IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 13 May 2024, accepted 3 June 2024, date of publication 5 June 2024, date of current version 14 June 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3410161

RESEARCH ARTICLE

Thermal Effect of Microwave Radiation on *Dactylopius opuntiae* in Morocco and Coaxial Probe for Permittivity Measurements

FATIMA ZAHRAE EL ARROUD[1], (Student Member, IEEE), KARIM EL FAKHOURI[2], YOUNESS ZAAROUR[1], (Student Member, IEEE), CHAIMAE RAMDANI[2], HAFID GRIGUER[1], (Member, IEEE), MARIAM AZNABET[3], (Member, IEEE), RAFIQ EL ALAMI[1], AND MUSTAPHA EL BOUHSSINI[2]

[1]DICE (Digital Innovation Center of Excellence) ,Department of Microwave Energy and Sensing (MES), Mohammed VI Polytechnic University, BenGuerir 43150, Morocco
[2]Agro BioSciences Program, College of Agriculture and Environmental Sciences, Mohammed VI Polytechnic University, BenGuerir 43150, Morocco
[3]Laboratoire System of Information and Telecommunications (LaSIT), Faculty of Science, Abdelmalek Essaâdi University, Tetouan 93000, Morocco

Corresponding author: Fatima Zahrae El Arroud (fatimazahrae.elarroud@um6p.ma)

This work was supported by the Mohamed VI Polytechnic University.

ABSTRACT *Dactylopius opuntiae* (*D. opuntiae*), commonly referred to as cochineal scale insect or wild cochineal, poses a considerable risk to cactus plantations globally. Various control methods, including chemical pesticides and biological treatments, have been employed to control the *D. opuntiae* pest. This paper presents an innovative approach to use microwave radiation as a pest management method for *D. opuntiae*, in cactus plantations. This method stands out due to its advantages of selective treatment, chemical free, and no environmental impact. This research work details the use of plane wave for simulating the influence of microwave radiation using electromagnetic model, on cactus pear and three distinct stages of adult females of the *D. opuntiae*. The findings demonstrated that the distribution of thermal energy indicates the ability of electromagnetic radiation to raise *D. opuntiae* 's thermal energy above that of the cactus pear at various industrial, scientific, and medical (ISM) band frequencies. Additionally, the developed microwave heating system demonstrates the capability of microwave radiation at 2.45 GHz to eliminate various stages of adult *D. opuntiae* without harming the host plant's quality. The study also explores the impact of adjusting input power and treatment duration to manage *D. opuntiae* effectively.

INDEX TERMS Cactus pear, coaxial probe, *D. opuntiae*, dielectric heating, permittivity.

I. INTRODUCTION

The prickly pear, a cactus plant known scientifically as *Opuntia ficus-indica* (L.) Mill. (Caryophyllales: Cactaceae), has been cultivated in Mexico for centuries and has since spread to other regions of the world [1]. Cactus have adapted to thrive in water-scarce environments, making them a valuable source of sustenance for both animals and humans [2]. The prickly pear fruit and seed oil are the primary products cultivated in many Mediterranean countries (Spain, Portugal, Morocco, Tunisia, Egypt, Israel, Lebanon, Turkey, and Greece), making it a target of interest for the pharmaceutical and cosmetic industries [3], [4], [5]. Despite the promising economic prospects associated with prickly pear cultivation, the Mediterranean basin has faced significant challenges related to the wild cochineal *D. opuntiae*, since its first detection in the region [6]. *D. opuntiae* is believed to have originated in Mexico, and over time it has spread to other parts of the world [7]. In September 2014, *D. opuntiae* invaded in Morocco, where it has since posed a significant threat to cactus plantations [8], inflicting serious harm in several of regions where prickly pear cacti are crucial

The associate editor coordinating the review of this manuscript and approving it for publication was Ines Domingues.

for preserving biodiversity and preventing desertification [6]. In Brazil, the devastation caused by *D. opuntiae* on *O. ficus-indica* for forage has led to a loss of 100,000 hectares, valued at 25 million dollars. Similarly, in Mexico, the attacks by this pest have led to decreased yields and an increase in production costs [9]. The mature female cochineal of *D. opuntiae* is a difficult insect stage, with a waxy covering that makes the use of insecticides or other control methods extremely difficult. When crushed, their bodies yield carminic acid, a naturally occurring color utilized in the food, cosmetic, and textile industries [10].

Both nymphs and adult females of the wild cochineal feed on plants by sucking sap from the cladode, leading to chlorosis (yellowing), and the subsequent destruction of the plant. The survival potential of plants can be compromised when the infestation rate exceeds 75% of the total insect population [11].

Morocco has made significant progress in developing integrated pest management (IPM) strategies to reduce the impact of wild cochineal [10]. In addition, the National Office of Food Safety (ONSSA) of Morocco has approved several insecticides to safeguard cactus crops and restrict further infestation [12]. Nevertheless, the adverse impacts of these pesticides on human health and the environment, coupled with the development of insect strains resistant to them, has emphasized the urgency of developing alternatives and non-chemical approaches. As a response to these concerns, there has been a growing emphasis on developing alternatives, such as using biological treatments (essential oils, plant extracts and entomopathogenic fungi and bacteria) [2], [10], [13].

The use of dielectric heating, which targets insect pests without harming host materials, presents a chemical-free substitute for postharvest insect control in agricultural commodities. This technique is based on radio frequency (RF) and microwave (MW) radiation, which covers a wide bandwidth ranging from 30 MHz to 300 GHz [14]. The strategy of employing RF and MW heating treatments based on thermal impact was suggested and accepted as a substitute treatment in several crops. The industrial, scientific, and medical (ISM) bands from RF to MW have been allocated by the US Federal Communications Commission (FCC) to avoid electromagnetic interference [15], [16]. RF and MW radiation make ions and polar molecules of the dielectric material move and rotate; this leads to the heating of the material [15]. Although it may appear novel, but dielectric heating was proposed in 1929 [17]. Dielectric heating has proven its effectiveness in controlling various insect pests, including codling moth [18], [19], Navel Orangeworm [20], [21], and Rice moth [22] affecting walnuts, as well as red flour beetle in almonds [23]. Moreover, this method has been shown to be useful in treating grains such as wheat, rice, corn, white maize, coix seeds that are infested by *Rhizopertha dominica* (Coleoptera: Bostrichidae) [24], [25], [26]. Dielectric heating has also been demonstrated to be effective in treating palms trees affected by *Rhynchophorus ferrugineus* (Olivier) (Coleoptera: Dryophthoridae) [15], [27], [28], [29], [30]. The quality of the host material remains uncompromised following treatment; this is due because of notable disparity in dielectric properties between pests and their host materials. On this approach, dielectric constant emerges as a critical parameter in the determination of the optimal frequency for dielectric heating treatment. As well as to build an EM model that could be used to simulate the effect of microwave radiation on pest and its host material [39].

Research efforts have been dedicated to measuring the permittivity values of various plant materials [31], [32], [33], [34], [35], [36], [37], [38], [39], and pests [18], [27], [39], [40], [41], enabling researchers to draw comparisons and gain a comprehensive understanding of how different pests and their host species respond to dielectric heating. Furthermore, permittivity values for cactus pear have been studied in previous research [42], [43], [44]. However, the permittivity values of *D. opuntiae* have never been measured before. To address this gap, this research paper is organized as follows. Section II presents how to assess the dielectric properties of pests and cactus using a coaxial probe complemented by overview of the electromagnetic models for cactus and wild cochineal. Additionally, Section III introduces thermal simulation findings utilizing the model developed in the previous section, elucidating the determination of whether *D. opuntiae* or the cactus pear displays higher susceptibility to the electromagnetic radiation treatment. Moreover, Section IV outlines an experimental investigation on dielectric heating for controlling *D. opuntiae* while safeguarding the quality of the cactus pear. The Section V summarizes the main findings of this study.

II. ELECTROMAGNETIC MODEL

An electromagnetic model of both plant and insect serves as a valuable tool for simulating the effects of microwave radiation on cactus pear plants infested by the wild cochineal. This approach allows us to analyze and compare the responses of these biological substances to electromagnetic radiation exposure, shedding light on which of the two, cactus pear or the wild cochineal, is more significantly affected by this form of energy. One critical challenge we encountered in constructing such a model is the absence of specific dielectric properties of *D. opuntiae*, that prompted us to focus on characterizing the dielectric properties of both cactus pear and *D. opuntiae*. Despite existing literature on *opuntia ficus indica*'s dielectric properties [42], [43], [44], our characterization ensures the accuracy of our model in representing the specific variety under study.

A. ELECTROMAGNETIC MODEL OF D. OPUNTIAE AND CACTUS PEAR

This study focuses on three distinct categories of adult females of *D. opuntiae*: young adult (small), pre-adult (medium-sized), and mature adult (big size - fully grown adult). To accurately measure the specimens' dimensions and provide them with forms that are close to reality, the three adult stages were first frozen and then lyophilized. Then,

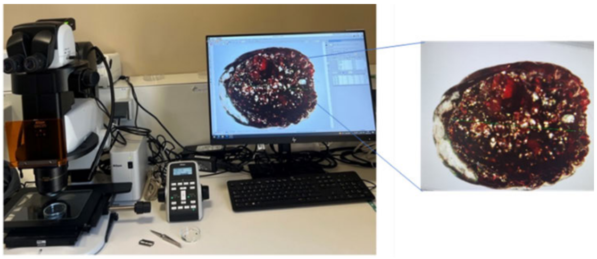

FIGURE 1. **Experimental setup for measuring adult *D. opuntiae* dimension.**

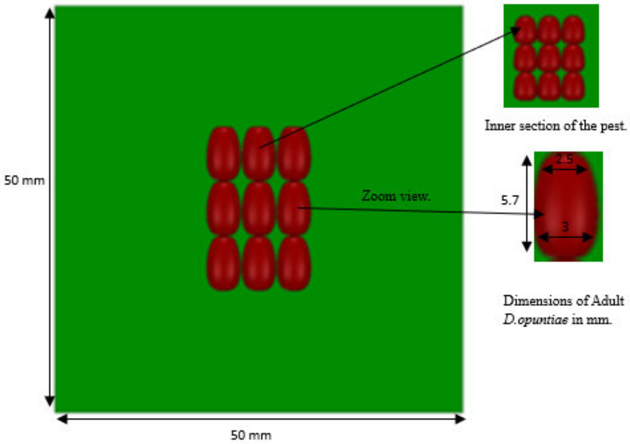

FIGURE 2. **Model of cactus pear infested by 3 × 3 *D. opuntiae* colony.**

a razor blender and fine forceps were used to dissect the insects with precision. The exact dimensions required for the electromagnetic model were then measured utilizing a Nikon SMZ25 stereo microscope, manufactured by Nikon, Japan. Image analysis was conducted using Nikon's imaging software, specifically NIS- Element Analysis D 4.20.00, to obtain precise visual representations (Fig. 1). In this study, each adult insect type was characterized by two permittivity values: the outer part represented by the skin's permittivity and the inner part by the insect paste's permittivity. Semicircular configurations were employed to depict young adults with a 2.2 mm radius and 0.1 mm thickness, pre-adults with a 3 mm radius and 0.17 mm thickness, and mature adults with a 4.2 mm radius and 0.2 mm thickness. The remaining portion of each semi circle was utilized to represent the inner part of adult females of the *D. opuntiae*. A cubical model, with dimensions of 50 mm 50 mm 10 mm, was employed to emulate the cactus pear (Fig. 2).

B. DIELECTRIC PERMITTIVITY MEASUREMENT

Dielectric properties are vitally important in dielectric heating of biological materials. These properties are represented by the dielectric constant ε' and the dielectric loss factor ε'', where the dielectric constant ε' describes a material's ability to store electromagnetic energy. Furthermore, the loss factor ε'' is associated with electromagnetic energy dissipation, which represents a material's capacity to convert electromagnetic energy to thermal energy [45]. The dielectric properties of insects and plants are used to identify which materials will absorb the most EM energy and produce the most thermal energy during dielectric heating [46]. According to (1), the electromagnetic energy stored by a dielectric material varies directly with real part of the permittivity (ε') and the applied electric field (E) and the power that characterizes the heat energy generated from EM energy (2), which is proportional to the applied frequency (f), electric field (E), and loss factor ε'' [47].

$$U = \frac{1}{2}\varepsilon'\varepsilon_0 E^2 (CV/m^3) \tag{1}$$

$$Q = 2\pi f \varepsilon_0 \varepsilon'' E^2 (W/m^3) \tag{2}$$

$$\varrho Cp \frac{\partial T}{\partial t} = Q \tag{3}$$

According to eq (2), whenever the electric field strength and frequency are constant, higher lossy materials generate more heat energy than lower lossy ones [45]. Moreover, the thermal energy generated by the same dielectric material could be enhanced by increasing the frequency or the applied electric field [48]. Equation (3) illustrates a direct correlation between Q and temperature distribution [20], Where ϱ is the density (Kg/m3), Cp is the specific heat capacity (J/kg.K), and T is the temperature (K). An increase in Q results in a corresponding rise in temperature distribution, leading to the mortality of insect pests. As demonstrated in [15], applying 1 KW of energy for 7 minutes proved sufficient to achieve the lethal temperature for the red palm weevil without compromising the quality of the palm.

Dielectric properties of both cactus pear and *D. opuntiae* were determined through the use of the open ended coaxial probe technique across a frequency range of 0.5 to 20 GHz. This technique is widely employed for permittivity measurements in biological tissues [16], [31], [32], [40], [41], [42], [49], [50], [51]. A coaxial probe in direct contact with the material under test (MUT), connected to a Keysight N5235B 10 MHz to 50 GHz PNA-L network analyzer (Fig. 3-a) was used for reflection coefficient measurement at the probe material interface following a short-air-water calibration technique [32]. Permittivity values were then extracted using the Keysight Materials Measurement Suite, Version 20.0.22083101 [40].

1) COMPLEX DIELECTRIC PERMITTIVITY OF D. OPUNTIAE

Dielectric constants and loss factors for *D. opuntiae* at three distinct adult stages, as visualized in Fig. 4, are detailed in Fig. 5. Skin measurements for each developmental stage of the insects were measured using a coaxial probe, ensuring direct contact with the insect (Fig. 3-b). Additionally, measurements were taken specifically for the paste associated with each developmental stage of the insects, across a large frequency band (0.5 GHz to 20 GHz). The wide frequency band utilized in this study, enabling researchers to capture a comprehensive view of how electromagnetic interactions vary with frequency in *D. opuntiae* tissues. The permittivity

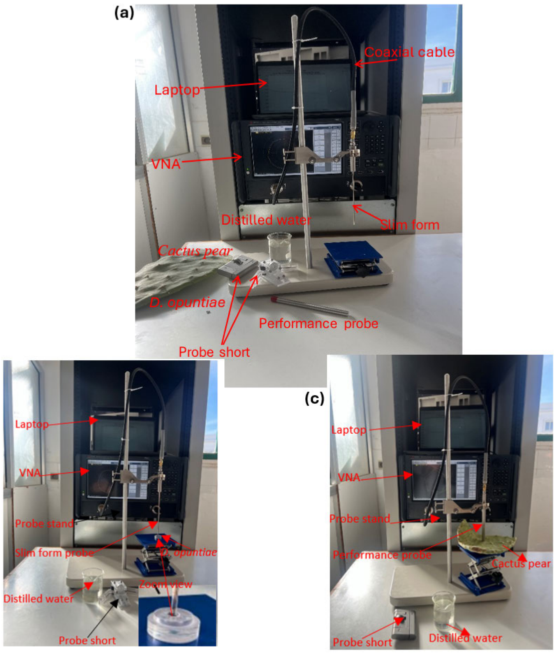

FIGURE 3. **(a)Experimental setup for permittivity measurement, (b) Photograph of the setup open ended coaxial probe for *D. opuntiae*'s permittivity measurement, (c) Photograph of the setup open ended coaxial probe for cactus pear's permittivity measurement.**

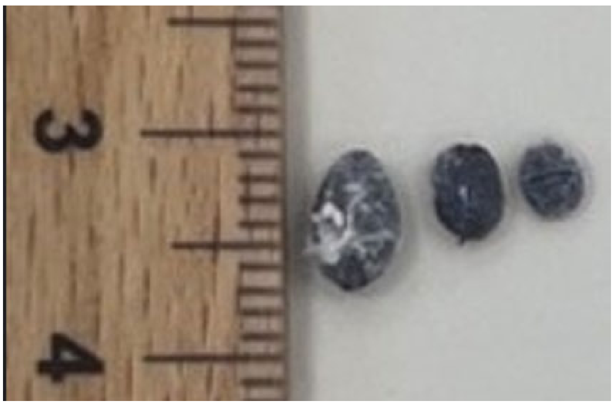

FIGURE 4. **Real size of the three stages of adult *D. opuntiae*.**

values of the insect paste remain consistent across all three stages, indicating an elevated level of similarity in the plots, while the skin's dielectric features of the three insect stages exhibited consistent trends Fig. 5. The real part ε' showed a declining pattern as the frequency increased; this behavior corresponds to the trends observed in the dielectric constant of adult's rice weevil [52], codling moth [40], cowpea weevil [53], and red flour beetle [54]. In contrast, the imaginary component ε''displayed an increase with the rising frequency until it reached a peak around 12 GHz, beyond which it exhibited a decreasing trend with further increases in frequency, aligning with results observed in the loss factor of adult rice weevil [52].

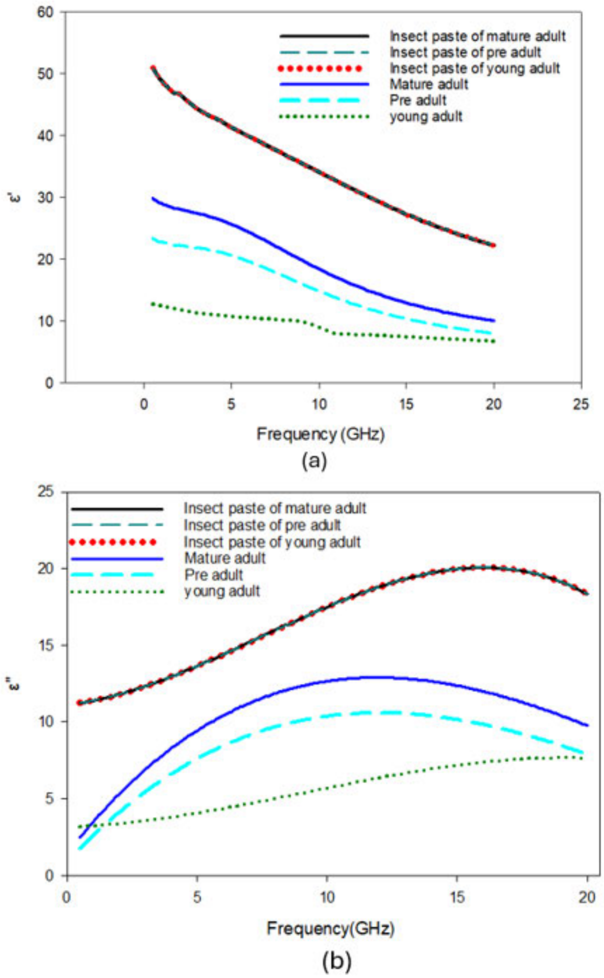

FIGURE 5. **Permittivity measurement of different stages of adult *D. opuntiae* in comparison with different stages insect paste (a) real part and (b) imaginary part.**

The reduced water content in young adult females of *D. opuntiae* contributes to lower complex permittivity value in this stage compared to the mature adults. The variation in permittivity between young and mature cochineal carries significant implications for their thermal energy production. Thermal energy generation within an organism is linked to the ability of its tissues to absorb and dissipate heat efficiently. Lower dielectric constant in young and pre-adult of the cochineal indicates a reduced ability to store electrical energy within their tissues (1) and suggests that young adults may produce less thermal energy compared to mature adult females (2).

2) COMPLEX DIELECTRIC PERMITTIVITY OF CACTUS PEAR

Dielectric measurements of cactus pear were conducted using a coaxial probe within a wide frequency range, spanning from 0.5 GHz to 20 GHz. These measurements were performed at different positions of the cladode (Fig. 3-c). The average values of both dielectric constant and loss factor (Fig. 6) show that as the frequency increases, the dielectric constant

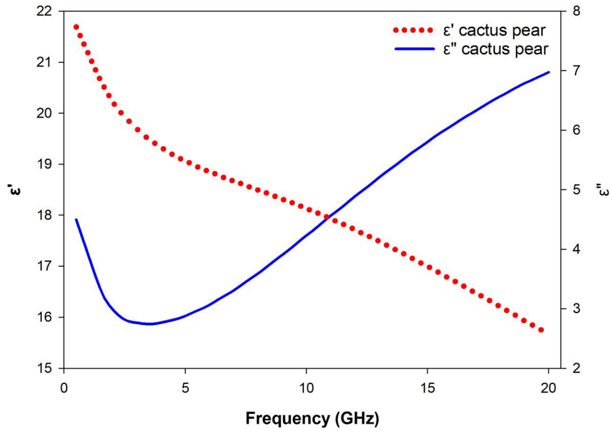

FIGURE 6. Plot of mean dielectric constant (ε') and dielectric loss factor (ε'') for cactus pear at ambient temperature. Data plotted are the mean of different positions of cactus pear.

TABLE 1. Comparison between dielectric properties of *D. opuntiae* adult females and cactus pear at ISM band.

Material	Permittivity	Frequency (MHz)		
		915	2450	5800
Fully developed adult	ε'	29.10	27.79	24.60
	ε''	4.13	5.44	10.12
Pre adult	ε'	22.79	22.03	19.79
	ε''	3.82	4.22	8.19
Young adult	ε'	23.74	22.48	20.79
	ε''	3.44	3.31	4.26
Cactus pear	ε'	21.49	20.04	18.88
	ε''	3.13	2.81	3.01

ε' exhibits a continuous decrease. This trend signifies a reduced ability of the material to store electrical energy at higher frequencies. Moreover, the loss factor ε'' displays a distinctive pattern. It sharply declines as the frequency increases until it reaches a minimum at approximately 2 GHz. Beyond this point, ε'' begins to rise again with further increases in frequency. The alignment of our findings with previous research documented in [42].

C. COMPARATIVE STUDY ON DIELECTRIC PROPERTIES OF D. OPUNTIAE AND CACTUS PEAR AT ISM BAND

Three frequencies, selected from the measured frequency range and falling within the ISM band, are employed to simulate the effects of microwave radiation on cactus pear and *D. opuntiae*. Table 1 presents a comparison of the dielectric properties of cactus pear and *D. opuntiae* at these frequencies. These findings anticipate that insects, characterized by their high dielectric properties, exhibit a significant capability to store EM energy and transforming it to thermal energy, in contrast to the plant. Consequently, it is reasonable to expect that insects will experience more substantial thermal effects than the plant across a range of ISM bands.

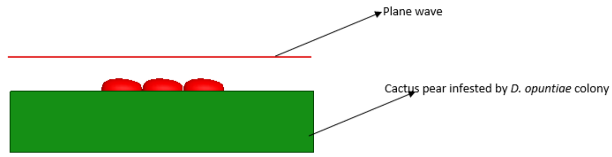

FIGURE 7. Thermal simulation setup.

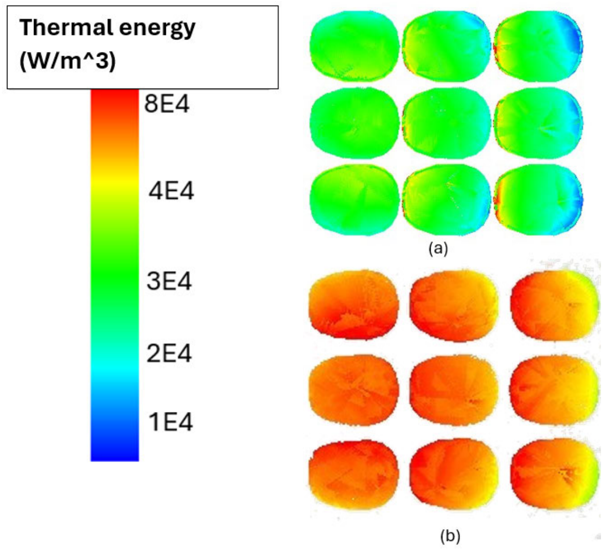

FIGURE 8. Microwave heating effects on (a) skin and (b) internal components of young adult *D. opuntiae* with a power density of 300 W/m^2 at 2.45 GHz.

III. THERMAL SIMULATION

The permittivity data obtained for both the cactus pear and adult of *D. opuntiae* (Fig. 5) and (Fig. 6) were employed in Ansys software to simulate the impact of microwave radiation on three developmental adult stages of *D. opuntiae* and cactus pear using plane wave as an excitation (Fig. 7), covering three frequencies within the ISM band, which constituted a portion of the measurement's frequency band.

The simulation was specifically directed at three distinct frequencies: 915 MHz, 2.45 GHz, and 5.8 GHz, additionally, two nominal power density levels, namely 300 W/m^2 and 600 W/m^2, were included as input parameters for the simulation using the plane wave. The thermal energy produced within the biological tissues was quantified using the designated input power density levels and frequencies. This study aims to determine which entity, whether *D. opuntiae* or the cactus pear, that exhibits greater sensitivity to the electromagnetic radiation treatment.

A. INPUT FREQUENCY OF 2.45 GHZ

1) MICROWAVE HEATING DISPARITIES BETWEEN INNER AND OUTER PORTIONS OF D. OPUNTIAE

In all adult stages of *D. opuntiae*, the inner part consistently exhibits higher thermal energy levels compared to

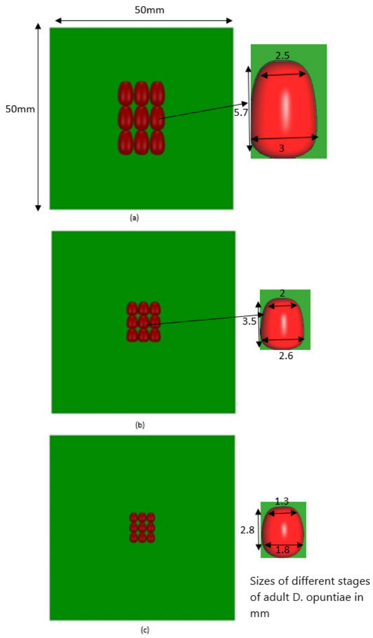

FIGURE 9. (a) Fully grown, (b) Medium, and (c) Young adults configuration.

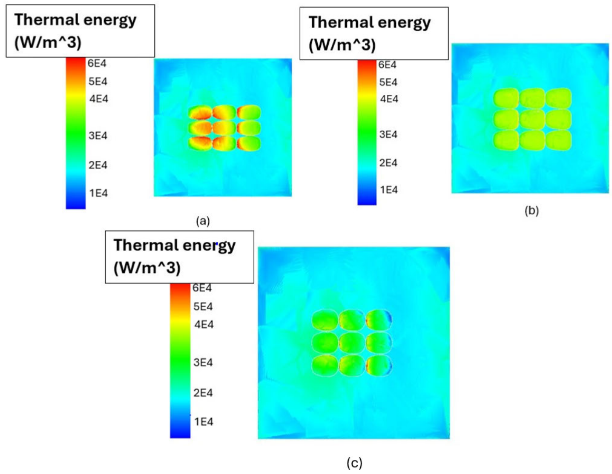

FIGURE 10. Comparative thermal energy distribution in cactus pear and *D. opuntiae* (a) fully developed adults, (b) intermediate, and (c)young, with a power density of 300 W/m^2 at 2.45 GHz.

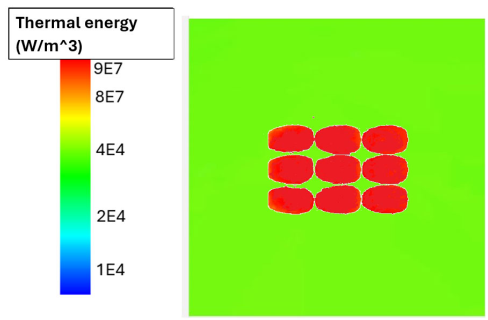

FIGURE 11. Thermal energy distribution on cactus pear and *D. opuntiae* adult with an input power density of 600 W/m^{2}at 2.45 GHz.

the surrounding skin. Fig. 8 shows the high difference between the thermal energy of the skin and the insect paste of the young adult. This discrepancy is primarily due to the inner part's higher loss factor (Fig. 5-b), which enhances its capacity to convert electromagnetic energy into heat.

2) COMPARATIVE DIELECTRIC HEATING RESPONSES OF THREE DEVELOPMENTAL STAGES OF ADULT D. OPUNTIAE AND CACTUS PEAR

To perform this experiment, the center of cactus cladode was infested by adult females of *D. opuntiae* (Fig. 9), the three adult stages and cactus pear were subjected to a uniform microwave heating and evaluate their reaction to microwave heating. The thermal energy distribution observed across the cactus pear and the three stages of adult models (Fig. 10), reveals that mature adult females of *D. opuntiae* is significantly more sensitive to microwave heating compared to the other developmental stages. Furthermore, a noteworthy finding is the comparatively lesser impact of microwave radiation on the cactus pear plant when compared to the three adult stages. This difference can be attributed to the elevated loss factor value exhibited by mature adult females of *D. opuntiae* in comparison to the other developmental stages contributes significantly to their increased sensitivity to microwave heating. Additionally, it is important to highlight that all developmental stages of adult *D. opuntiae* exhibit higher loss factor values at 2.45 GHz when compared to the cactus pear plant (1). This distinction emphasizes the intrinsic differences in thermal susceptibilities between the pest and the host plant.

3) EFFECT OF POWER INCREASE

The remainder of this simulation study will concentrate solely on evaluating the impact of dielectric heating on cactus pear infected with fully developed *D. opuntiae*. This choice of fully developed stage is representative of the prevalent life stage encountered in cactus pear. Thermal energy distribution patterns (Fig. 11) when subjected to a power density of 600 W/m^2 at 2.45 GHz, it is evident that as the power density level increase, both the cactus pear and adult *D. opuntiae* exhibit a corresponding rise in thermal distribution. Notably, this analysis indicates that adult *D. opuntiae* individuals are more affected by microwave radiation compared to the cactus pear plant.

B. INPUT FREQUENCY OF 915 MHZ AND 5.8 GHZ

At two discrete frequencies, a constant power density of 300 W/m^2 was applied to cactus pear hosting adult *D. opuntiae* at a fully developmental stage. The resulting thermal energy distribution (Fig. 12) reveals that the increase in frequency was found to correlate with an elevation in the thermal distribution levels of both the cactus pear and *D. opuntiae*. Conversely, a reduction in frequency led to a

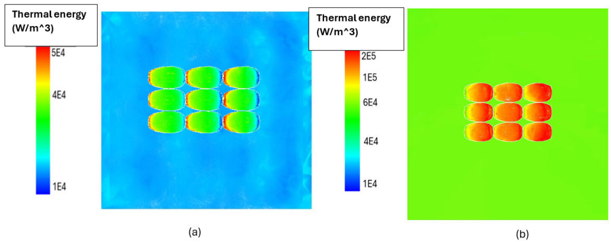

FIGURE 12. **Thermal distribution of cactus pear and adult *D. opuntiae* at (a) 915 MHz and (b) 5.8 GHz with an input power density of 300 W/m^2.**

TABLE 2. **A comparison of the thermal energy distribution of cactus pear and fully developed adult within the ISM band.**

Material	Thermal energy (W/m^3)	Frequency (MHz)		
		915	2450	5800
Fully developed adult	Q	1.3E4	4.5E4	1.9E5
Cactus pear	Q	1E4	1.5E4	4E4

proportional decrease in thermal distribution within both the host plant and the insects. This observation is in accordance with the established linear relationship (2), which describes the direct correlation between thermal energy and frequency. It is noteworthy to mention that the cactus pear displays varying degrees of susceptibility to electromagnetic radiation compared to *D. opuntiae* at different frequencies. The plant is less affected than *D. opuntiae*.

Based on the outcomes of thermal simulations, frequency within the ISM band, namely 5.8 GHz, is identified as optimal choice for controlling adult *D. opuntiae* in cactus pear, due to discernible differentials in thermal energy distribution between insects and plants, conversely; minimal divergence in distribution was observed at 915 MHz (2). However, for experimental investigation, solely the 2.45 GHz frequency will be utilized to assess its effect on mortality rates of adult *D. opuntiae* across various developmental stages. This selection is facilitated by the ready availability of high power sources, such as magnetrons, operating at this frequency in the market.

IV. EXPERIMENTAL STUDY RESULTS

In order to assess microwave radiation on both the quality of cactus pear and the mortality rate of *D. opuntiae*, a microwave heating system is employed in our experimental approach. This setup use magnetron as a high power source, resonating at a frequency of 2.45 GHz connected to a horn antenna (Fig. 13). The antenna and the treated material were situated at a separation of 1cm.

A. EVALUATING THE PHYTOTOXICITY OF CACTUS PEAR

The microwave heating system utilized in this study can produce a range of power levels spanning from 300W to 600W. These powers, applied at various durations, were subjected to study their impact on the phytotoxic response of the entire cladode. The central aim of this study was to identify the optimal duration for each power, while maintaining the plant in good quality without showing any symptoms of phytotoxicity. The level of phytotoxicity in the plant was conducted based on the emergence of yellow areas following treatment. A high level of phytotoxicity is indicated by the manifestation of yellowing across half of the cladode after treatment, whereas a low level of phytotoxicity is denoted by the presence of only minor yellowed areas.

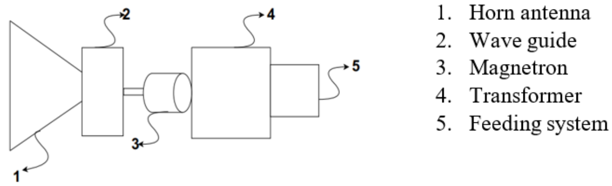

FIGURE 13. **Microwave radiation setup.**

TABLE 3. **Impact of 2.45 GHz Microwave Radiation at Varied Power Levels and Durations on the Phytotoxicity of Cactus Pear.**

Power	Duration					
	20min	10min	5min	4min	2min	1min
	Phytotoxicity					
300W	+++	++				
375W	+++	++	+			
500W	+++	+++	++	+		
600W	+++	+++	++	+	+	

+++ High level of phytotoxicity
++ Middle level of phytotoxicity
+ Low level of phytotoxicity
No phytotoxicity

The entire cladode was utilized in this study, positioned 1cm away from the horn antenna. Table 3 illustrates the impact of microwave radiation at various power levels and durations on the phytotoxicity of the plant. Notably, at 300W, there is a significant phytotoxicity as manifested by appearance of yellow zones on the cladodes, particularly under extended exposure time. The observation showed that the shorter treatment period is associated with less phytotoxicity. A 5-minute treatment at 300W shows no apparent phytotoxicity. The optimal treatment duration, demonstrating no phytotoxic effects on the plant, was reduced to 4 minutes, 2 minutes, and 1 minute for power levels of 375W, 500W, and 600W, respectively.

B. EVALUATING THE MORTALITY OF D. OPUNTIAE

Cactus pear cladodes without infestation were grown in plastic pots (27 cm diameter, 24 cm height) under green-house conditions at 30°C. The cultivation substrate consisted of a blend of one-third soil, one-third sand, and one- third peat. The plants were then subjected to highly infested cladodes sourced from the Marchouch area (32 14’31.9”N 8 16’42.7”W). Placing each infested cladode between two pots, an intentional artificial infestation occurred after

TABLE 4. Mortality rate of adult female cochineal *D. opuntiae* at their various stages of development exposed to various microwave radiation powers and treatment durations up to 192 hours after application.

Power (W)		300	375	500	600
Duration of treatment (min)		5	4	2	1
Development stages	Time after treatment (h)	% Mortality			
Young female	2 h	A 70.00 bcd	A 56.67cd	B 90.00cd	A 53.33abcde
Young female	24 h	B 100.00 d	B 100.00e	B 100.00d	A 70.00bcde
Young female	48 h	A100.00 d	A 100.00e	A100.00d	A 86.67cde
Young female	72 h	A 100.00 d	A 100.00e	A 100.00d	A 93.33de
Young female	96 h	A 100.00 d	A 100.00e	A 100.00d	A 100.00e
Young female	120 h	A 100.00 d	A100.00e	A 100.00d	A 100.00e
Young female	144 h	A 100.00 d	A 100.00e	A 100.00d	A 100.00e
Young female	168 h	A 100.00 d	A 100.00e	A 100.00d	A 100.00e
Young female	192 h	A 100.00 d	A 100.00e	A 100.00d	A 100.00e
Pre-adult female	2 h	AB 53.33 abcd	B 73.33cde	A 6.67a	A 0.00a
Pre-adult female	24 h	AB 73.33 cd	B 100.00e	B 90.00cd	A 16.67ab
Pre-adult female	48h	A 76.67 cd	A 100.00e	A 96.67cd	A 43.33abcde
Pre-adult female	72h	A 80.00 cd	A 100.00e	A 100.00d	A 60.00abcde
Pre-adult female	96h	A 86.67 cd	A 100.00e	A 100.00d	A 70.00bcde
Pre-adult female	120h	A 100.00 d	A 100.00e	A 100.00d	A 76.67bcde
Pre-adult female	144h	A 100.00 d	A 100.00e	A 100.00d	A 76.67bcde
Pre-adult female	168h	A 100.00 d	A 100.00e	A 100.00d	A 80.00bcde
Pre-adult female	192h	A 100.00 d	A 100.00e	A 100.00d	A 80.00bcde
Adult female	2h	A 0.00 a	A 0.00a	A 0.00a	A 0.00a
Adult female	24h	A 16.67 ab	A 16.67ab	A 13.33ab	A 3.33a
Adult female	48 h	A 40.00 abc	A 46.67bc	A 40.00b	A 23.33abc
Adult female	72 h	A 56.67 bcd	A 50.00bc	A 70.00c	A 30.00abcd
Adult female	96 h	A 76.67 cd	A 60.00cd	A 83.33cd	A 63.33abcde
Adult female	120 h	A 86.67 cd	A 70.00cde	A 86.67cd	A 73.33bcde
Adult female	144 h	A 93.33 cd	A 73.33cde	A 100.00d	A 80.00bcde
Adult female	168 h	A 100.00 d	A 86.67de	A 100.00d	A 96.67e
Adult female	192 h	A 100.00 d	A 90.00de	A 100.00d	A 100.00e

Mean for three replications for each treatment; SE: standard error. Lowercase letters indicate significance in columns,Capital letters indicate significance in rows ($P < 0.05$).
Different Lowercase letters within columns indicate significant differences in mortality among the different development stages at different time after treatment for each microwave radiation power (LSD test: $P < 0.05$); Capital letters indicate significance in rows in terms of mortality for each development stages at the same time after treatment exposed to various microwave radiation powers (LSD test: $P < 0.05$).

20 days exposure period. The infestation involved colonies exhibiting various stages of adult females with a waxy covering on their bodies, these specimens were rigorously chosen for the experiments. Three developmental stages of adult females of *D. opuntiae*, was assessed under optimal power and duration conditions that demonstrated non-toxic effects on the cactus pear (as outlined in table 3). Biological trials were conducted employing a completely randomized design (CRD) with three replicates per power and duration for each treatment. Ten adults, ten pre-adults, and ten young females of *D. opuntiae* without wax were individually positioned on cactus pear pieces of identical dimensions with an entomological brush placed in Petri dishes (9 cm diameter) to replicate the pests' natural conditions during treatment and mortality rate assessment. Microwave radiation, emitted by a horn antenna situated at 1cm from the Petri dishes, was applied to the three stages of adult female of the cochineal. The mortality of adult females for the three developmental stages was observed over an 8-day period following treatment, employing a binocular microscope (Motic DM-143). Dead females displayed a distinct dark brown coloration and dehydration of their bodies.

1) STATISTICAL ANALYSIS

All data were analyzed by Genstat (22nd Edition, VSN International, UK) with stage of development of adult females and time after treatments as factors and percentage of mortality as response variables. Analysis of variance (ANOVA two ways) was used to evaluate the main and interaction effects of stage of development of *D. opuntiae* adult females and time after treatments at the same power (as fix factor). Means were compared using Fisher's least significant differences (LSD) test at ($p < 0.05$) and least square means were used for pairwise comparisons of the main factors. In addition, One-way analysis of variance (ANOVA) and Tukey's Test were used to compare the effects of different powers on percentage of mortality at each development stages of cochineal *D. opuntiae* at the same time after treatment, which were considered as fix factors.

2) PEST MORTALITY

The mortality rates of all development stages of *D. opuntiae* adult females using various microwave radiation powers and treatment durations at different time after treatments are presented in Table 4. Mortality of *D. opuntiae* adult females was significantly affected by the exposure interval ($p < 0.001$) at the same radiation powers (Table S1). The interaction of development stages of *D. opuntiae* and time after treatments was significant at 300 W ($p < 0.05$) and highly significant at 375 W and 500 W ($p < 0.001$), respectively. However, this interaction was not significant at 600 W ($p < 0.05$)(Table S1). The total mortality rate reached 100% for young female only 24 h after exposition to 300W applied in 5min. However, using the same power and exposure time needs 120 h and 168 h to reach 100% mortality for pre-adult females and mature adult females, respectively. Similarly, at the power of 375W, the total mortality of the young females and pre-adult females was reached quickly only 24 h after treatment. However, adult female mortality using the same power required longer time to control, reaching 90% mortality, 192 hours after treatment.

For 500 W at 2 min application, the total mortality reached 24 h after application for the young females. This power requires more time (72 h) to kill all the pre-adult females and 144 h to destroy all the mature females. For the highest tested power 600 W applied in 1 min, the total mortality of the young females was reached 96 h after treatment. However, this same power recorded between 70 to 80 mortalities against pre-adult females as maximum, at 96 h and 168 h after application. Surprisingly, this same power reached 96 and 100% mortalities against mature females, 168 and 192 h after treatment. The permittivity values for various stages of *D. opuntiae* indicate that adult females are expected to experience a heightened mortality rate due to their elevated loss factor values, leading to increased thermal energy compared to other stages. However, the experimental results suggest that, among all the tested powers and durations, young females are more sensitive to microwave radiation, while fully grown adults are less sensitive. This sensitivity contrast could be attributed to the smaller thickness of young females compared to other stages, as elaborated in Section II. Storage pests like *Amyelois transitella* (Lepidoptera: Pyralidae) [20], *Callosobruchus maculatus* (Coleoptera: Bruchidae) [55], *Sitophilus oryzae* (Coleptera: Curculionidae [56], [57], and the *R. ferrugineus* [29] exhibit a comparable trend. Larvae, when subjected to dielectric heating, display lower resistance and a shorter lethal time compared to adult.

The comparison of means between mortalities at different tested powers on young females and pre-adult females at the same exposure interval revealed a substantial difference in mortalities only 2 and 24 hours after application (Table 4). However, the statistical analysis using one way ANOVA showed no difference between the tested powers on adult females (mature) at different exposure interval as fix factor. According to (1) the rise in power is a corresponding rise in the thermal energy of the tested material, expected to result in an increased mortality rate. However, the actual results, discovered after a 48-hour treatment period, indicate no significant variance in the mortality rates among various stages of adult females. This observation may be attributed to the correlation between the heightened power level and the reduction in treatment duration.

V. CONCLUSION

The application of dielectric heating for the control of *D. opuntiae* is introduced on cactus plants. The proposed electromagnetic model employs the measured permittivity values. The electromagnetic model is then utilized to simulate the distribution of thermal energy in cactus pear and on various stages of adult females *D. opuntiae* using plane wave as an excitation. The thermal energy distribution indicates that cactus pear is less impacted by microwave radiation compared to the three stages of adult female *D. opuntiae* at the three tested frequencies of ISM band. Notably, the thermal energy distribution highlights that the mature adult female is more sensitive to microwave radiations than the other developmental stages. The experimental findings demonstrate the efficacy of microwave radiation in effectively managing diverse developmental stages of adult *D. opuntiae*. Optimal power levels and durations ensuring no toxic impact on the plant, result in complete mortality across different stages of adult females *D. opuntiae*, with a notable sensitivity observed in young adults to microwave radiations. The increase in power levels correlates with reduced treatment durations, thereby expediting the entire treatment process. Further investigation will explore the complex effects of microwave radiation on the fertility, DNA damage, hatching of eggs, weight, growth, and feeding behaviour of adult female *D. opuntiae*. This research will also provide a novel approach to pest management.

ACKNOWLEDGMENT

This work was supported by the Mohamed VI Polytechnic University.

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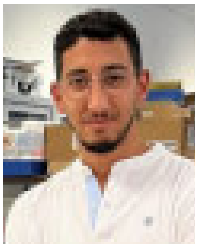
FATIMA ZAHRAE EL ARROUD (Student Member, IEEE) received the bachelor's degree in electronics and the M.Sc. degree in telecommunication systems engineering from Abdelmalek Essaâdi University, Tetouan, Morocco, in 2018 and 2020, respectively. She is currently pursuing the Ph.D. degree with the Department of Microwave Energy Sensing (MES), Digital Innovation Center of Excellence (DICE)-University of Mohammed VI Polytechnic, Benguerir, Morocco. In 2020 She held a position as a Research Assistant with the Information and Telecommunication Systems Laboratory (LaSIT), Faculty of Sciences, Tetouan.

KARIM EL FAKHOURI is a former entomology with the International Center for Agriculture Research in the Dry Areas (ICARDA), from 2014 to 2021. He is currently an Assistant Professor with the College of Agriculture and Environmental Sciences, Mohammed VI Polytechnic University, Morocco. He works on the development of IPM options to control the main insect pests using a combination of genetic resistance, cultural practices, botanical insecticides with new formulations, and biological control. He teaches a variety of entomological topics for both master's and Ph.D. students, including introduction to entomology, host plant resistance, integrated pest management, and semiochemicals. To date, he has authored 25 publications, two patents, and more than 40 presentations. He was a recipient of the CGIAR Borlaug Fellowship Program, in 2018, working on pheromones to control tree fruit insect pest in the laboratory and field at Michigan State University. From 2019 to 2021, he was awarded again with a new research grant for continuation and extension of the Norman E. Borlaug Fellowship Research Program in collaboration with Michigan State University focusing on semiochemical research to control faba bean stem borer Lixus algirus in Morocco.



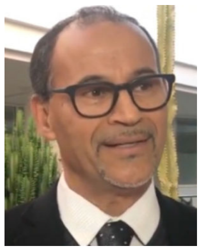
YOUNESS ZAAROUR (Student Member, IEEE) received the bachelor's degree in electronics from Cadi Ayyad University, and the M.Sc. degree in electronics and telecommunication from Abdelmalek Essaâdi University, Morocco, in 2018 and 2020, respectively. He is currently pursuing the Ph.D. degree with the Microwave Sensing and Energy (MES) Department, University Mohammed VI Polytechnic (UM6P), Benguerir, Morocco. In 2020, he held a position as a Research Assistant at the Information and Telecommunication Systems Laboratory (LaSIT) Department, Faculty of Sciences, Tetouan, Morocco. He is currently working in monitoring biological microwave sensors. He has been awarded the Erasmus + Mobility Grant. Additionally, he has actively participated in numerous conferences and has been recognized for his exceptional contributions, receiving four gold medals in different categories, including medical and agricultural applications.

CHAIMAE RAMDANI received the bachelor's degree in bioengineering and the M.Sc. degree in experimental technique and methodologies in biotechnology from the Faculty of Science and Technology of Tangier, Morocco, in 2011 and 2013, respectively, and the Ph.D. degree in entomology from the International Center for Agricultural Research in the Dry Areas (ICARDA)/University Ibn Tofail Kénitra, Morocco, in 2022. In 2023, she joined the AgroBioSciences Program, College of Agriculture and Environmental Sciences, Mohammed VI Polytechnic University, Morocco, where she is currently a Research Engineer.

HAFID GRIGUER (Member, IEEE) received the master's degree from the University of Metz, in 2005, and the Ph.D. degree in microelectronics from the National Institute of Applied Sciences, Rennes, in 2010. He is currently the Vice Director of the Digital Innovation Center of Excellence (DICE), Mohammed VI Polytechnic University, Morocco. His work spans digital industrialization, developing innovative sensor and microwave antenna concepts for industrial and medical use. An inventor holding multiple patents, he has authored numerous articles and book chapters. He is a member of the IEEE for contributing significantly to the field of electronic systems engineering.

MARIAM AZNABET (Member, IEEE) received the M.Sc. and Ph.D. degrees in telecommunication engineering from the Public University of Navarre, Pamplona, Spain, in 2008 and 2009, respectively, and the D.E.S.A degree in telecommunications systems from Abdelmalek Essaâdi University, Tetuan, Morocco, in 2005. She is currently a Professor of Electronics and Telecommunications at Abdelmalek Essaadi University. Her current research interests include metamaterials and frequency-selective surfaces.

RAFIQ EL ALAMI received the Engineering degree from Ecole Mohammadia d'Ingénieurs and a joint MBA from UM6P/Columbia University. He is the Director of the Digital Innovation Center of Excellence (DICE), DICE is a center that collaborate with all UM6P's departments to apply digital technologies (big data, AI, crowd sourcing, mobility) to accelerate research and innovation. Before Joining UM6P Rafiq has spent 18 years in different management positions at Microsoft, USA.



MUSTAPHA EL BOUHSSINI received the Ph.D. degree in entomology from Kansas State University. He is currently a Professor of entomology and the Head of the Biodiversity and Plant Sciences Program, Mohamed VI Polytechnic University. Since 2005, he has been an Adjunct Professor with Kansas State University. He was a Principal Entomologist with the International Center for Agricultural Research in the Dry Areas (ICARDA) for 24 years. He has received several awards, including the Lifetime Achievement Award for Plant Resistance to Insects from the International Plant Resistance to Insects Association (IPRI), in 2018, and the Scientist Award from the International Branch of the Entomological Society of America, in 2014.