pupae with reduced dimensions representative of earlier developmental stages. This finding highlights the potential of MWI as a non-invasive tool capable of detecting even small-scale infestations that are invisible to conventional inspection methods. Among the reconstruction approaches applied, the Delay and Sum (DAS) and Delay Multiply and Sum (DMAS) algorithms were employed, with DMAS offering improved accuracy in localization as shown in Figures 6, 7.

Furthermore, MWI maintained its performance in more complex scenarios involving multiple pupae at advanced developmental stages, as shown in Figure 8. The system successfully resolved and localized multiple targets simultaneously, confirming its robustness for detecting infestations of varying size and density. Together, these results demonstrate that MWI, particularly when combined with DMAS reconstruction, has strong potential as a field-deployable, non-destructive tool for early detection and spatial mapping of RPW infestations in palm trunks.

### Experimental findings on RPW detection

Figure 9 shows a comparison between an uninfected palm trunk and a trunk infested with large pupae of the RPW at two different locations, using the DMAS algorithm. The results demonstrate the ability of the MWI system to detect both the presence and position of the Red Palm Weevil at varying depths within the trunk. Subsequently, two large pupae of the RPW were embedded at different locations inside the palm trunk, and Figure 10 illustrates the DMAS algorithm's effectiveness in clearly detecting them in the experimental setup. The localization accuracy was computed by comparing the estimated pest position with the ground-truth location. The obtained displacement corresponds to a localization accuracy of approximately 93%, indicating that the proposed method can reliably estimate pest position with high spatial precision.

Unlike previous studies (Bait-Suwailam et al., 2022), which was limited to numerical simulations and demonstrated only the capability of microwave sensors to detect the presence or absence of RPW based on frequency shifts, the present work takes a significant step forward by experimentally validating these findings. Here, MWI was applied to real palm trunks containing pupal-stage phantoms, confirming not only the feasibility of detection but also the ability to accurately localize RPW pupae at different depths and positions. This progression, which moves from purely simulation-based analysis to experimental implementation, bridges the gap between theory and practice, providing a more realistic assessment of the technology's performance under controlled field conditions. By demonstrating both detection and spatial localization in a real host environment, this work

reinforces the value of MWI as a practical, non-invasive diagnostic tool that can be deployed for early pest detection in palm tree cultivation systems.

## Conclusion

In this study, a pest phantom was successfully developed to realistically mimic RPW pupae infestation inside a palm trunk, providing a reliable platform for evaluating the potential of Microwave Imaging (MWI) as a non-destructive detection technique. The proposed MWI system employs a wideband Vivaldi antenna array operating in the 1.6–5.9 GHz frequency range, achieving a maximum gain of 8.5 dB. The imaging setup consists of a ten-element multistatic configuration, where one antenna acts as the transmitter and the remaining nine serve as receivers. This configuration provides a richer set of scattered field data, improves image reconstruction quality, eliminates the need for complex switching hardware, and reduces overall system cost and mechanical complexity.

Simulation and experimental results obtained from real palm trunks containing pupal-stage phantoms confirm that the developed MWI system is capable of reliably detecting and localizing RPW infestations. The system demonstrated successful performance for different target sizes, depths, and spatial locations, and was also able to detect multiple targets simultaneously. This capability is essential for practical early detection systems in real agricultural environments. Overall, these findings highlight the strong potential of MWI as a novel non-destructive tool for agricultural pest detection, providing valuable high-resolution information about the number, location, and spatial distribution of RPWs inside palm trunks.

Future work will focus on evaluating the MWI system under more realistic and biologically relevant conditions. Young palm trees grown in large pots will be used as experimental subjects to better mimic field scenarios. This approach will allow assessment of infestations in living hosts with natural moisture content, tissue structure, and physiological processes. Such experiments will provide a closer representation of real field conditions while maintaining controlled and repeatable laboratory measurements.

Further investigations will also extend detection capabilities beyond the pupal stage to mobile stages of RPW, such as larvae and adults. A fast-switching system will be developed to acquire scattering data within seconds, ensuring consistent measurements despite pest movement. In addition, indirect infestation indicators, such as tunnels, feeding galleries, frass deposits, and boreholes, will be explored. Finally, future research will integrate advanced image reconstruction techniques, including machine-learning-assisted algorithms, and investigate metamaterial-based or reconfigurable antenna designs to further enhance imaging resolution, penetration depth, and sensitivity. Collectively, these developments will move MWI closer to becoming a deployable, field-ready technology for early RPW detection and management, with significant potential to reduce economic losses and support sustainable date palm cultivation.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

FE: Funding acquisition, Resources, Formal Analysis, Data curation, Methodology, Software, Visualization, Writing – original draft. MZ: Supervision, Writing – review and editing. QA: Validation, Writing – review and editing, Supervision, Project administration. KE: Methodology, Validation, Writing – review and editing. YZ: Formal Analysis, Writing – review and editing, Data curation, Visualization. CR: Writing – review and editing. ME: Supervision, Writing – review and editing. HG: Project administration, Writing – review and editing, Validation, Supervision.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

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