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Review article

Dielectric heating for controlling field and storage insect pests in host plants and food products with varying moisture content

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ABSTRACT

At the intersection of insect control and sustainability goals, dielectric heating emerges as a promising solution. In agriculture, where insect pests can reduce agricultural yields and the nutritional quality of crops under field and storage conditions. Chemical pesticides are often used to manage pests but owing to their deleterious consequences on humans and the environment, chemical-free treatments have become the preferred option. Among the existing options, applying radio frequency (RF) and microwave energy for the purpose of dielectric heating has proven to be a successful alternative to chemical pesticides for controlling some major insect pests. This review offers an overview of dielectric heating for pest control in both storage settings and field environments, which addresses pests that impact materials with varying moisture contents (MC). The review highlights the limitation of this technology in controlling insect pests within bulk materials, leading to non-uniform heating. Additionally, it discusses the application of this technology in managing pests affecting materials with high MC, which can result in the degradation of the host material's quality. The review suggests the combination of different techniques proven effective in enhancing heating uniformity, as well as leveraging the non-thermal effects of this technology to maintain the quality of the host material. This is the first review providing an overview of the challenges associated with employing this technology against high moisture content (MC) materials, making it more advantageous for controlling storage pests. Overall, the review indicates that research should particularly emphasize the utilization of this sustainable technology against insect pests that inflict damage on high (MC) substances.

1. Methodology

This review employed bibliometric analysis using Scopus, Google Scholar, and Web of Science databases to assemble data. The search, based on keywords such as "Radio frequency and microwave heating," Complex permittivity," and "Dielectric heating and insect control," yielded 695 publications. These comprised articles (89.928 %), reviews (9.496 %), proceedings papers (4.317 %), preprints (0.576 %), meeting abstracts (0.432 %), book chapters (0.288 %), and editorial materials (0.144 %). Network analysis, including with frequently used keywords, was performed using VOSviewer processing software, revealing relationships among keywords, and

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Abbreviations

RF	Radio frequency
MC	Moisture content
FAO	Food and Agricultural Organization
EMW	Electromagnetic Wave
VNA	Vector Network Analyzer
NRW	Nicolson–Ross–Weir
PV	Peroxide Values
FA	Fatty Acid
dp:	Penetration depth
FFA:	free fatty acid
J	Joule
RPW	Red Palm Weevil

offering a comprehensive overview of current dielectric heating research for pest control (illustrated in Fig. 1-c).

The analysis also facilitated an examination of research significance. The leading countries in publishing the relevant articles were categorized, with the USA having the highest number (150), followed by China (80) and Italy (70), as shown in Fig. 1-a. The publication trends showed a significant increase from 2017 to 2019 and a slight decrease from 2018 to 2019, followed by a subsequent rise between 2019 and 2021. The peak of publications in 2021, from 2004 to 2023, indicates a growing interest in the topic, as depicted in Fig. 1-b.

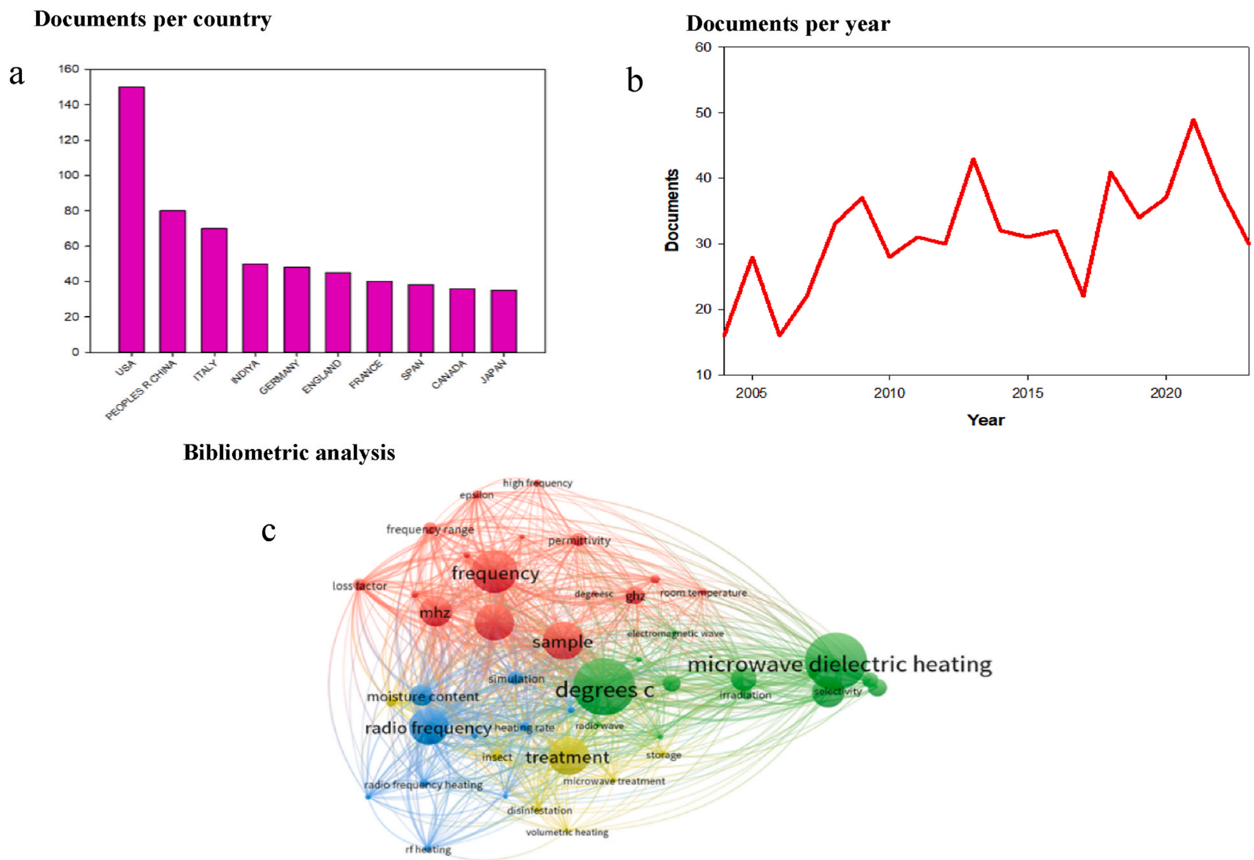


Fig. 1. (a) The leading countries in publications on dielectric heating for pest control, (b) number of publications per year, and (c) bibliometric network of keywords in publications on dielectric heating for pest control.

1.1. Inclusion and exclusion criteria

Full-text research articles published in the referenced databases that evaluated the use of dielectric heating for pest control, reported positive results, and addressed the quality of the host material after treatment up to the end of 2023 were eligible for inclusion in this systematic review. Studies were excluded if they: (1) did not test the selectivity of dielectric heating, (2) were literature reviews, meta-analyses, books, unpublished articles, doctoral theses, commentaries, abstracts of conferences and congresses, or case reports, (3) were not written in English or French, or (4) were not quantitative studies.

1.2. Data extraction

Data extraction for this systematic review began with 695 studies selected from the largest reference databases. After removing duplicates, 405 relevant reports remained. Titles and abstracts were then reviewed by two independent investigators according to inclusion and exclusion criteria. In cases of disagreement or uncertainty, a third researcher was consulted. This process resulted in the exclusion of 308 studies that did not meet the inclusion criteria. In the end, 97 studies were included in the systematic review. All authors approved all included articles, with no conflicts between them.

During the data extraction, the risk of bias was assessed for each study. Notably, there was a risk of publication bias in the current study. Impact of electromagnetic radiations on the mortality and fertility of the insect pest and on the quality of the host material were the primary outcomes, and the used system for dielectric heating was considered the secondary outcomes of the study.

2. Introduction

Agricultural pest management is a crucial aspect of modern farming, essential for safeguarding crops from insect pests that significantly reduce crop quality and yields. According to a 2021 report by the Food and Agricultural Organization (FAO) [1], pests are responsible for destroying up to 40 % of global crops, resulting in losses of approximately $220 billion. While chemical pesticides have traditionally been the main method for insect management, their negative impacts on human health and the environment, along with the growing issue of insect resistance, highlight the urgent need to develop alternative insect control strategies.

Dielectric heating has been found to be an effective and chemical-free method for controlling insect pests in storage settings and field insects that affect low-MC materials [2–4]. The industrial, scientific and medical (ISM) bands from RF to microwave have been allocated by the US Federal Communications Commission (FCC) to avoid electromagnetic interference [4,5]. Interaction of electromagnetic radiation with a dielectric material cause the ions and polar molecules of the dielectric material to move and rotate, which leads to heating of the material [4]. The dielectric heating effectiveness is determined by dielectric properties which determine whether the pest or the host material will be more affected by the heating process [6]. These properties are characterized by the real part (ε'), which indicates a material's ability to store electrical energy, and the loss factor (ε''), which measures the conversion of electrical energy to thermal energy [7]. Dielectric properties determine whether the pest or the host material will be more affected by the heating process. Materials with a high dielectric loss factor are more affected by electromagnetic radiation [8]. The optimum frequency for a dielectric heating system is within the ISM band, where the insect's loss factor is higher than that of the host material, to ensure selective treatment. Several studies have been conducted using various measuring techniques for agricultural materials' dielectric characteristics, including the coaxial probe method [9], free space technique [10] and rectangular waveguide technology [11]. The choice between these techniques is determined by the frequency, the accuracy needed, the temperature, the nature of the material, the sample size/thickness, the cost, and whether there is contact or no contact, destruction or no destruction [12].

This technology is not fundamentally new for pest control, and it was previously studied and reported since the 1930s [13]. It has been suggested as a substitute for chemical fumigation for pest management in postharvest agricultural production, including against insect pests of walnut in storage settings [3,14–17] as well as the cowpea weevil (*Callosobruchus maculatus*), Indian meal moth (*Plodia interpunctella*) [18], and rice weevil (*Sitophilus oryzae*) [19,20]. Furthermore, microwave and RF heating have been investigated as nonchemical alternatives for controlling field insect pests, including the red palm weevil *Rhynchophorus ferrugineus* [2,4,21–23] and the African bollworm *Helicoverpa armigera* [24–26].

The main objective of this review is to supply a complete understanding of the current state of research on the use of dielectric heating for the management of insect pests in storage settings and field pests. Furthermore, the paper aims to provide an in-depth assessment of the applicability of dielectric heating for insect control in materials of both low and high moisture content (MC), to illuminate the challenges that researchers have encountered when utilizing this RF technology and to provide a potential solution for applying dielectric heating to materials with high levels of moisture.

3. Different methods for dielectric characteristics measurement

The interaction of an external electromagnetic wave with the material under test is demonstrated by the dielectric characteristics of materials, namely, permittivity [27].

These Incident waves undergo scattering, refraction, reflection, and absorption, their behaviors predicted by measuring the dielectric characteristics of the material [28]. Understanding these characteristics is fascinating for microwave based methods such as insect disinfestation heating [20,22] and remote sensing systems, offering plant identification [28,29] or determine the water needs of plants [30,31] based on crop permittivity during EM wave interaction.

Several methods, resonant and no resonant, exist for measuring dielectric characteristics using microwave theory. No resonant methods provide an overall understanding across frequencies, while resonant approaches offer precise insights at discrete frequencies [32,33]. Coaxial probes, rectangular waveguides, and free space are the most commonly used techniques for assessing the dielectric properties of agriculture and food commodities [34], each with distinct advantages and disadvantages (Table 1). Coaxial probing, is employed in dielectric heating studies for insect and host material characterization [34–37] Additionally, rectangular waveguide(RW) technique has been applied to characterize various plant types for remote sensing applications [29,30,38–41]. Given that most biological and agricultural crops exhibit minimal magnetic field reaction, the complex permeability μ can often be approximated by the magnetic permeability of free space μ_0 [31,42].

3.1. Coaxial probe

The probe method was developed by Stuchly (1980) [43]. The approach has the benefits of being nondestructive, requiring minimal sample preparation, and minimizing sample disruption [44]. It also offers broadband measurements and may be used to determine the dielectric characteristics of liquid, semisolid, and solid materials with a high loss tangent (loss tangent>0.5) [45]. This technique is based on the measurement of the reflection coefficient at the tip of a coaxial cable in contact with the substance being tested (Fig. 2-a) [36]. The sample permittivity relates to the observed phase and amplitude of the reflected signal (S11) [44], and the dielectric probe kit software has helped in data collection and permittivity calculations [35]. According to an assessment of waveguide and coaxial probe techniques in Ref. [46], the coaxial probe approach is significantly more accurate, simpler to use, and more timesaving than the waveguide transmission/reflection technique (Table 1).

3.2. Rectangular wave guide method

A form of transmission line technology is the rectangular waveguide method. It is a destructive process, the waveguide's dimensions must match that of the MUT, and contact between the two is needed [12] Therefore, if there is an air gap between the sample and the waveguide, the results will be greatly inaccurate [47]. These factors, along with the limited band of this approach, favor coaxial probe and free space techniques over transmission line techniques (Table 1). The fundamental advantage of the rectangular waveguide is the close communication between the EMW and the sample without external interference. It is necessary to place the material between the two waveguides (Fig. 2-b), which will be subjected to the EMW produced by the vector network analyzer (VNA) [27]. Several methods, including the Nicolson–Ross–Weir (NRW) [30] and new noniterative transmission and reflection methods [48], might be used to calculate the sample permittivity from the measured phase and amplitude of the transmission coefficients (S11 and S22) and reflection coefficients (S12 and S21). The conventional and widely used NRW approach [28] uses equations (4)–(6) to calculate the dielectric constant as a complex number [48].

$$\varepsilon_r = \left(1 - \frac{\lambda_0^2}{\lambda_c^2}\right) \times \left(\frac{\lambda_{0g}}{\wedge}\left(\frac{1-\Gamma}{1+\Gamma}\right)\right) + \frac{\lambda_0^2}{\lambda_c^2 \times \left(\frac{\lambda_{0g}}{\wedge}\left(\frac{1+\Gamma}{1-\Gamma}\right)\right)} \quad (4)$$

$$\frac{1}{\wedge} = -\left(\frac{1}{2\pi L}\ln\left(\frac{1}{T}\right)\right)^2 \quad (5)$$

$$\lambda_{0g} = \frac{1}{\sqrt{\frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2}}} \quad (6)$$

Table 1
Comparison between different techniques for permittivity measurement.

Technique	Parameter	Frequency range	MUT type	Advantages	Disadvantages
Waveguide	ε, μ	Narrow	Solid	- Direct contact between the MUT and the EMW - Gives permittivity and permeability of the MUT	- Can be used only for solid materials. - Sample preparation (destructive) - Measurement at narrow band - A small air gap between the MUT and waveguide aperture will affect the obtained results.
Coaxial Prob	ε	Large	Solid, semi solid and liquid	- Can be used for different material types - No sample preparation is needed (Nondestructive) - Measurement at large frequency band	- A small air gap between MUT and tip of the coaxial probe affects the obtained results
Free space	ε	Large	Solid	- No sample preparation is needed (Nondestructive) - Measurement at large frequency band	- Interference of the EMW with the surroundings

MUT: Material under test, EMW: electromagnetic wave.

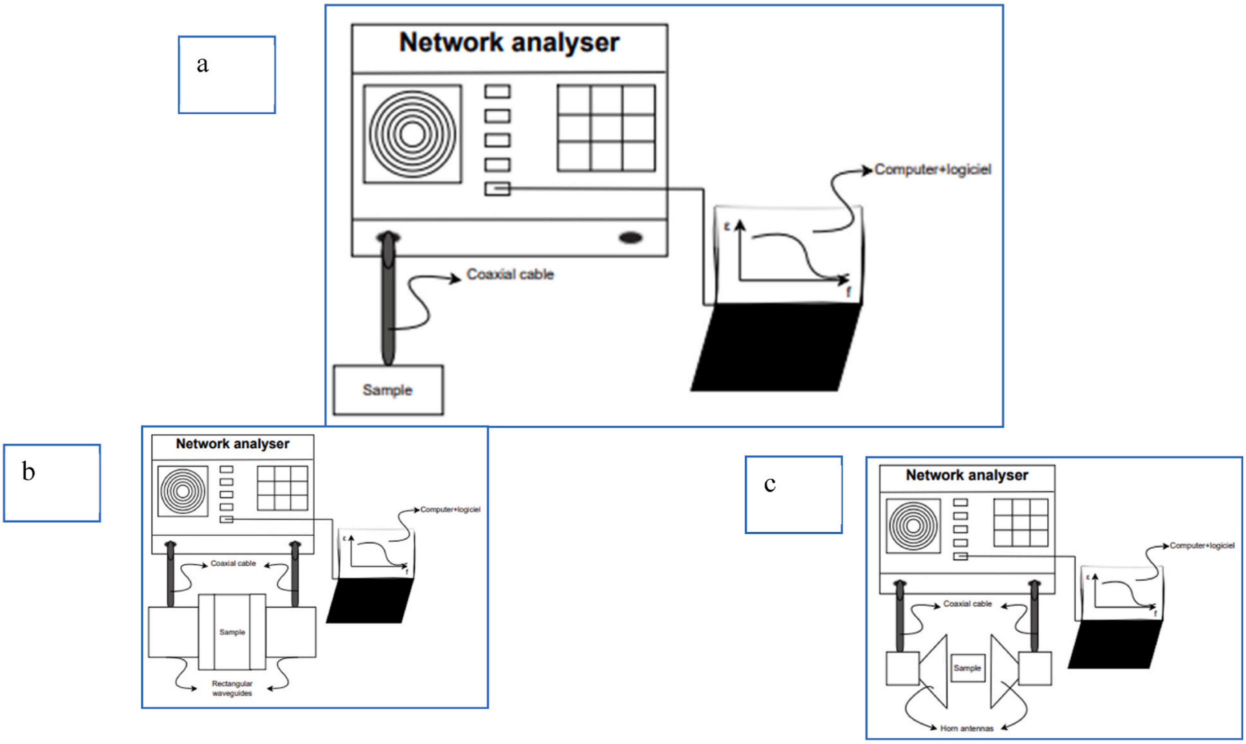


Fig. 2. Three distinct procedures for permittivity measurement (a) coaxial probe, (b) rectangular waveguide, (c) free space.

where λc is the waveguide cutoff frequency, L is the sample thickness, T is the transmission coefficient and Γ is the reflection coefficient.

3.3. *Free-space technique*

The free-space method, comparable to coaxial probing, has the benefit of being a nondestructive technique for determining the dielectric properties of materials across a broad frequency and temperature range. Nevertheless, it permits reflection and transmission measurements without having direct contact with the material [49]. However, only the reflection coefficient may be obtained from the coaxial probe in direct contact with the sample [32]. Using the free-space transmission method, in the experimental setup illustrated in Fig. 2-c, a sample is positioned between a transmitting and a receiving antenna, and both the attenuation and phase shift are quantified [50]. The material measurement program has the capacity to ascertain the inherent electromagnetic characteristics of several dielectric and magnetic materials using the observed [S] parameters by the vector network analyzer (VNA) [32]. Numerous types of biological materials, such as almonds [51], cactus and wheat [50], have been characterized using this method.

The main limitations of this technique are interference of the EM wave with the surroundings, reflections within the sample, and interference between the sample and the antennas. This can be mitigated by using horn/lens antennas that generate a plane wave near the transmitting antenna [52]. Because of the lens, the technique is quite costly. In contrast, a permittivity measurement may be performed across a large frequency and temperature range without the need for sample preparation on a variety of materials, including solid, semisolid, and liquid (Table 1). This explains the more common use of the coaxial probe than the free-space approach.

4. Dielectric heating principles

Dielectric heating uses two types of high-frequency electromagnetic waves: RF, or capacitive heating, and microwave, or radiated heating. These waves occupy adjacent regions within the electromagnetic spectrum, with microwave exhibiting higher frequencies than radio waves. They travel at the speed of light, are reflected by metal, are propagated through materials with electrical neutrality and are absorbed by materials with electrical charge. This absorption by electrically charged materials, such as biological materials like agricultural crops, results in the generation of heat [53,54].

Dielectric heating operates by converting electromagnetic energy to thermal energy through the sustained high-speed mobility of ions and dipoles [54,55]. Electrical valves are used in RF systems to generate electromagnetic energy, which is subsequently transmitted via transmission lines, where electrodes (capacitors) are utilized as applicators. On the other hand, for power generation, microwave systems use magnetrons that flow via a waveguide to be radiated or applied to cavities [53].

Biological materials consist of polar molecules and ions. When these molecules and ions are exposed to an electric field, dipolar polarization occurs, with bipolar molecules rotating to align with the electric field direction, and ionic conduction also occurs, with ions flowing back and forth in the direction of the electric field (Fig. 3) [56,57]. The concept behind using this technique for pest control is that it can kill insects without any harmful effects on the host material, a balance that is possible to achieve because of the value of the insect's loss factor compared to that of the host material, as demonstrated in numerous studies [3,15,20,58,59].

Dielectric properties are vitally important in the dielectric heating of organic substances. The dielectric constant (ε') and the dielectric loss factor (ε'') characterize these properties, with ε' illustrating a material's electromagnetic energy storage capacity. Additionally, ε'' is connected to the dissipation of electromagnetic energy (EM), indicating a material's proficiency in converting this energy into heat [56]. The dielectric properties of insects and plants are used to identify which materials will absorb the most energy and produce the most thermal energy during dielectric heating [60]. According to Eq. (1), the power that characterizes the heat energy generated from EM energy is proportional to the applied frequency (f), loss factor (ε'') and electric field $\left(E^2\right)$ [53].

$$Q = 5.563 \times 10^{-11} \text{ f } \varepsilon'' E^2 \tag{1}$$

The electric field strength and frequency remain constant in materials with higher loss properties, which produce a greater amount of thermal energy compared to those with lower loss properties [56]. Moreover, the thermal energy generated by the same dielectric material could be enhanced by increasing the frequency or the applied electric field [61]. If the exposure period or applied power were increased, a higher temperature might be obtained with the same material.

The penetration depth at which the power decreases by 1/e or 36.8 % of its transmitted value is expressed as:

$$d_p = \frac{c}{2\pi f \sqrt{2\varepsilon' \left[\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1\right]}} \tag{2}$$

where f is the frequency and (ε') and (ε'') represent the real and imaginary components of the relative permittivity. The wavelength in RF ranges from 22 to 360 times longer than that of microwave frequencies [8], which makes it a preferred option for pest control in bulk materials such as grain because of the low dp at low frequencies, as indicated in Refs. [3,15,20,58,59,62,63]. However, the greatest challenge in employing RF radiation for insect control is the inevitable nonuniform heating, as reported in Ref. [64]. The index measuring the uniformity of heating in the material under test is suggested by Ref. [65] as:

$$\lambda = \frac{\Delta\sigma}{\Delta\mu} \tag{3}$$

where $\Delta\sigma$ denotes the elevation in the standard deviation (SD) of the product temperature, while $\Delta\mu$ indicates the mean product temperature throughout the treatment period. A small λ value represents a uniform heating. Various studies have concentrated on improving uniformity through the utilization of hot air, crop mixing, movement, mixing and rotation [18,64,66]. Table 2 compares multiple methods for uniformly heating biological tissues with RF radiation.

All the employed techniques can be utilized to improve heating uniformity, but using a rotation device as a sample container or mixing the material during RF treatment is particularly effective in achieving the lowest value of λ (Table 2). The size of the material being evaluated might impact the heating uniformity index; for example, the heating uniformity index of whole walnut kernels was approximately 0.12, while that of cracked kernels was approximately 0.08 [44]. The same findings were obtained according to Ref. [42] when the rotating device was utilized to increase the heating uniformity of various samples of granular foods by 16 r/min. The smallest diameter for mung beans had the best RF heating uniformity [42].

5. Dielectric heating for insect control

The investigation of dielectric heating, utilizing both RF and microwave, aims to manage one of the most damaging field insect

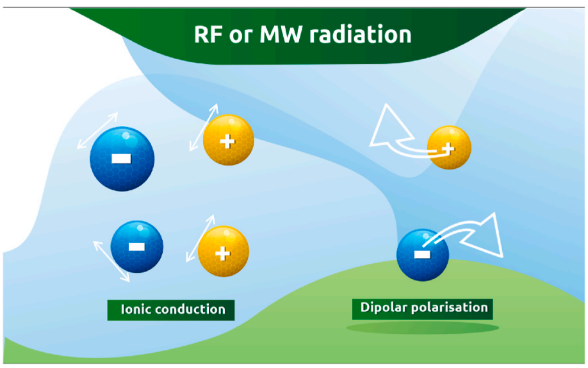


Fig. 3. Ions and dipolar molecules under radio frequency and microwave mechanisms.

Table 2
Comparison of different techniques to improve heating uniformity for insect control in storage settings using radio frequency technology.

Host Material	Technique for λ improvement	F(MHZ)	P(KW)	λ (RF)	λ (RF + technique)	λ IMPROVEMENT (%)	ref
Coix seed	Rotation device as sample container	27.12	6	0.135	0.015	12	[67]
Milled rice	Mouvement:	27.12	6	0.168	0.118	5	[68]
	X direction			0.168	0.132	3.6	
	Y direction			0.177	0.132	4.5	
	Z direction						
Milled rice	Mixing (15s*2)	27.12	6	0.174	0.05	12.4	[68]
Lentil	Hot air	27	6	0.079	0.068	1.1	[18]
Lentil	Movement	27	6	0.079	0.077	0.2	[18]
Lentil	Hot air + movement	27	6	0.079	0.061	1.8	[18]
Lentil	Hot air + movement + mixing	27	6	0.079	0.086	–	[18]
Mung bean	Hot air	27	6	0.096	0.069	2.7	[66]

RF: radio frequency.

pests [69]. RF heating follows the same concept as microwave heating but uses different electromagnetic frequencies. In the 300 MHz to 300 GHz microwave spectrum, only 0.915 GHz, 2.45 GHz, 5.8 GHz, 24.125 GHz were employed for industrial purposes. The most common RF frequencies are approximately 13.5, 27, and 40 MHz [16]. There is a general consensus that the impact of RF and microwave radiation are mostly thermal in nature [70]. Materials, including agricultural commodities, are able to preserve electric energy from RF or microwave radiation and transform it into thermal energy [71]. The thermal energy generated by a dielectric substance at a particular frequency and electric field relies on the loss factor (Equation (1)) [6].

5.1. *Insect pests in storage settings*

Insect pests in storage settings reduce agricultural product quality directly via feeding damage and indirectly via the production of webbing and frass. Annual estimates indicate losses of cereal grains of around 10 % in North America and potentially reaching 50 % in Africa and Asia [72]. Losses occur both preharvest in the field and during storage (postharvest) [73]. Mycotoxins, fungi, and insect fragments threaten grain quality.

Pesticides, fumigants, heat, cold, and mechanical pressure have been used to control insects in postharvest products such as grains, nuts, and fruits. The first two approaches, which are unfortunately extremely widespread, constitute an immediate risk to human wellness and the ecosystem, and the latter three are time-consuming and laborious. However, the use of heat with RF radiation or microwaves while keeping the host grain at ambient temperature remains one of the best approaches to control insect pests in storage settings, as there are no deleterious impacts on the host material physicochemical qualities. When dry grain and insects are heated, insects reach the lethal temperature due to their higher water content compared to the host material, while dry grain contains less water than the insect body, making the grain amenable to many of the available technologies based on the heating principle either through RF radiation or microwaves at specific frequencies, powers, and times of exposure [74,75]. When addressing storage pests in

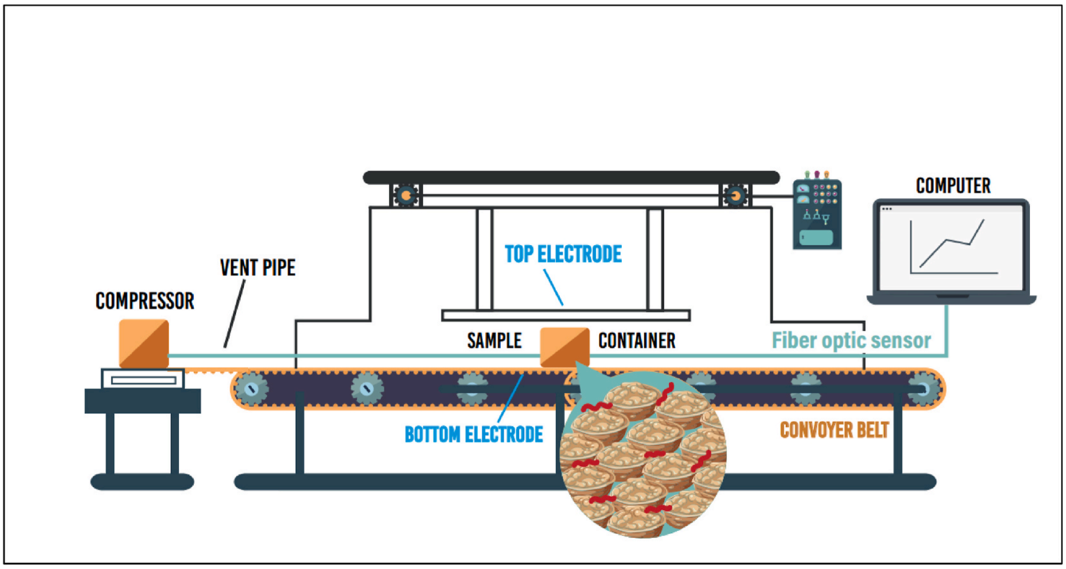


Fig. 4. A schematic view of the experimental radio-frequency device (COMBI 6-S, Strayfield International Limited, Wokingham, UK) used to control *A. transitella* in walnuts.

high moisture content fruits, it's common to observe a degradation in the quality of the fruits after treatment [76].

5.1.1. Navel orangeworm (Amyelois transitella [Walker])

The navel orangeworm (*Amyelois transitella* (Walker)) (Lepidoptera: Pyralidae) is a primary pest of almonds, pistachios, and walnuts in California [77]. Its host plants also include carob, figs, oranges, grapefruit, and others [78]. This insect is known to cause considerable damage to nut during storage, making them unsuitable for consumption or sale (Fig. 6-b). Approximately 80 % of the world's almonds, 24 % of pistachios, and 29 % of walnuts are grown in the United States, predominantly in California, where this insect often inflicts major economic damage [78,79]. For nuts, *A. transitella* larvae (Fig. 6-a) are a significant secondary pest of walnuts because they lack the ability to breach the husk or shell of the nut and instead rely on previous larval feeding entrances produced by *Cydia pomonella* [80]. As a result, there is limited resistance or tolerance possible against *A. transitella* infestation, and many farmers plan on a 2 % crop damage loss from this insect. Currently, integrated pest management of *A. transitella* in the field incorporates a combination of orchard cleaning, strategically-timed insecticide applications, timely harvest, and, notably, mating disruption, which was introduced recently, in addition to the sterile insect approach [77]. Currently, phosphine is the primary postharvest treatment against this pest [81,82]. Many researchers have presented a new and sustainable strategy employing RF and microwave heating interventions as substitute quarantine treatments against *A. transitella* in nuts. According to Ref. [3], third- and fifth-instar larvae and pupae of *A. transitella* on unshelled walnuts were heated to 48 °C, 50 °C, 52 °C, and 55 °C using an RF experimental-scale setup (Fig. 4) at 27 MHz (6 kW). According to the findings, the fifth instar exhibited the highest heat resistance among *A. transitella* life stages (Table 3). This is due to the fifth instar larvae having a lower loss factor than larvae of earlier instars or to its low MC. When the larvae were heated to 55 °C for 5 min, 100 % fifth instar mortality was achieved. Third instar and pupae mortality, on the other hand, reached 100 % after only 4 min of exposure at 52 °C.

The two key markers of walnut quality are peroxide values (PV) and fatty acid (FA) values; walnuts of a good grade should have PV and FA levels less than 1.0 mEq/kg and 0.6 %, respectively. A comparison between the walnuts used as the control and the walnuts exposed to RF treatment in terms of their PV, FA and MC values is mentioned in Table 4. The results showed that RF treatment was capable of achieving 100 % mortality in *C. pomonella* while preserving the quality of the walnuts (Table 4) [3]. This is because the insect is characterized by a larger permittivity and loss factor than the host material, allowing it to absorb more energy and create a high heat rate (Table 5).

The use of an industrial-scale radio frequency system (Fig. 4) effectively controlled *A. transitella* in walnut. 100 % of fifth instar larvae mortality was reached when the kernel and shell temperatures were approximately 58 °C and 61 °C, respectively (Table 6), whether this radiation was employed after sizing (option 1) or air drying (option 2) (Fig. 5). Additionally, with FA and PV values of less than 0.6 % and 1 mEq/kg, respectively, walnut quality remained unchanged even after up to 20 days of storage [15].

The findings of these investigations show that RF treatments have the potential to be a successful method for controlling *A. transitella* in stored walnuts at the industrial scale. It offers an appropriate strategy for insect control without compromising the quality of these nuts (Table 7) while also lowering the need for hazardous chemical pesticides.

5.1.2. Cowpea weevil (Callosobruchus maculatus)

The cowpea weevil *Callosobruchus maculatus* (F.) (Coleoptera: Chrysomelidae) (Fig. 8-b), represents a significant menace to economically crucial leguminous grains in the field and in storage settings. This pest is found worldwide but is considered endemic to Africa and Asia [86]. Infestation by *C. maculatus* frequently starts in the legume pods, and during the storage period, female weevils affix their individual eggs to the surface of the seeds. When the eggs hatch, the larvae enter the seed, where they complete their whole life cycle.

The feeding activity of *C. maculatus* larvae on seeds causes reduced seed density, lower germination rates, and compromised nutritional value. Heavily infested seeds become unsuitable for human consumption (Fig. 8-a), leading to significant economic losses [87]. In Nigeria, an approximate 3 % loss in annual production during the 1961/62 period resulted from the infestation of *C. maculatus* [88]. To protect stored legume seeds from *C. maculatus* attacks, conventional insecticides are employed by farmers. However, this approach has significant drawbacks, including adverse effects on nontarget species, negative impacts on the preservation of the ecosystem and the evolution of resistance in pests [87,89]. Dielectric heating is employed to address the issue of this pest infestation in black gram beans [90]. The treatment involves using a 10 kW RF system operating at 40.68 MHz, which consists of a generator linked to an applicator designed to deliver precise and controlled RF energy to the samples. The used system is equipped with two parallel rectangular electrodes in a flat-plate configuration intended to hold the sample in between the electrodes (Fig. 7-a). In addition to the RF system, an industrial-scale 2900W microwave dryer system (Fig. 7-b) is also used to control this pest. This microwave system utilizes two powerful magnetrons, generating high power levels for effective treatment. The power cables guides the RF energy to the

Table 3
Mortality in three life stages of *A. transitella* after radio frequency heating at different exposition times with an input power of 0.8 KW.

Temperature + holding time (Power)	Third instar	Fifth instar	Pupae	Ref
48 °C + 25 min (0.8 KW)	87.4	26.5	27.9	[3]
50 °C + 10 min (0.8 KW)	97.6	38.0	59.3	[3]
52 °C + 4 min (0.8 KW)	99.8	73.5	98.2	[3]
55 °C + 5 min (0.8 KW)	–	100	–	[3]
55 °C + 10 min (0.8 KW)	–	100	–	[3]

Table 4
Impact of radio frequency energy on quality factors in unshelled walnuts after 20 days at 30 °C storage.

Treatment	PV (mEq\kg)	FA (%)	MC (%) Kernel	MC (%) Shell	Ref
Walnut without treatment	0.64	0.21	2.6	7.8	[3]
Treated walnut with RF (55 °C + 5 min)	0.37	0.22	2.2	7.1	[3]
Treated walnut with RF (55 °C + 10 min)	0.36	0.15	2.4	7.7	[3]

PV: Peroxide values, FA: fatty acid, MC: moisture content.

Table 5
Walnut kernel and *A. transitella* larvae dielectric loss factors at microwave and radio frequencies at 20 °C.

Material	Frequency (MHz)				Ref
	27	40	915	1800	
Walnut kernel	0.26	0.7	2.9	1.8	[83]
A. transitella larvae	307	212.6	16	12.7	[83]

Table 6
Mortality of fifth instar *A. transitella* larvae and final kernel and surface temperatures of walnuts before and after RF treatment.

	Kernel Temperature (°C)		Surface temperature (°C)		5th instar larvae mortality		Ref
	Control	RF	Control	RF	Control	RF	
Unwashed walnuts (Option 1)	24	58	24	63	0 %	100 %	[15]
Hot air-dried walnuts (Option 2)	27.5	59	26.5	64	0 %	100 %	[15]

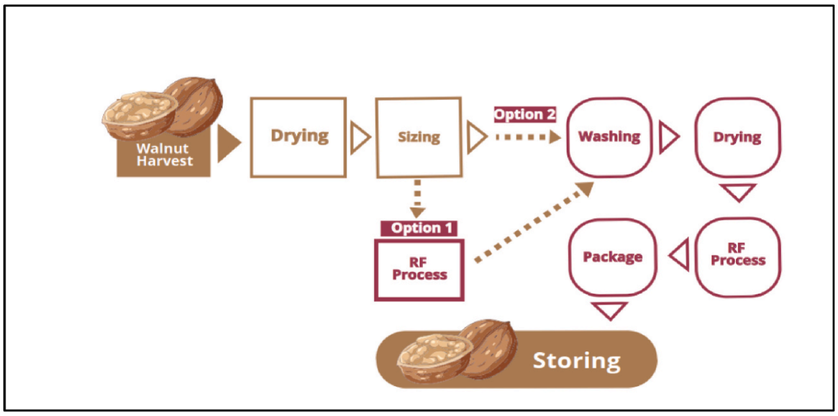


Fig. 5. Two settings for the application of radiofrequency treatment to control *A. transitella* larvae in unshelled walnuts.

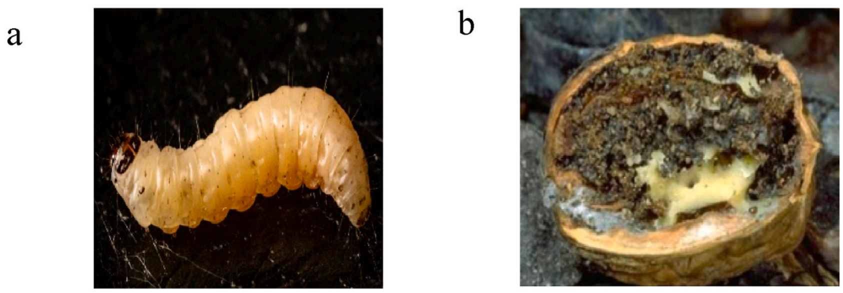


Fig. 6. (a) Larvae of *A. transitella* (b) damage caused by *A. transitella* in walnut [84,85].

Table 7
Chemical and physical characteristics of unshelled walnuts before and after RF treatment.

Quality factors	PV (mEq\kg)		FA (%)		MC (%) Kernel		MC (%) Shell		Ref
	Control	RF	Control	RF	Control	RF	Control	RF	
Option 1	0.71	0.86	0.20	0.20	3.2	3	7.2	6.3	[15]
Option 2	0.74	0.82	0.23	0.22	3.3	3	7.4	6.4	[15]

PV: peroxide values, FA: fatty acid, MC: moisture content.

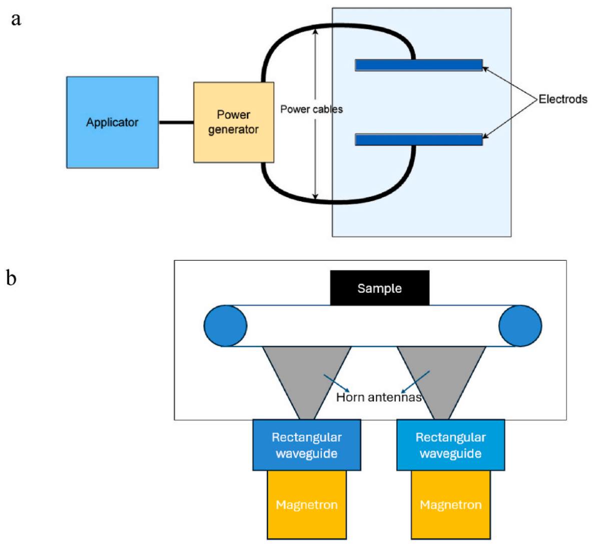


Fig. 7. Schematic view of (a) radio frequency (40.68 MHz; Make: Lakshmi Insta 10/4) and (b) microwave pilot scale systems (Make: Enerzi MW system; Model: PTF 2515) used for *C. maculatus* control in black gram beans.

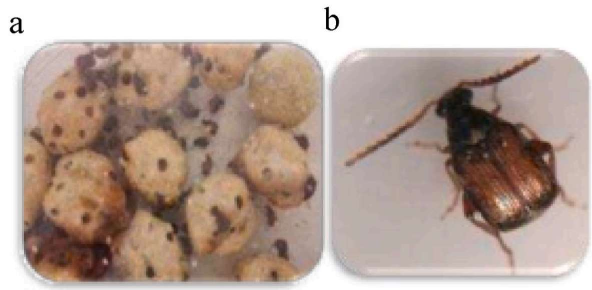


Fig. 8. (a) Seeds infested by *C. maculatus* (b) Adult *C. maculatus* [91].

Table 8
Required treatment time to achieve lethality for complete disinfestation of the *C. maculatus* life stages exposed to radio frequency (RF) and microwave radiation.

Treatment type	Life stages	Lethal time (min)	Ref
Radio frequency (40.68 MH) 365W	Egg	3.62	[90]
	Larvae	5.64	
	Pupae	6.28	
	Adult	5.35	
MICROWAVE (2.45 GHz) 230 W	Larvae	9.82	[90]
	Pupae	10.68	
	Adult	10.13	

dryer chamber, where the black gram samples are treated. According to Ref. [90], radiation at 2.45 GHz with 230 W led to the complete death of *C. maculatus* larvae, pupae, and adults in 9.82, 10.68, and 10.18 min, respectively. In comparison, RF heating achieved overall mortality in just 5.64, 6.28, and 5.35 min for all *C. maculatus* life stages, with insect eggs experiencing the shortest lethal time of 3.62 min (Table 8). These findings highlight the rapid and effective nature of both microwave and RF radiation in controlling *C. maculatus* [90].

The differences in dielectric characteristics seen throughout the insect life cycle stages (Table 9) can be used to explain the discrepancy in lethal time for the various stages of *C. maculatus*. When compared to adults, larvae have higher dielectric characteristics; this implies that total mortality occurs more quickly. Pupae and larvae have very similar dielectric characteristics [92], which suggests that the required treatment times to reach lethality should be equal. However, pupae have the longest required treatment time for lethality, which may be attributed to the protective covering of the pupal stage. The total disinfestation process takes longer with the microwave treatment than with the RF treatment. This difference can be attributed to RF having a higher dp than microwave. The longer the microwave treatment lasts, the more the host plant material is exposed to microwave radiation, degrading the quality of the host material [90]. A higher loss factor in the pest compared to that in the host material may contribute to better quality of the host material after RF treatment.

5.1.3. Codling moth (Cydia pomonella L.)

The codling moth, *Cydia pomonella* L. (Lepidoptera: Tortricidae), is a significant pest affecting worldwide pome fruit production, causing the most damage in commercial orchards of apples, pears, quinces, cherries, and walnuts [93]. The female moth deposits individual eggs on the leaves of trees [94]. The larvae (Fig. 10-a) subsequently feed on the fruit pulp and cores, creating holes, tunnels, and galleries in the fruit (Fig. 10-b). Fruit falls from the tree as a result of the infection, lowering the market value of the affected fruits [95]. Fumigating with methyl bromide (MeBr) has been shown to be a successful treatment for addressing *C. pomonella* during storage [96]. However, the US. Environmental Protection Agency (EPA) has removed MeBr from the approved chemical register and progressively reduced its production since 2005 due to its great potential for ozone depletion. Other fumigants, such as phosphine, often need lengthy fumigation times (>10 h). The use of microwave and RF heating techniques for insect control may be an alternative to fumigation. It is improbable that insects would acquire resistance to this treatment, unlike with chemical fumigants, and it minimizes damage to fruit quality. The primary reason for selecting microwave or RF technology to control *C. pomonella* is due to its ability to quickly elevate the internal temperature of the target material, where the insects reside, while maintaining the surface temperature at the ambient level [20,76]. Numerous studies have explored the impact of RF or microwave radiation on the mortality of *C. pomonella* without damaging host material quality [16,20,76].

The mortality of third and fourth instar *C. pomonella* as an insect pest of unshelled walnuts in storage settings treated with an RF pilot scale at 27 MHz (6 KW) (COMBI 6-S, Strayfield International Limited, Working-ham, UK) (Fig. 4) [16,20] as well as third instar *C. pomonella* in cherries treated in a microwave heating chamber at 915 MHz (5 KW) (Model IV-5, Microdry Inc., Crest-wood, KY) [76] is shown in Table 10. The mortality of *C. pomonella* in walnut increased linearly with the treatment duration, with 100 % insect mortality achieved after 3 min of heating. The microwave treatment proved ineffective for third instar *C. pomonella* in cherries, particularly 'Rainier' cherries. In 3.3 min, 62 % of third instar larvae died in 'Bing' cherries, but only 7 % were killed in 'Rainier' cherries. The unusual variation in insect mortality in the two distinct cherry types might be attributed to a difference in the loss factor in the two cherry varieties, which affects their heating rate (Eq. (1)). Additionally, some insects were present on the surface of the cherries during the treatment, but the lethal temperature for the insects was only reached for those insects inside the fruit. Notably, the surface temperature of the 'Bing' cherry was lower than that of the area near the pit, as shown in Fig. 9 [54].

The walnut fatty acid (FA) and peroxide value (PV) levels after 3 min of RF treatment were less than 0.6 % and 1 mEq/Kg, respectively, indicating that 3 min of RF treatment of *C. pomonella* in walnut may achieve 100 % insect mortality without impacting the quality of the host material [6,13]. Nevertheless, only 67 % and 7 % larval mortality were achieved in 'Bing' and 'Rainier' cherries, respectively, within the 3.3-min period during which the microwave influenced the cherry quality [54]. This is attributed to the significant contrast in the loss factor between the pest and the host material in the RF band as opposed to the microwave frequency band (Table 11).

5.1.4. Lesser grain borer (Rhyzopertha dominica)

The lesser grain borer, *Rhyzopertha dominica* (Coleoptera: Bostrichidae), is a significant pest affecting stored grains (Fig. 12) that originates from the Indian subcontinent [98]. This insect breeds and develops on a variety of cereals, including maize, rice, and wheat, as well as other substrates that contain starch [99]. It is mainly found in cereal stores, food processing facilities, and animal feed storage areas [98,99]. Within the kernel, the larvae undergo development, while the adults feed on grains [100]. Both adults and larvae cause damage by feeding on grains, leading to weight loss and the production of frass [98]. *R. dominica* has the ability to reduce

Table 9
Dielectric properties (ε' and ε'') of various stages of *C. maculatus* at ambient temperature and three frequencies.

Frequency (MHz)	*C. maculatus* (Larvae and pupae)		*C. maculatus* (Adult)		Ref
	ε'	ε''	ε'	ε''	[92]
40	50	168	55	104	
200	36	40	34	29	
915	30	15	28	10	

Table 10
Mortality of third- and fourth-instar *C. pomonella* larvae in walnuts and cherries treated with radio frequency and microwave radiation.

Instar larvae of *C. pomonella*	Host material	Treatment (min)	Power (KW)	Mortality (%)	References
3rd and 4th instars	Walnut	1(RF)	3	47.5	[16]
3rd and 4th instars	Walnut	2(RF)	3	78.6	[16,20]
3rd and 4th instars	Walnut	3(RF)	3	100	[16,20]
3rd instar	'Bing' cherry	2 (MICROWAVE)	1	17	[76]
3rd instar	'Bing' cherry	2.8 (MICROWAVE)	1	38	[76]
3rd instar	'Bing' cherry	3.3 (MICROWAVE)	1	62	[76]
3rd instar	'Rainier' cherry	2 (MICROWAVE)	1	5	[76]
3rd instar	'Rainier' cherry	2.8 (MICROWAVE)	1	9	[76]
3rd instar	'Rainier' cherry	3.3 (MICROWAVE)	1	7	[76]

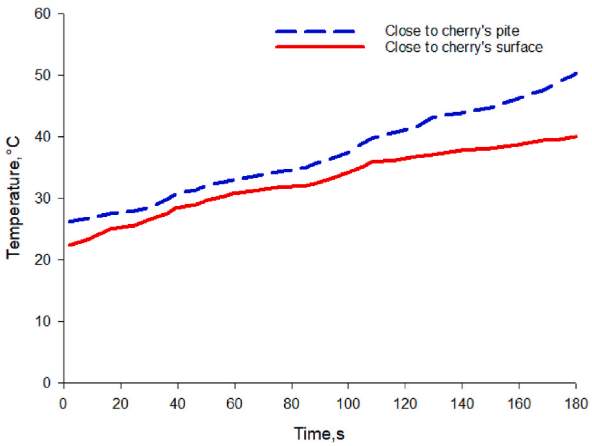


Fig. 9. Comparison of temperature distribution between core and surface of Bing cherries during 915 MHz microwave treatment at different exposure times.

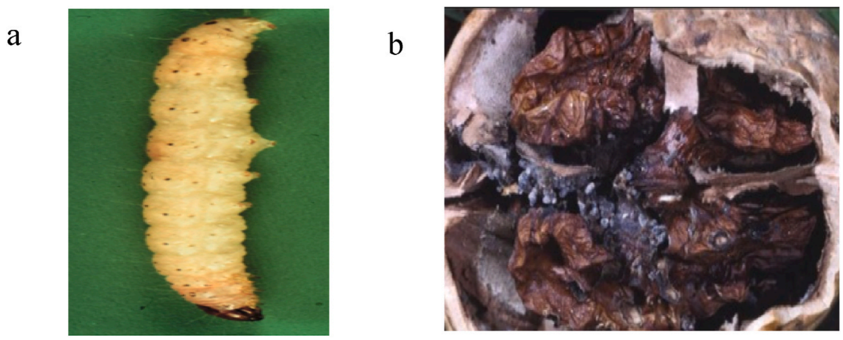


Fig. 10. (a) Larvae of *C. pomonella* and (b) damage caused by *C. pomonella* in walnut [97].

Table 11
Dielectric loss factor of *C. pomonella* larvae, cherry and walnut at different microwave and radio frequencies at ambient temperature.

Material	Frequency (MHz)					
	27	40	915	1800	2450	Ref
Cherry	293	198.5	16.4	16	–	[83]
Walnut	0.26	0.7	2.9	1.8	–	[83]
Cydia pomonella	238	163	11.7	12	16	[67,83]

grains to dust and cause significant damage, resulting in weight losses of up to 40 % [98]. Stored-grain insect pests, particularly *R. dominica*, are responsible for substantial damage to stored grains and their byproducts in Palestine. Losses attributed to these insect pests account for at least 15 % of the total in stored grains each year [101]. The high mobility of *R. dominica*, facilitated by its flying ability, increases infestation in stored milled rice. Therefore, both bulk storage settings such as bag stacks or silos and smaller quantities meant for retail sale to consumers are susceptible to *R. dominica* attacks [102]. Chemical methods have been the prevailing means of managing grain insects, and their use comes with various inconveniences and potential risks to the environment and human health [102,103]. There is a pressing need to develop alternative techniques for controlling insect pests in storage settings while minimizing environmental impacts and ensuring the safety of stored grains for consumers. One alternative technique is dielectric heating, which is effective in controlling *R. dominica* across various host materials, by utilizing an RF instrument capable of generating 2000 W energy at four radio frequencies (6.78, 13.56, 27.12 and 40.68). Temperature sensors automatically determine and display the sample's temperature on a monitor once it is placed between electrode plates, as shown in Fig. 11. In Ref. [104], adult *R. dominica* individuals were placed inside a nylon mesh bag, which was then positioned in the center of a polyethylene box filled with grain. The lethal temperature for adult *R. dominica* remains constant across different host materials, attributed to the close permittivity values among them. However, the lethal time for adult *R. dominica* in wheat is shorter compared to this insect pest in rice or corn. The treatment frequency influences the lethal time, with higher frequencies resulting in a decrease in the lethal time (Table 12). Nevertheless, the significant difference in dielectric properties between adult *R. dominica* and the various host materials (Table 13) underscores the effectiveness of this technology as an efficient approach for pest control without causing any harmful effects to the host material.

5.1.5. Rice moth (Corcyra cephalonica)

China leads the global production of walnuts, contributing over 50 % (2.52 trillion megagrams) of the total output (4.50 trillion megagrams). The USA follows with 0.59 trillion megagrams, and Iran comes next with 0.32 trillion megagrams [109]. Walnuts are acknowledged for their role in reducing serum cholesterol, lowering blood pressure, and mitigating the risk of heart disease [109]. The primary cause of walnut loss during storage is insect pests, with the rice moth (*Corcyra cephalonica* L.) (Lepidoptera: Pyralidae) being a significant contributor [58]. This insect pest of storage settings reduces the product quality directly by feeding and indirectly through the production of webbing and frass (Fig. 13). It is estimated that annual losses of cereal grains due to insect pests in storage settings, including *C. cephalonica*, are approximately up to 50 % in Africa and Asia and 10 % in North America [72].

The control of *C. cephalonica* primarily involves the use of chemical fumigation as the treatment method [72,109]. By utilizing various radio frequencies and treatment times, the RF system used for the control of *R. dominica* in a range of crops (Fig. 11) has also been adapted for the control of fifth instar *C. cephalonica* in unshelled walnuts. To achieve this, researchers randomly placed larvae inside a single walnut. To achieve the implantation, the nut was split in half along the suture and then secured with electrical tape (without affecting the RF field). Notably, the fifth instar exhibited 100 % mortality after 60 min of exposure to a high frequency of 40.68 MHz (Table 14). The novel feature of this treatment had no negative impacts on the host material quality in terms of the values for MC, peroxide value (PV), and free fatty acid (FFA) [58]. Another method utilizing microwave ovens operating at a frequency of 2.45 GHz was evaluated to control the same developmental stage of *C. cephalonica* in wheat grains. In this case, a much shorter treatment duration of only 50 s was sufficient to achieve mortality of the pest without causing any harmful effects to the quality of the wheat grains (Table 14) [72].

The findings covered above demonstrate the possibility of employing microwave heating as an effective and secure method for controlling *C. cephalonica* infestations in stored grains. In contrast to RF treatments, microwave treatments have certain disadvantages, linked to their low penetration depth compared to RF treatments. For this reason, RF treatments are often preferred when dealing with infestations in massive quantities of stored grain.

5.1.6. Rice weevil (Sitophilus oryzae)

One of the most serious pests impacting stored cereals worldwide, including barley, maize, rice, and wheat, is the rice weevil (*Sitophilus oryzae)* L. (Coleoptera: Curculionidae) (Fig. 14). Usually, *S. oryzae* attacks begin in the field [98,100,111]. Beginning with a tiny hole drilled into a rice kernel by females, an egg is deposited in the cavity, and the opening is sealed with a gelatinous secretion. The larvae of rice weevils complete their development inside the seed kernel, and upon reaching adulthood, they cut an exit hole to emerge. This invasion by the insect leads to losses in grain weight and a reduction in rice quality by facilitating the infection of

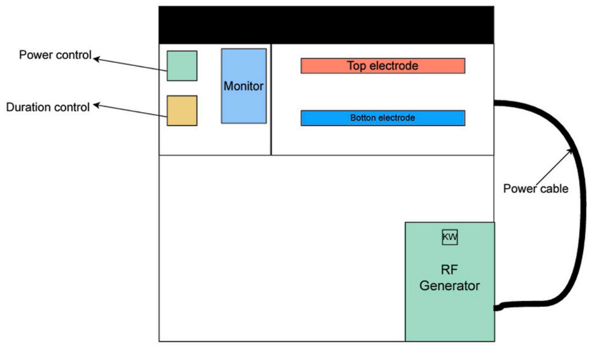


Fig. 11. Pilot-scale radio-frequency heating chamber used to control *R. dominica*.

Fig. 12. Corn infested by adults *R. dominica* [105].

Table 12
Radio frequency conditions for 100 % mortality of adult and fourth instar larvae of *R. dominica* on four different host materials.

Target insect	Host material	Frequency (MHz)	Power (W)	Lethal temperature (°C)	Lethal time (min)	Ref
R. dominica (adult)	Wheat	6.78	2000	58	30	[104]
		13.56			18	
		27.12			10	
		40.68			9	
R. dominica (adult)	Rice	27.12	2000	58	11.5	[104]
R. dominica (adult)	Corn	27.12	2000	58	11.5	[104]

Table 13
Dielectric properties of *R. dominica*, wheat, and corn at 27.12 MHz under ambient temperature conditions.

Frequency (MHz)	*R. dominica*		wheat		corn		Ref
	ε′	ε″	ε′	ε″	ε′	ε″	[106–108]
27.12	23	18	4	0.4	5	0.8	

Fig. 13. Rice infested by adult *C. cephalonica* [110].

microorganisms [100]. Stored maize experiencing significant infestations of *S. oryzae* may show weight losses ranging from 30 to 40 %, although typical losses hover around 4–5%. Additionally, brown rice subjected to infestation was observed to lose 19 % of its initial kernel weight over a 14-week period. Chemical fumigation is the technique most employed to control this insect, utilizing a highly residual active compound.

As an alternative management option, an RF block that produces 7 kW of power at 27.12 MHz, functioning at a temperature of 50 °C, through the assistance of heated air for a period of 3 min, provides a more suitable and efficient solution. Two hundred grams of rice containing fifty eggs, fifty larvae, and twenty-five adult *S. oryzae* beetles were positioned between the two electrodes in this RF block. The results were 100 % mortality achieved at the egg stage, followed by 97.6 % mortality at the larval stage. The efficiency of the RF treatment was shown to vary according to the insect developmental stage. However, the adult stage was less sensitive to RF treatment than the earlier stages, requiring the higher temperature of 55 °C and the same treatment duration of 3 min for 100 % mortality to be achieved. In contrast, the surviving adults exposed to lower temperatures and shorter durations of treatment

Table 14
Radio frequency and microwave conditions for 100 % mortality of fifth instar larvae of *C. cephalonica* and host material quality after treatment.

Target insect	Host material	Frequency (MHz)	Power (W)	Lethal temperature (°C)	Lethal time (min)	Host material quality	Ref
C. cephalonica (5th instar larvae)	Walnut	6.78	2000	–	60	Good quality	[58]
C. cephalonica (5th instar larvae)	Walnut	13.56	2000	–	60	Good quality	[58]
C. cephalonica (5th instar larvae)	Walnut	27.12	2000	–	60	Good quality	[58]
C. cephalonica (5th instar larvae)	Walnut	40.68	2000	–	40	Good quality	[58]
C. cephalonica (5th instar larvae)	Wheat grain	2450	–	55	0.83	Good quality	[72]

Fig. 14. Cereals infested by *S. oryzae* [105].

demonstrated a decline in egg production when compared to the untreated adults [112].

Along a different line, researchers have explored the potential of both RF and microwave in targeting adult *S. oryzae*. A pilot-scale RF setup at 27.12 MHz, like the previous method, was employed for controlling the adults. However, in this modified approach, a conveyor belt was introduced to facilitate movement of the sample between the two electrodes. This addition aimed to enhance the heating uniformity throughout the material under testing. Furthermore, a lower power output of 6 kW was used in this adjusted method. Complete mortality of adult *S. oryzae* was achieved using the modified RF approach at a temperature of 50 °C after a period of 6 min (Table 15). This extended treatment time.

ensured the efficacy of the RF treatment in controlling the pest population [113]. In comparison, the use of a microwave oven at 2.45 GHz was also explored to control the infestation of thirty adult *S. oryzae* in 100 g of wheat seeds. Only 30 s of treatment time was needed to completely kill all adults using a 700 W microwave oven (Table 15) [75,114].

These studies demonstrate the potential of RF and microwave as effective methods for pest control, particularly targeting different developmental stages of *S. oryzae*. The RF method, with its higher power and longer treatment time, has been shown to be effective in targeting eggs and larvae, while the microwave method has offered a quick and efficient solution for controlling adult populations. Rice and wheat seeds subjected to RF and microwave heat treatment showed no significant change in their primary structural characteristics [75,112–114]. This is because of the difference in permittivity between the host material and the insect pest at the applied frequencies (Table 16). Consequently, the insect pest exhibits a greater absorption of radiation and generates higher thermal energy compared to the host material.

5.1.7. *Red flour beetle (Tribolium castaneum)*

The red flour beetle *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) is a widespread pest found in stored grain worldwide [117]. This insect presents a substantial risk to both the quantity and quality of stored products due to its high reproductive capacity [118]. As powder-feeding insects, both larvae and adults cause considerable damage by feeding on processed foods and other products

Table 15
Radio frequency and microwave conditions for complete mortality at various stages of *S. oryzae* and dielectric heating effect on the host material.

Target insect	Host material	Treatment type	Frequency (MHz)	Hot air temperature (°C)	Power (W)	Lethal time (min)	Host material quality	Ref
S. oryzae (eggs, larvae)	Rice	RF + Hot air	27.12	50	7000	3	Good quality	[112]
S. oryzae (Adult)	Rice	RF + Hot air	27.12	50	6000	6	Good quality	[113]
S. oryzae (Adult)	Wheat seeds	MICROWAVE	2450	–	480	0.5	Good quality	[75, 114]

Table 16
Dielectric properties of *S. oryzae*, rice and wheat seed at radio frequency and microwave frequencies.

Frequency (MHz)	*S. oryzae*		Rice		Wheat seed		Ref
	ε′	ε″	ε′	ε″	ε′	ε″	[115,116]
27.12	**8**	**2.3**	**-**	**-**	**4**	**0.4**	
915	**6.5**	**2**	**1.9**	**0.853**	**3.8**	**0.35**	
2450	**4**	**0.4**	**1.65**	**0.35**	**2.8**	**0.3**	

Fig. 15. Corn infested by *T. castaneum*.

(Fig. 15), leading to annual losses amounting to billions of dollars [119,120]. In Canada alone, an estimated 8–10 % of oil seeds are lost annually due to pest insects, resulting in millions of dollars of economic losses. To control *T. castaneum*, various fumigants and synthetic insecticides have been widely used, but their effectiveness has diminished due to insect resistance [121]. Therefore, microwave heating is one such innovative approach that is used to prevent *T. castaneum* infestation of cereals and grains. According to Ref. [59], 100 g of almonds infested with *T. castaneum* were subjected to a microwave oven operating at a frequency of 2.45 GHz with varying power levels ranging from 120 W to 600 W and exposure times between 30 s and 90 s. All *T. castaneum* life stages exhibited complete mortality when exposed to a microwave power of 480 W for 60 s (Table 17). The impact of increasing the temperature during microwave treatment on almond quality has been verified by analyzing the peroxide value, fatty acid content, water activity, color difference, and moisture loss. According to this study, almonds maintained good quality within acceptable limits after microwave treatment. This may be due to the difference in the dielectric characteristics of *T. castaneum* and almonds (Table 18), with *T. castaneum* being characterized by high dielectric properties, which makes it more vulnerable to the effects of microwave radiations than almonds.

5.1.8. *Fruit flies*

Fruit flies, which belong to the family Tephritidae, are known to be a highly damaging insect pest that impacts a wide range of fruits and vegetables worldwide [124]. The peach fly, *Bactrocera zonata* (Diptera: Tephritidae), and the Mediterranean fruit fly (Medfly), *Ceratitis capitata* Wiedemann, are two significant species belonging to the same family and are the source of significant risks and damage to many host plants. Female fruit flies lay their eggs under the fruit skin, using their ovipositor to penetrate the fruit surface. After hatching, the first-stage larvae create galleries inside the fruit, feeding on the pulpy material. This feeding activity not only damages the fruit but also exposes it to secondary infection by microorganisms. As a result, larval development inside infested fruit accelerates the rate of ripening, leading to premature detachment and fruit falling to the ground [124,125]. *C. capitata* has been shown to cause an annual global economic burden exceeding two billion dollars, primarily attributed to fruit damage. Additional economic ramifications arise due to the enforcement of quarantine measures on fresh produce originating from countries affected by *C. capitata*. These restrictions severely limit the export opportunities available for the producing nations [126]. Similarly, *B. zonata* is considered one of the most destructive fruit flies in India, with 25 %–100 % crop loss. In Pakistan, *B. zonata* alone accounts for 25–50 % of guava fruit loss. The annual economic cost of these fruit flies is estimated at €320 million in the Middle East and approximately €190 million in Egypt. Traditionally, insecticide applications have been extensively employed to manage peach fruit fly. However, their potential adverse effects, including toxicity to nontarget organisms, promotion of insect resistance to insecticides, environmental pollution, and residues in food, have raised concerns and warrant the investigation of alternative chemical-free techniques [126]. One such alternative and chemical-free technique for controlling these pests is the use of dielectric heating. The use of microwave heating technologies to treat these fruit flies has shown to be viable. Numerous studies have investigated the thermal impact of microwave on the mortality of various life stages of these insects by exposing them for durations of 10–30 s to treatment in a microwave oven running at a frequency of 2.45 GHz and power of 700 W. The first and second instars of *C. capitata* and *B. zonata* both exhibited 100 % mortality

Table 17
Almond host material quality under treatment for complete mortality of *T. castaneum*.

Target insect	Host material	Frequency (GHz)	Power (W)	Lethal time (s)	Host material quality	Ref
T. castaneum (Larvae, pupae, adults)	Almond	2.45	480	60	Good quality	[59]

Table 18
Dielectric constant (ε′) and loss factor (ε″) of *T. castaneum* and almond at microwave and radio frequencies at room temperature.

Frequency (MHz)	*T. castaneum* (Adult)		Almond		Ref
	ε′	ε″	ε′	ε″	[83,92,122,123]
27.12	–	–	5.9	1.2	
40	–	–	5.9	1.5	
915	52	20	1.7	5.7	
1800	–	–	5.8	2.9	
2450	46	15	1.6	0.1	

(ε′): Dielectric constant; (ε’’): loss factor.

Table 19
Mortality rate of various stages of *C. capitata* and *B. zonata* exposed to microwave radiation for 30 s.

Target insect	Frequency (GHz)	Power (W)	Mortality (%)	Ref
C. capitata (1st and 2nd instar)	2.45	700	100	[127]
C. capitata (eggs)	2.45	700	89.6	[127]
B. zonata (1st and 2nd instar)	2.45	700	100	[127]
B. zonata (eggs)	2.45	700	89.6	[127]

Table 20
Dielectric properties of *C. capitata* and apple under ambient temperature at four frequencies.

Frequency (MHz)	*C. capitata* (egg)		*C. capitata* (larvae)		Apple		Ref
	ε′	ε″	ε′	ε″	ε′	ε″	[83,128]
27.12	107.6	235.1	98.4	341.8	64.6	92	
40	85.8	168.5	83.1	237.4	74.7	61.1	
915	47.4	15.6	49.1	19.2	77	10	
1800	45.5	11.9	48.4	14.4	70.4	10.8	

with 30 s of treatment, while egg mortality only reached 89.6 % (Table 19). The influence of microwave on the quality of the host material is a key element in the effective use of dielectric heating for insect control but is not discussed in many investigations [127]. The dielectric characteristics of *C. capitata* and apples differ significantly, as shown in Table 20 [83,128]. Therefore, the use of RF can be a successful technology for controlling *C. capitata* in apples without causing any harmful effects on the host material quality. The disparity in mortality rates among various stages of these fruit fly pests is attributed to the variations in dielectric parameters specific to each stage. The eggs of *C. capitata* exhibit lower dielectric properties than the larvae (Table 20) [83,128]. Dielectric parameters, such as the dielectric constant and loss factor, determine how effectively a material absorbs and converts electromagnetic energy into heat. The eggs of *C. capitata* exhibit lower absorption and conversion of electromagnetic energy into thermal energy than the larvae. Consequently, the mortality rates of eggs exposed to high-frequency microwave radiation may be lower than those of larvae [127].

Table 21 presents a comparison of energy efficiency among various systems used for dielectric heating control of storage pests. The microwave oven system exhibits the highest energy efficiency at 80 %, followed by the COMBI 6-S system from Strayfield International Limited, UK. Other systems include the RF heating chamber (Model IV-5 by Microdry Inc., KY), Enerzi MW system (Model: PTF 2515, 40.68 MHz), and Lakshmi Insta 10/4 RF heating block. The microwave oven system’s high energy efficiency means it uses less energy to achieve the same output as other systems, thus reducing resource use and environmental impact. However, due to its small size, it is not suitable for industrial-scale applications, as it can only treat a limited number of crops at a time. In contrast, the COMBI 6-S system is more appropriate for industrial use due to its larger capacity and high energy efficiency compared to other industrial-capable systems.

In conclusion, the COMBI 6-S system from Strayfield International Limited, UK, with an efficiency of 50 %, stands out in terms of energy efficiency, sustainability, and industrial applicability. It uses energy more efficiently and has a reduced environmental impact. Additionally, crops treated with this system are immediately ready for storage, making it more advantageous compared to other

Table 21
Energy efficiency of various dielectric heating systems used in this manuscript to control storage pests.

Dielectric heating system	Energy efficiency(%)	Ref
COMBI 6-S, Strayfield International Limited, Working- ham, UK)	50	[113]
Microwave oven	80	[64]
Make: Enerzi MW system; Model: PTF 2515	8	[90]
40.68 MHz; Make: Lakshmi Insta 10/4	3.65	[63]
Model IV-5, Microdry Inc., Crest- wood, KY	20	[76]
RF heating chamber	21	[63]
RF heating block	3.6E-5	[115]

systems.

5.2. Dielectric heating for field insect control

Dielectric heating is not commonly employed for the management of field insect pests, primarily because these insects tend to infest crops with high MC. As a result, the use of this technology can adversely affect the host material quality. Given this challenge, it is crucial to explore alternative approaches that can effectively control insects without compromising the host plant quality. However, there is difficulty in utilizing dielectric heating technology as a novel and durable solution for field insect pest control while avoiding harm to the physiochemical characteristics of crops and their nutritional quality. For many reasons, including the complexity of the wild environment, the influence of environmental conditions, the nature of the host plant, the biology and movement, and the sensitivity of different insect life stages, there has been little investment in the development of technologies based on dielectric heating to control field insects, in addition to challenges in designing reliability into high-frequency RF and microwave systems adapted to the host plant. Only two main field insect pests have been investigated in more detail, and the other affecting high moisture content crops [24], with one impacting low MC crops [129].

5.2.1. Red palm weevil (Rhynchophorus ferrugineus)

The red palm weevil (RPW), *Rhynchophorus ferrugineus* (Olivier) (Coleoptera: Curculionidae) (Fig. 18-a), is a significant insect pest of the date palm *Phoenix dactylifera* L. and is the only weevil whose geographic distribution has extended from its native location in southern and southeastern Asia to the whole globe. *R. ferrugineus* is a hidden and fatal tissue borer of the date palm, causing tunnel development and significant tissue destruction (Fig. 18-b) by larval feeding [130]. To manage *R. ferrugineus* in date palms, both preventive and curative pesticide sprays are used [131–133]. Preventive pesticide treatments through regular spray regimens, on the other hand, are frequently excessive and unneeded. The use of different organophosphates (chlorpyriphos, fenitrothion), carbamates (carbaryl), pyrethroids (cypermethrin), and neonicotinoids (imidacloprid) at the early stage of attack is necessary for the curative treatment of *R. ferrugineus*-infested palms. However, substantial concerns have been raised concerning the environmental contamination produced by these treatments, particularly in public areas where ornamental palms are cultivated [21]. As a result, there is much interest in pest management technologies that have a low environmental impact [9]. Several studies [7–9,64] have investigated the use of microwave radiation for *R. ferrugineus* control in a sustainable way.

According to Ref. [21], palm treated with microwave radiation at 2.45 GHz (1 kW) had an inner temperature range from 40 to 60 °C, while the outer temperature reached more than 80 °C, and the larvae died once it reached 50 °C (Fig. 16-A, B, D). The limited penetration depth of both healthy and damaged palms (Table 22) prevents radiation from reaching the inner section of the palm; additionally, insects in the outside area of the palm experience lethal temperatures faster than those in the interior [21,36].

According to Ref. [23], larvae, pupae and adults of RPW exposed to microwave radiation generated by a waveguide at 2.45 GHz (Fig. 16-E) showed that larvae reached a lethal temperature more quickly than adults. Since a greater loss factor is observed for larvae than for adults at 2.45 GHz (Table 22), Eq. (1) states that larvae create more thermal energy [36]. The same results were obtained in Ref. [134], where microwave energy applied at 2450 MHz (500 W) for RPW disinfestation indicated that the cuticle, muscle, and midgut of larvae were damaged after 40 s. While adult cuticles and muscles required 4 min to be destroyed, adults required a longer time than larvae to achieve 100 % mortality (Table 23). To evaluate the effectiveness of microware treatment [23], performed a set of experiments on larger *Phoenix canariensis* palms (50 cm diameter) to estimate the efficacy of the treatment and the effect of the induced thermal stress. Eight of the thirteen palms had been infested. A commercially available ring applicator (Ecopalm ring, Bielle s.r.l.) was used to treat four infested palms and two healthy palms (Fig. 17). Notably, the larvae demonstrated a surprising resilience despite their high permittivity compared to the adults (Table 23). In contrast, the adults exhibited more damage, which is due to the lower palm penetration depth. Moreover, the larvae's presence on the interior of the palm might provide them with protection, while adults situated on the outside face higher risks, leading to increased damage at this stage of development [23]. In general, insects in outer areas experience fatal temperature faster than those in the interior part because of the low palm penetration (Table 22).

To transform this technology into an alternative to chemical pesticides for *R. ferrugineus*, a multi-frequency system should be employed. This would allow the radiation to effectively eliminate pests on the surface area of the tree's trunk when using high frequencies, as well as pests within the inner areas when using low frequencies. Additionally, research should target the egg stage of the pests to eradicate them before they reach more advanced developmental stages.

According to Ref. [136], research on the histological aspects of the male and female *R. ferrugineus* reproductive systems irradiated with microwaves (2.45 GHz, 100 W) was conducted at three distinct exposure times (5 s, 15 s, and 30 s). Based on these findings, the researchers suggest that microwaves might be a successful way to reduce *R. ferrugineus* populations because they can limit or eliminate this insect's reproductive capabilities. However, according to Ref. [21], the microwave conditions used are insufficient to induce mortality.

5.2.2. Cotton bollworm (Helicoverpa armigera)

Helicoverpa armigera (Hubner) (Lepidoptera: Noctuidae) is considered one of the most devastating pests worldwide. *H. armigera* is a polyphagous species that feeds on over 180 hosts from 70 plant families (Fig. 20) and it is found in Europe, Africa, Asia, and Oceania [137,138]. Several researchers from around the world have emphasized integrated pest management strategies to reduce *H. armigera* damage, which include the use of resistant cultivars, cultural practices such as intercropping with trap crops, the use of biological agents, and biological and chemical control measures. Farmers generally use more insecticides to control *H. armigera*; however, careless use of pesticides has resulted in lingering residues, the development of insecticide resistance, and undesirable adverse side

Table 22
Dielectric properties of palms and adults and larvae of red palm weevil.

Material	Relative permittivity	Loss factor	Penetration depth (cm)	Ref
Damaged palm	50.7	–	1.3	[21,36]
RPW (Larvae)	37.5	14	5	[21,36]
RPW (Adults)	5	2	10	[21,36]

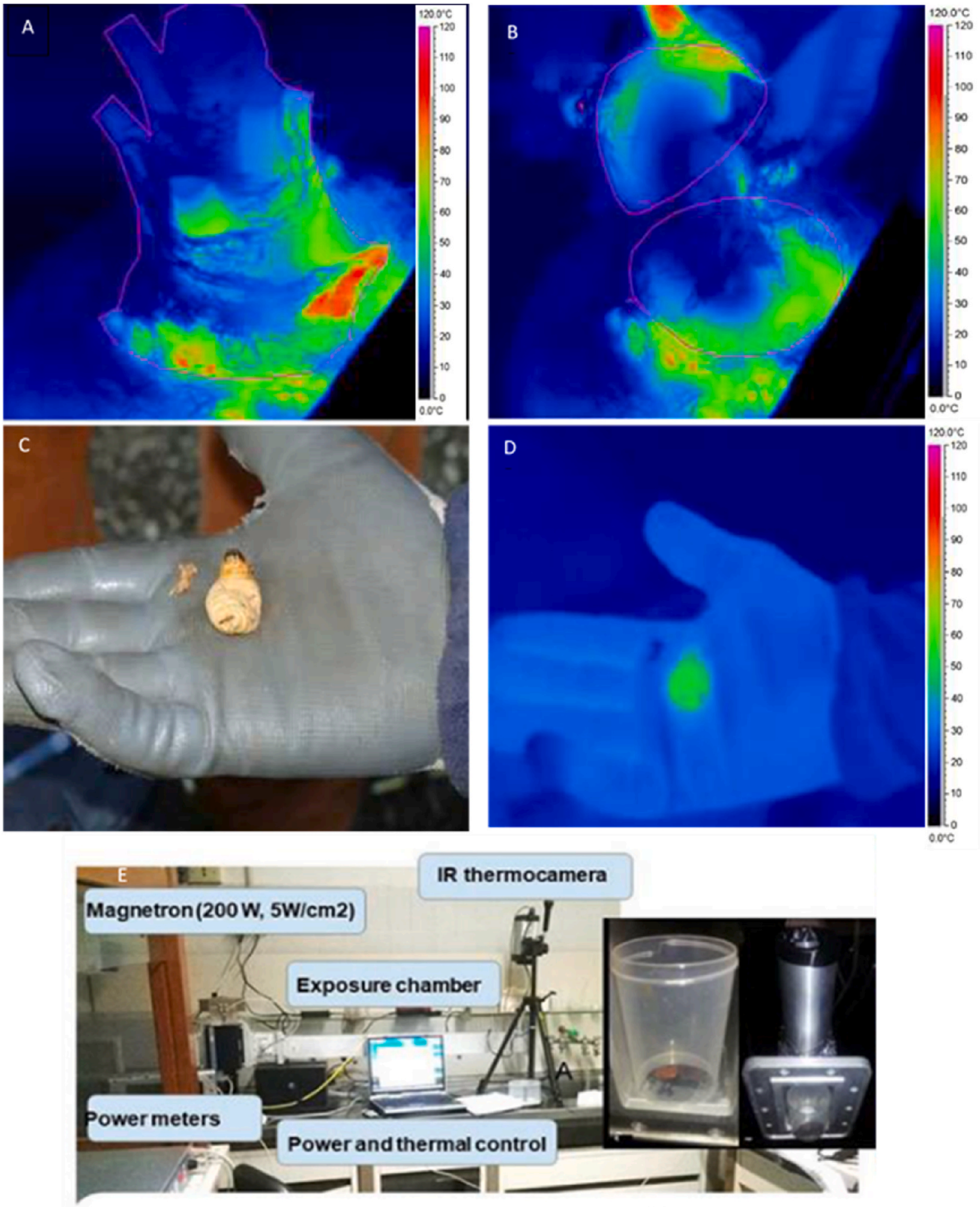


Fig. 16. (A) The external temperature of the palm; (B) the section temperature of the palm; (C, D) A thermograph of a dead RPW [21]; (E) microwave radiation setup [23].

Table 23
Effect of microwave treatment at 2.45 GHz on the mortality of various stages of RPW on a palm of 50 cm diameter at different exposure durations.

	% mortality			
Treatment duration (min)	**Adult %**	**Larvae %**	**Pupae %**	**Ref**
30	25	–	100	[23]
45	92	40	100	[23]
45	58	–	67	[23]
45	67	100	100	[23]

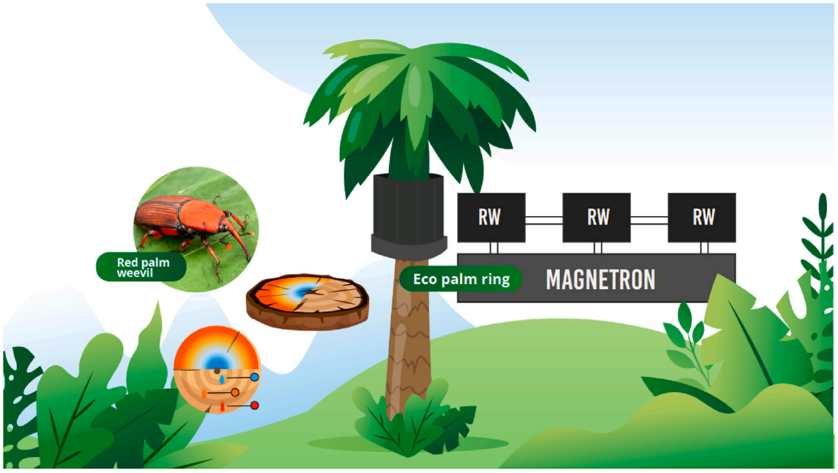


Fig. 17. A large-scale system (Eco Palm Ring) used to control *R. ferrugineus* in palm trees under field conditions.

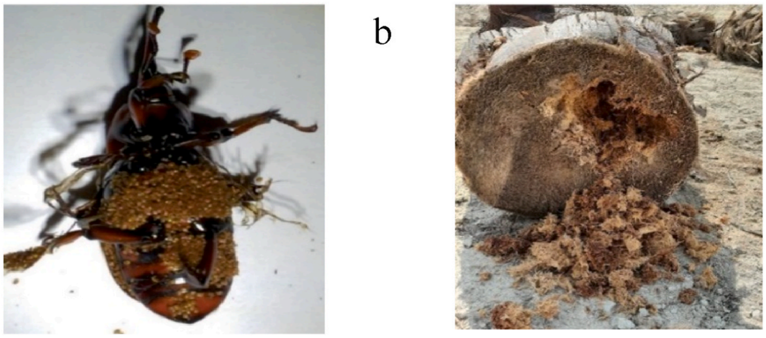
a b


Fig. 18. (a) Adult *R. ferrugineus* (b) damage caused by *R. ferrugineus* on the palm [135].

effects on natural enemies, humans, and the environment [137,139]. A laboratory-scale microwave system has been designed as an innovative approach for controlling *H. armigera* infestations in tomato plants (Fig. 19). This system comprises a high-power level generator, which is then directed at the test material (MUT) positioned between the two electrodes. As reported in Refs. [24,26], a tomato plant affected by *H. armigera* is placed between the two parallel electrodes and exposed to a power of 250 W at 2.45 GHz and 915 MHz, with early egg hatching observed after 10 min of treatment, resulting in disturbance of the insect pest's life cycle. Interestingly, the study findings showed that the power level at 250 W used in the microwave treatment did not significantly affect the different *H. armigera* larval instars at either frequency (Table 24). Moreover, the microwave treatment did not show adverse effects on the quality of the tomato plants. Utilizing high-power microwave radiation can result in significant larval mortality. However, it is crucial to consider its potential impact on the quality of tomatoes. Tomatoes are known to have a high loss factor at 2.45 GHz, as reported in Ref. [63], resulting in an increase in temperature and an adverse effect on quality. When employing microwave or RF radiation to control insects in environments with high MC, it is advisable to focus on exploiting the nonthermal effects of this energy. To achieve this, researchers should investigate the influence of radiation on both the reproductive capacity of adult insects and the growth of larvae. By conducting such studies, it becomes possible to determine an optimal low power level that will effectively control the insects without negatively affecting the host material quality.

The availability data from literature discusses two systems for field pest control: the industrial-scale Eco Palm Ring with an energy

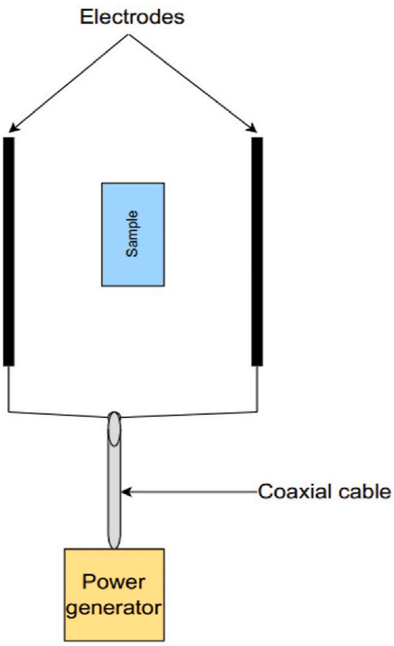


Fig. 19. Schematic view of the laboratory-scale system (Parallel plate electrodes) used to control *H. armigera* in tomato plants.

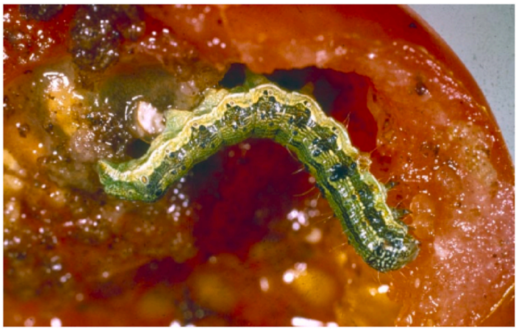


Fig. 20. Tomato crop affected by *H. armigera* larvae [140].

Table 24
Microwave radiation effect on different life stages of *H. armigera*.

Insect	Host material	Frequency (MHz)	Power (W)	Duration (min)	MICROWaVE radiation effect	Ref
H. armigera (eggs)	Tomato	915–2450	250	10	Early hatching	[24,26]
H. armigera (1st-5th instar larvae)	Tomato	915–2450	250	10	No effect	[24,26]

efficiency of 50 %, and a lab-scale two parallel plate system used to control *Helicoverpa armigera*, which has an energy efficiency of 25 % [24]. Effective field pest treatment requires systems tailored to the specific pest and host material [2]. The Eco Palm Ring, designed specifically for palm trees, demonstrates higher energy efficiency compared to the lab-scale system used for tomato plants. However, the Eco Palm Ring still loses half of its total energy, indicating a need for further research to enhance its sustainability and reduce its environmental impact.

To improve its versatility, the Eco Palm Ring should be evaluated on other pest affecting tree-trunk and modified to accommodate different tree types. This involves adjusting power and frequency settings and developing interchangeable rings and flexible attachments for various trunk sizes and shapes. Additionally, incorporating pest detection sensors or microwave imaging systems could detect pests based on permittivity differences between healthy and infested trunks. These monitoring systems would also facilitate early pest detection, allowing for optimal treatment timing and energy use optimization.

6. Nonthermal effect of microwave radiation and radio frequency

The utilization of RF and microwave radiation has emerged as a promising strategy for addressing various agricultural pest issues by using their thermal impact on insect death. Notably, the potential impact of this radiation on histological lesions and the reproductive system of pests has been the focus of attention of [129,136]. Dissected organs of RPW were treated by microwave radiation at 2.45 GHz (200 W) for 30 s. Severe pathological alterations were shown in the organs of the treated insects compared to the untreated insects using light microscopy and histological images. The reproductivity of the pests decreased, and the number of eggs laid decreased from 207 for the untreated samples to 27 for the irradiated samples. The microscopic abnormalities in the irradiated RPWs included lesions of varying degrees of severity, from degeneration to necrosis, and these changes were greater as the irradiation period increased. The degeneration and necrosis of germinal cells, which increased with the increase in the irradiation duration and the temperature, were confirmed in the histological lesions of the ovaries and testes of RPWs [129]. The results in numerous studies have supported the findings that reproductive tissues of many adult insects exposed to microwave treatments have reduced reproductive capacity, with such reductions likely caused by heat damage to sperm cells and ovarian tissues [6,15,141]. Additionally, when temperatures rise to extremely elevated levels, the effects on gonad and gamete maturation become more pronounced. Moreover, studies have shown that RF exposure levels that are well within the current recommendations can diminish fertility and induce DNA damage in insects, birds, amphibians, and mammals, as well as lower sperm counts, sperm motility, and sperm motility in humans [75]. The fertility of both male and female fruit flies (*Drosophila melanogaster*) was shown to be reduced by exposure to a modulated GSM 900 MHz cell phone signal [129]. In a later study [145], Drosophila fruit flies were exposed to a cell phone transmitting GSM 900 MHz at 0.40 microwave/cm^2 or GSM 900 MHz at 0.29 microwave/cm^2 for six consecutive minutes per day for six days. The exposure induced fragmented DNA during oogenesis. Cell death scores in the ovaries of female flies ranged from 39 to 63 % compared to 7.8 % in control groups [74]. Recent research by [146] demonstrated that exposure to GSM 900 MHz modulated cell phone transmissions at 0.35 microwave/cm^2 (=350 W/cm^2) for 6 min during ovarian development can significantly slow ovarian maturation and reduce the size of ovaries in Drosophila fruit flies [142]. Numerous studies conducted in recent years have demonstrated that nonthermal levels of RF and microwaves can negatively affect insect and mammal reproduction and cause DNA damage. However, further research on other parts of the insect body and systems, including the respiratory, nervous, and digestive systems, is needed to fully validate and better understand the possible effects and mode of action of these insect control methods.

7. Dielectric heating advantages and limitations

To effectively control insect pests in storage settings in bulk materials, RF technology is considered preferable due to the limited penetration depth of microwave radiation. Nevertheless, current RF systems designed for insect control in storage settings encounter a significant challenge in the form of nonuniform heating. As a result, researchers have been actively investigating various models aimed at enhancing heating uniformity [67,68], with the goal of improving the overall efficacy of insect control in such systems, whereas the use of microwaves is preferable if a low dp is needed, as in the case of the RPW, in which the radiation primarily targets the trunk of the palm ensures that radiation does not penetrate deep into the trunk and adversely affects the palm's quality.

In dielectric heating, the dielectric property of the treated material, especially the permittivity, is a critical value that determines its susceptibility to RF and microwave radiation. For storage and field insect pests affecting low MC materials, where insects exhibit higher permittivity compared to the host material, dielectric heating proves successful. In contrast, for pests affecting high-MC materials, the use of dielectric heating can compromise the host material quality. These materials are characterized by a high permittivity, rendering them more sensitive to electromagnetic (EM) energy [24,76]. This challenge made the technology more useful for insect pests in storage settings that often infest low-MC crops. To control pests infesting high MC materials, leveraging microwave radiation's effect on insect reproductive capabilities, growth, and egg hatching disruption has proven to be a suitable approach. This strategy interferes with the pest's life cycle and ensures effective pest control in such conditions.

The utilization of dielectric heating for controlling insect pests in storage settings has demonstrated successful outcomes, leading to the development of an industrial scale system dedicated to management of various insect types. For instance, it was evaluated to prevent *A. transitella* from harming walnuts, and the results were encouraging. Additionally, a microwave-based system has been developed specifically for combatting the RPW under field conditions.

The topics of dielectric heating addressing the challenge of nonuniform heating for insect control in bulk materials and alternative control methods for high-MC host materials remain crucial focal points for ongoing scientific research in pursuit of more efficient and sustainable insect management strategies.

8. Study limitations

One of the limitations of this systematic review is the limited number of studies, particularly those on specific insect pests using industrial-scale control systems, which made it difficult to compare the findings. Additionally, the analysis focused on studies reporting positive results and on those reporting the quality of host material after treatment, which may lead to publication bias.

9. Conclusion and prospects

1. Dielectric heating proves effective in managing storage pests impacting low moisture content materials and field pests infesting tree trunks. By analyzing dielectric properties, researchers gain insights into which component, the host material, or the pest, is more

susceptible to dielectric heating, thus informing targeted pest management strategies. Key to successful dielectric heating is the careful selection of optimal frequency and power settings, ensuring thorough pest eradication while safeguarding the quality of the host material. To map out the future of pest management, it is essential to delve into the potential of dielectric heating technology and examine its emerging opportunities and prospects.

- Several research focused on the use of rotated holders or uniformly spaced electrodes to enhance the heating uniformity during the dielectric heating for bulky materials. However, using a combination of low frequency, more uniformly spaced electrodes and rotated holders during RF treatment might be a promising option for improving heating uniformity.
- Further investigations on dielectric measurements of agricultural products are needed to understand the impact of RF and microwave radiation on various kinds of materials (host plants).
- Given the distinct dielectric properties of insect pests compared to host materials, particularly in instances of low moisture content, employing a microwave imaging system becomes feasible for identifying the presence and positioning of insect pests within bulk materials. This includes cases where pests affect the tree trunk, necessitating the selection of an appropriate frequency based on the pest's location and the desired depth of penetration.
- More emphasis should be placed on the application of dielectric heating for insect control in high MC materials; a nonthermal effect could be used to control this type of material, allowing host material quality to be maintained. By employing low power levels that do not cause pest mortality but instead impact their reproductive capability and growth.
- More studies should be conducted on high MC materials in the field, utilizing a new treatment approach: sterilizing the male insect pests and dispersing them in the host material area to reduce their population thereby affecting their reproductive capacity. This treatment method would preserve the quality of the host material while exclusively targeting the insect pests.
- Further research efforts should focus on the development of dielectric heating systems incorporating insect pest control for enhancing pest management practices, ensuring food safety, and conserving energy. Detecting insect pests early is essential to minimize widespread damage and address food insecurity. Traditional pest detection methods, which rely on manual techniques, often lack efficiency and promptness. Therefore, it is vital to adopt advanced insect pest detection technologies to proactively anticipate, prevent, and manage pest infestations. Integrating these technologies into agricultural practices empowers farmers to swiftly detect pests, enabling proactive management strategies that improve yields and reduce losses.

Microwave imaging systems present an innovative approach to pest detection, relying on significant disparities in dielectric properties between the host material and the target pest, which indicate the promising potential of this technology. The system of microwave imaging can be integrated into dielectric heating systems for insect control. This integration enables targeted treatment and radiation emission only at pest-infested areas, thereby enhancing sustainability and effectiveness.

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Declaration of competing interest

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

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