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Factors Influencing Radio Frequency Disinfestation of Dried Figs Based on Dielectric Properties and Heat Tolerance

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Abstract:

Radio-frequency (RF) disinfestation, owing to its efficient and selective heating, is a promising method for controlling pests in stored dried figs. This study investigated the dielectric properties of dried figs and the Indianmeal moths (*Plodia interpunctella*) and evaluated the thermal tolerance of the Indianmeal moth during RF treatment. Dried figs with moisture contents of 12%, 16%, and 20% and the Indianmeal moths at the egg, young-larval, and late-instar stages were examined. The effects of frequency, temperature, and moisture content on fig dielectric properties were determined; the dielectric responses of 20%-moisture figs and insects were compared; and stage-specific insect heating rates were measured. Mortality was assessed under RF heating with hot-air holding at 45, 48, 51, and 54 °C with holding times of 2, 4, 8, and 12 min. Across 10–3000 MHz, the dielectric constant and loss factor of dried figs showed frequency-dependent trends, generally decreasing with frequency but increasing with temperature and moisture content. At 20% moisture, both parameters were significantly lower in figs than in the Indianmeal moths at 20–80 °C, with the disparity increasing at higher temperatures. At 50 °C, 27.12 MHz showed the largest loss-factor contrast (209.04) between dried figs and late-instar Indianmeal moth larvae, indicating the greatest selective RF heating potential. Early-instar larvae heated fastest, at 4.01 °C min^{-1}, whereas late-instar larvae exhibited the greatest heat tolerance. Mortality increased significantly with temperature and holding time. These findings provide a basis for safe, efficient, and environmentally friendly RF disinfestation of dried figs.

Keywords: dried figs; Indianmeal moth ;disinfestation; radio frequency; dielectric properties; heat tolerance.

Introduction

Fig (*Ficus carica L.*) is an important economic fruit crop in China. (Gharibzahedi et al., 2019; Wu et al., 2025). Its fruits are rich in bioactive components such as polysaccharides, flavonoids, and phenolic compounds, and possess high nutritional value and development potential (Liu et al., 2023; Xue et al., 2026; Yang et al., 2023b). However, fresh figs have a moisture content as high as 80%, and, due to their thin skin, tender flesh, and high sugar content, are highly susceptible to decay and deterioration after harvest, which severely restricts the circulation of fresh fruit (Yang et al., 2023a; Jin et al., 2024; Ding et al., 2025) . Therefore, drying is an important approach to extending the storage period of figs. Nevertheless, during long-term storage, infestation by storage pests has become a major factor affecting the quality and commercial value of dried figs (Altunç et al., 2025; Galán et al., 2024) . According to statistics, pest infestation can cause losses of 39% to 68% in dried figs(Cetinkaya et al., 2006) . Common storage pests include the Indianmeal moth, Carpophilus hemipterus, and Amyelois transitella (Wang et al., 2025; Yüksel et al., 2023) . Compared with other storage pests, the Indianmeal moths can reproduce up to seven generations per year in warmer regions, and its mating, oviposition, and adult emergence can occur at any time of day. While feeding, it can spin silk webs, accelerating product deterioration. Moreover, it is difficult to detect and readily develops resistance to chemical agents, resulting in severe damage and challenging control (Li et al., 2025).

For a long time, chemical fumigation has been the primary method for controlling storage pests. However, due to concerns regarding health risks, pesticide residues, resistance development, and environmental regulations, the storage pest management system is gradually shifting from reliance on chemical insecticides toward more integrated prevention and control strategies (Gvozdenac et al., 2024). In this context, alternative methods such as physical control and biological control have attracted considerable attention, among which thermal treatment is one of the most promising technologies. Nevertheless, conventional thermal treatment usually requires heating both the stored product and the pests together, which not only consumes high energy but may also impair product quality. In recent years, radio frequency (RF) heating has demonstrated promising application potential in agricultural product disinfestation because of its high heat transfer efficiency and selective heating characteristics. For example, Appugol et al. (2022) achieved complete mortality of the groundnut bruchid (*Caryedon serratus*) in peanuts using RF treatment. Indumathi et al. (2023) evaluated the control efficacy of RF heating at 40.68 MHz and 10 kW against the red flour beetle (*Tribolium castaneum*) in coarse wheat flour. Hou et al. (2022) investigated the application of high-temperature short-time RF treatment for pest control in adlay using a 6 kW, 27.12 MHz RF system with an electrode gap of 110 mm, and the results showed that higher temperatures required shorter times for complete insect mortality. Existing studies have mostly focused on evaluating the application effects of RF treatment, while in-depth analysis of its insecticidal mechanism remains lacking. In RF disinfestation of agricultural

products, the dielectric properties of the material and the heat tolerance of the pests are key factors. In particular, the RF selective heating mechanism in specific material systems such as dried figs, as well as the heat tolerance of the target pests, has yet to be clarified, which limits the application effectiveness of this technology in controlling storage pests in dried figs.

In view of this, this study aims to investigate the factors influencing RF disinfestation of dried figs while balancing insecticidal efficiency and product quality. First, dried figs with predetermined moisture contents (12%, 16%, and 20%) and Indianmeal moths at different developmental stages (eggs, early-instar larvae, and late-instar larvae) were used as research subjects. The dielectric properties of dried figs with different moisture contents were studied over the range of 10–3000 MHz, representative frequencies were selected, and the differences in dielectric properties between Indianmeal moths at different developmental stages and dried figs were analyzed to explore the conditions under which these differences are maximized. Second, by measuring the heating rates of Indianmeal moths at different developmental stages under RF treatment, the time required to heat to a specified temperature was determined. Mortality was then assessed under combinations of different temperatures (45 °C, 48 °C, 51 °C, and 54 °C) and hot-air holding times (2, 4, 8, and 12 min), so as to investigate the differences in heat tolerance among developmental stages. Finally, by integrating the analyses of dielectric properties and heat tolerance, this study is expected to provide a theoretical reference and technical basis for the safe, efficient, and green control of storage pests in dried figs.

Materials and Methods

Sample preparation

The dried figs used in this study were purchased from Jiuding Wholesale Market in Shihezi City. Prior to the experiments, dried figs with uniform appearance were selected, cleaned, sealed in polyethylene bags, and stored in a refrigerator at 4 °C to reduce the rates of moisture evaporation and oxidation.Based on a review of the relevant literature and market research, the moisture content of dried figs on the market typically ranges from 10% to 20% (Wang et al., 2022). Therefore, three representative moisture contents of 12%, 16%, and 20% (w.b.) were selected for the investigation of dielectric properties. To achieve precise adjustment of the moisture content of dried figs, the amount of deionized water required to reach each predetermined moisture content was first calculated. The water was then uniformly sprayed into the polyethylene bags containing the samples. Subsequently, the sealed samples were stored in a refrigerator at 4 °C for 3 days, during which they were shaken once every 12 h to ensure uniform moisture distribution within the samples. After treatment, the moisture contents of the dried figs reached 12.08 ± 0.24%, 15.96 ± 0.18%, and 20.03 ± 0.52%, respectively.

The Indianmeal moths used in this experiment were purchased from Donghailao Ecological Laboratory. The rearing method is shown in Fig. 1. The moths were reared in an artificial climate chamber under constant conditions of (28 ± 2) °C, relative humidity of (65 ± 5)%, and a photoperiod of 14:10 (L:D). The diet was prepared by pulverizing wheat and sequentially adding yeast, glycerol, and honey at a ratio of 100:4:8:4, followed by thorough mixing. The prepared diet was then dispensed into pest-rearing dishes and inoculated with Indianmeal moths.

The Indianmeal moths were divided into three representative developmental stages—eggs, early-instar larvae, and late-instar larvae—based on their growth and developmental characteristics and behavioral habits (Hou et al., 2019; Ye et al., 2026). Fig. 2 shows Indianmeal moths at different developmental stages, and Table 1 lists the developmental stage classification, characteristics, screening requirements, and mortality evaluation criteria for Indianmeal moths.

Fig.1 Cultivation of test pests

Fig.2 The Indianmeal moths at different developmental stages

Table 1

Age and stage division and characteristics of the Indianmeal moth

Age	Egg	Early instar larvae	Late instar larvae
	Early instar larvae	2nd–3rd instar	5th–6th instar
Morphological characteristics	Ovoid in shape, approximately 0.3–0.4 mm in size, milky white, with one end slightly pointed.	Light yellow, approximately 3–6 mm in body length, with a darker head and distinct body segments.	Reddish in color, with a body length ranging from 8 to 12 mm, cylindrical in shape, slightly swollen in the middle, and an orange-red head.

Activity habit	Eggs are often located on the surface of the product or within cracks of the fruit, occasionally occurring singly or in clusters.	Larvae spin silk to bind food particles into small balls or lumps, conceal themselves within them to feed, tunnel through the interior of the food, and gradually spread outward.	Highly active with a voracious appetite; bores into and consumes large quantities of dried fruits, grains, and other commodities. It moves through the food mass, excreting copious frass and causing conspicuous damage, and eventually seeks suitable sites for pupation.
Filtering requirements	Preliminary observation was carried out under a stereomicroscope, and eggs with a light yellow, smooth, and undamaged surface were selected.	The Petri dishes containing the Indianmeal moths were placed at room temperature for 5–7 h, after which active early-instar larvae and late-instar larvae were selected.	
Mortality assessment criteria	The eggs were observed for signs of shrinkage, hardening, or blackening. Those showing no obvious changes were incubated under suitable conditions for 6 days, after which the hatching of eggs in each group was recorded.	If the pest body appeared shriveled and shrunken, with darkened or even blackened coloration, and exhibited conspicuous changes such as scorching or damage on the body surface; or if the pest showed no response and lost mobility when gently touched with a fine brush on any part of the body, it was considered dead.	

Experimental instruments and equipment

Table 2

Experimental instruments and equipment

Equipment	Model	Manufacturer
Freezer	BCD-267G	Guangdong Hisense Rongsheng Refrigeration Co., Ltd.
Blender	MJ-25BM01A	Guangdong Midea Premium Electrical Appliance Manufacturing Co., Ltd.
Electro-thermal constant-temperature forced-air drying oven	101-3A	Shanghai Senxin Experimental Instrument Co., Ltd.
Artificial climate chamber	RGX-300E	Tianjin Taiste Instrument Co., Ltd.
Closed refrigeration and heating circulation unit	ZT-20-200-30H	Zhengzhou Great Wall Industry & Trade Co., Ltd.
Impedance analyzer	E4991B-300	Agilent Technologies, Inc., USA
Radio frequency drying test chamber	SO-6F	Strayfield Ltd., UK
Infrared thermal imager	FLIRE75	FLIR Systems, Inc., USA
Fluorescent fiber-optic thermometer	HQ-FTS-I9C01	Xi'an Heqi Optoelectronic Technology Co., Ltd.
Low-noise multi-blade centrifugal fan	DF-2.3	Zhejiang Supai Electromechanical Co., Ltd.

Fig.3 Structure diagram of the dielectric property measurement

Fig.4 Structure diagram of a RF and hot air heating device

Determination of moisture content and density of dried figs

To reduce the effects of differences in sample compaction and packing density on the dielectric measurement results, the mass of the sample loaded was calculated based on the density of samples at different moisture contents, so that all samples had a consistent volume and packing conditions during testing. It was necessary to ensure that the density remained consistent before and after pulverization. The moisture content of dried figs was determined by the oven-drying method. A 120 g sample of dried figs was selected, cut into pieces, and placed in a tray. The total mass was recorded as Wz1, and the tray mass was recorded as Wp. The sample was then placed in an oven set to 105 °C for drying. The sample was removed and weighed every 0.5 h. When the sample mass tended to stabilize, the total mass of the material and the tray at this time was recorded as Wz2. The initial moisture content M0 was calculated as follows:

$$M_0 = \frac{W_{z1} - W_{z2}}{W_{z1} - W_p} \times 100\% \quad (1)$$

Since the density variation of dried figs can affect their dielectric properties, the liquid displacement method was adopted in this study to measure the density of dried figs with different moisture contents. Toluene (C7H8) was selected as the displacement liquid (Yamaga et al., 2025) . The mass of dried figs was denoted as m. For each moisture content level (12%, 16%, and 20%), 20 g of dried figs were randomly selected, cut into pieces, and placed into a 250 mL Le Chatelier pycnometer. The displaced liquid volume V was measured, and the density ρ of dried figs was calculated using the following formula:

$$\rho = \frac{m}{V} \quad (2)$$

Measurement of the dielectric properties of dried figs and the Indianmeal moths

The dielectric properties of dried figs and Indianmeal moths were measured using a dielectric property measurement system in this study. Since dried figs contain a large number of heat-sensitive components, seven temperature gradients from 20 to 80 °C were selected for measuring the dielectric properties of dried figs and Indianmeal moths, over a frequency range of 10–3000 MHz, with moisture contents of dried figs at 12%, 16%, and 20%.

Sample preparation: Prior to the experiment, dried figs were ground into powder using a magnetic stirrer. The volume of the sample holder cylinder (r = 20 mm, h = 51 mm) was measured, and the sample mass was calculated based on the density at different moisture contents to ensure that the density of dried figs remained consistent before and after grinding. The powder was then loaded into the cylinder and pressed into a cylindrical specimen with a flat surface. The structure and composition of the dielectric property measurement system are shown in Fig. 3. For the dielectric property tests of Indianmeal moths, 50 early-instar larvae and 50 late-instar larvae were separately selected from the Petri dishes. They were then cleaned and, once the body surface was free of moisture, placed into a clean sample holder and compacted.

Measurement: During the test, the temperature was set on the closed refrigeration and heating circulation unit. When

the target temperature was reached, the dielectric properties of the materials were measured over the frequency range of 10–3000 MHz. Prior to measurement, the bottom of the sample holder was sealed with a rubber stopper to ensure full contact between the sample and the probe without any gaps. The temperature sensor element penetrated through the center of the rubber stopper. The sample holder was then placed on a lifting platform, and the height of the platform was adjusted to ensure complete contact between the sample and the probe.

Determination of heat tolerance of the Indianmeal moths under radio frequency heating and hot-air holding conditions

Temperature is a critical factor affecting the growth and reproduction of the Indianmeal moths. The range of 40–48 °C is generally regarded as the sublethal high-temperature zone, within which the Indianmeal moths ceases development. In the processing of dried fruits and other agricultural products, the treatment temperature is usually controlled below 60 °C to preserve nutritional content and flavor to the greatest extent. Studies have shown that most storage pests can be effectively killed within the range of 40–55 °C without compromising the quality of agricultural products. Therefore, to achieve effective disinfestation while maintaining the quality of dried fruits, it is necessary to investigate the effects of different temperatures and exposure durations in a radio frequency (RF) field on the mortality of the Indianmeal moths at various developmental stages, taking into account its physiological characteristics. This would allow the most heat-tolerant stage to be identified and provide a basis for setting RF heating parameters.

This experiment aimed to compare the heat tolerance of the Indianmeal moths at three developmental stages. To ensure identical heating conditions across all treatments, the RF system was operated at a fixed output power of 6 kW with an electrode gap of 160 mm.

Before the formal experiments, RF heating was applied to the Indianmeal moths at each developmental stage to determine the time required to reach the target temperature, and the heating process was monitored. Temperature measurements were conducted using a fiber-optic sensor and an infrared thermal imager. The tip of the fiber-optic sensor was specially prepared: a groove was cut into the side wall of the Petri dish for insertion of the sensor, and double-sided tape was attached to the front end. the Indianmeal moths individuals were arranged closely in a circle along the double-sided tape to ensure good thermal contact between the insects and the sensor. During heating, the infrared thermal imager was used to capture temperature images from directly above the Petri dish at a distance of 0.5 m. Each image capture was completed within 10 s, after which the Petri dish was immediately returned to the RF cavity to continue heating.

The target temperatures were set to 45 °C, 48 °C, 51 °C, and 54 °C. Before heating, the RF cavity was preheated to the target temperature using hot air. At an electrode gap of 160 mm, the Indianmeal moths was heated to the target temperature by RF treatment. The RF system was then turned off, and hot air was used to hold the insects at the target

temperature for 2, 4, 8, or 12 min, respectively, so as to simulate the thermal death behavior of the insects after reaching the target temperature during RF treatment and to investigate the effects of different temperatures and holding times on the mortality of the Indianmeal moths at various developmental stages.

Statistical analysis

Unless otherwise stated, all data in this study are expressed as the mean ± standard deviation (x ± s) of three replicate experiments. Data were processed and analyzed using Microsoft Office Excel 2021, and figures were generated using Origin 2022.

Results and discussion

Apparent density of dried figs with different moisture contents

Table 3 presents the density of dried figs at different moisture contents. As the moisture content of dried figs increased from 12% to 20% (wet basis), its density decreased from 1.216 to 1.115 g/cm³. This phenomenon has also been observed in walnuts; the underlying reason is that the rate of water absorption and swelling exceeds the rate of weight gain, leading to significant density variations. To reduce the influence of differences in sample compaction and packing density on dielectric testing results, it was necessary to ensure consistent density before and after grinding in this study.

Table 3

Density of dried figs under different moisture contents

Moisture content / (%, w.b.)		Apparent density / (g/cm³)
Dried figs	12	1.216 ± 0.007
	16	1.168 ± 0.011
	20	1.115 ± 0.005

Effect of frequency on the dielectric properties of dried figs

Fig. 5 and 6 show the variation in the dielectric properties of dried figs as a function of frequency over the range of 10–3000 MHz at temperatures of 20–80 °C and moisture contents of 12%, 16%, and 20%. As shown in Fig. 5a and Fig. 6a, at a moisture content of 12%, both the dielectric constant and the dielectric loss factor of dried figs were lower than 15, indicating a relatively low level. This phenomenon can be attributed to the fact that at low moisture contents, the water in dried figs is mainly bound by hydrophilic components such as proteins and sugars, which reduces the amount of free water. Consequently, both the dielectric relaxation loss caused by bound water and the ionic conduction loss caused by free water are maintained at relatively low levels (Zhang et al., 2019). In recent years, many researchers have measured the dielectric properties of various nut kernels under the same frequency range of 10–3000 MHz and similar conditions, and reported dielectric parameter values lower than 15 for peanuts, lower than 9 for macadamia nut kernels, and lower than 11.5 for walnut kernels, which are consistent in magnitude with the dielectric parameters of dried figs measured in this study (Lei et al., 2024; Ling et al., 2016; Mao et al., 2022).

At all three moisture contents of 12%, 16%, and 20% (w.b.), both the dielectric constant and the dielectric loss factor of dried figs decreased with increasing frequency, and the rate of decrease was significantly reduced at higher frequencies. The dielectric properties in the radio frequency band were greater than those in the microwave band. At 50 °C, as the frequency increased from 10 MHz to 300 MHz, the dielectric constant of dried figs with a moisture content of 16% decreased from 20.20 to 10.13, and the loss factor decreased from 21.15 to 1.71, representing reductions of 49.85% and 91.91%, respectively (Fig. 5b and Fig. 6b). When the frequency further increased from 300 MHz to 3000 MHz, the two

parameters decreased to 8.59 and 1.30, respectively, with reductions of only 15.20% and 23.98%. This phenomenon is attributed to the fact that ionic conduction dominates at low frequencies. As the frequency increases to 300 MHz, ionic conduction weakens, and the proportion of dipole relaxation, which has a comparatively smaller influence on the dielectric properties, increases. Similar trends have also been observed in studies on the dielectric properties of apples (Zhou et al., 2019) and paddy rice (Deng et al., 2024). Given the notable differences in the variation trends of the dielectric parameters of dried figs across different frequency bands, five frequencies commonly used in industry and scientific research (13.56, 27.12, 40.68, 915, and 2450 MHz) were selected for subsequent analysis so as to comprehensively characterize the dielectric properties, covering the radio frequency to microwave bands.

Fig.5 shows the variation curves of the dielectric constant of dried figs with moisture contents of 12.08% (a), 15.96% (b), and 20.03% (c) as a function of frequency.

Fig.6 shows the variation curves of the dielectric loss factor of dried figs with moisture contents of 12.08% (a), 15.96% (b), and 20.03% (c) over frequency.

Effect of moisture content and temperature on the dielectric properties of dried figs

The temperature variation of dried figs during the drying process can be represented by the surface temperature and the core temperature. In this study, infrared thermography was used for monitoring the surface temperature, and fiber-optic temperature measurement was adopted for monitoring the core temperature. To further investigate the thermal treatment mechanism of dried figs under microwave or radio frequency heating and to provide a theoretical reference for the variation patterns of the dielectric properties of materials during dielectric heating, five frequencies commonly used in industry and scientific research (13.56, 27.12, 40.68, 915, and 2450 MHz) were selected. Through experimental analysis, the suitable temperature and moisture content for the disinfestation treatment of dried figs were explored.

As shown in Figs. 7 and 8, the dielectric properties of dried figs in the radio frequency band were higher than those in the microwave band, and the difference increased with increasing moisture content of the samples. For example, at a temperature of 50 °C, when the moisture content increased from 12% to 20%, the loss factor of dried figs at 27.12 MHz increased from 1.57 to 40.95, an increase of 39.38; under the same conditions, the loss factor at 915 MHz increased from 0.56 to 6.59, an increase of 6.03. The reason is that at low moisture contents, water exists in a monomolecular layer state, and the electrical conductivity is not significantly affected by the solvent effect; when the moisture content increases, a multi-layer water structure is formed, and the conductivity increases accordingly (Li et al., 2026). This result is consistent with the selective heating behavior observed by Wei Shuo (Wei et al., 2021) in radio frequency treatment of corn kernels with different moisture contents. In addition, when the temperature exceeded 60 °C, the loss factor of dried figs in the radio

frequency band increased significantly. Hernández (Hernández-Nava et al., 2025) demonstrated that the dielectric properties of materials increase with increasing temperature, as higher temperatures enhance ion mobility and strengthen ionic conduction. Therefore, in RF disinfestation of dried figs, the treatment temperature should be kept below 60 °C as much as possible, and the moisture content of dried figs should be at a relatively low level, so as to maintain a low dielectric loss factor.

Fig.7 Relationship between the dielectric properties of dried figs at specific frequencies and moisture content and temperature, 12.08% (a), 15.96% (b), and 20.03% (c)

Fig.8 Relationship between dielectric loss factor of dried figs at specific frequencies and moisture content and temperature, 12.08% (a), 15.96% (b), and 20.03% (c)

Comparison of dielectric properties between dried figs and Indianmeal moth

By selecting appropriate radio frequency (RF) values, temperatures, and moisture contents, significant differences in the dielectric constant and dielectric loss factor between Indianmeal moths and dried figs were achieved. During dielectric heating, the ability of a material to convert electromagnetic energy into thermal energy depends on its loss factor, and the loss factor is positively correlated with the heating rate. Therefore, RF energy is preferentially absorbed by Indianmeal moths, and the heating rate of the pests is higher than that of dried figs, ensuring efficient disinfestation while reducing adverse effects on product quality. Thus, the dielectric properties of Indianmeal moths are key to selective heating. To simplify the analysis, this study directly compared the dielectric properties of the two materials. Considering that at the same frequency, dried figs with higher moisture contents exhibit significantly higher dielectric loss factors, the 20% moisture content represents the high-loss condition most unfavorable to selective heating. To highlight the differences in dielectric response, dried figs with 20% moisture content were used as the representative sample for all subsequent comparisons. Regarding the selection of RF frequencies, lower frequencies offer strong penetration and uniform heating but relatively low efficiency, whereas higher frequencies exhibit weaker penetration but higher heating efficiency. In addition, dried figs have lower dielectric loss factors at higher frequencies. To balance heating uniformity, heating efficiency, and differences in dielectric response, two frequencies, 27.12 MHz and 915 MHz, were selected from the five frequencies commonly used in industry and scientific research for experimental analysis.

Fig. 9 and 10 compare the dielectric properties of dried figs (20% w.b.) and Indianmeal moths at different developmental stages at 27.12 MHz and 915 MHz. The results showed that, within the same frequency range, the dielectric loss factors of samples at different developmental stages differed significantly, following the order of early-instar larvae > late-instar larvae > eggs. During RF treatment at 20–80 °C, both the dielectric constant and loss factor of dried figs with 20% moisture content remained significantly lower than those of Indianmeal moths at all developmental stages, and the

differences gradually widened with increasing temperature, making Indianmeal moths the preferential heating target. This selective heating characteristic highlights the superiority of RF technology and is of great significance for improving disinfestation efficiency and minimizing product quality damage caused by high temperatures. Furthermore, compared with the microwave band (915 MHz), the difference in dielectric loss factor between dried figs and Indianmeal moths was substantially larger at the RF band (27.12 MHz), revealing a more prominent advantage of the RF band in selective heating. Therefore, to more effectively exploit the differences in dielectric properties for targeted thermal kill, subsequent heat tolerance experiments on Indianmeal moths at different developmental stages were all conducted using RF heating at 27.12 MHz.

Fig.9 Comparison of the relationship between dielectric constant and temperature of high-moisture dried figs and the Indianmeal moth at different developmental stages at 27.12 MHz and 915 MHz (a - 27.12 MHz, b - 915 MHz)

Fig.10 Comparison of the relationship between dielectric loss factor and temperature of high-moisture dried figs and the Indianmeal moths at different developmental stages at 27.12 MHz and 915 MHz (a - 27.12 MHz, b - 915 MHz)

Comparison of heating rates of Indianmeal moth at different developmental stages under radio frequency heating

Fig. 11 shows the infrared thermographic images of Indianmeal moth eggs, early-instar larvae, and late-instar larvae during radio frequency (RF) heating. It can be seen from the figure that, during the heating process, the temperature in the middle portion of the insect body was relatively higher than that in the head and tail regions. This is because the tissue structure and moisture content of the middle portion differ from those of the head and tail, resulting in higher efficiency of RF energy absorption and conversion. As heating time increased, the temperature gradually became more uniformly distributed over the entire insect body, although a certain temperature gradient could still be observed. Fig. 12 presents the temperature rise of Indianmeal moths during RF heating monitored by both fiber-optic temperature measurement and infrared thermal imaging. It can be seen from the data that the temperature of Indianmeal moths exhibited a continuous upward trend with increasing RF heating time. At the initial heating stage, the heating rates of eggs, early-instar larvae, and late-instar larvae measured by both methods were relatively moderate. Taking the temperature changes recorded by the fiber-optic sensor as an example, the heating rates during the first 0–2 min were 1.94, 2.62, and 2.34 °C/min, respectively. This is because, at the initial stage, the uneven distribution of water and other RF-energy-absorbing substances within the insect body restricted the rate of temperature rise, and the temperature difference between the insects and the surrounding environment led to heat dissipation from the insects, resulting in relatively low heating rates.During the later stage of RF heating (3–8 min), the heating rates of Indianmeal moths at different developmental stages were 4.04, 4.47, and 4.42 °C/min, respectively. This is attributed to the fact that, as heating continued, the water within the insect body was gradually heated, leading to increased water mobility and thus improved heating efficiency. The higher the dielectric loss factor, the faster

the heating rate under RF heating conditions.

Fig.11 Infrared thermogram of the Indianmeal moths at different developmental stages under radiofrequency heating

In this study, two temperature measurement methods, namely fiber-optic temperature measurement and infrared thermal imaging, were employed to monitor the temperature changes of Indianmeal moth at different developmental stages during radio frequency (RF) heating. To reduce experimental error, the average temperature of five individual moths extracted from the infrared thermographic images was taken as one replicate result. Fig. 12 presents the temperature–time curves of Indianmeal moth eggs, early-instar larvae, and late-instar larvae under the RF field. During the initial heating stage, the temperature differences between the two measurement methods at the same time point were relatively small, with a maximum difference of 1.05 °C observed at the young larval stage and a minimum difference of 0.8 °C at the egg stage. As the treatment time increased, the temperatures measured by infrared thermography gradually became lower than those measured by fiber-optic sensing, with a maximum difference of 1.9 °C observed at the young larval stage. This may be attributed to the fact that, when using the infrared thermal imager, the moths needed to be removed from between the RF electrode plates for image acquisition, and the large temperature difference between the insects and the surrounding environment caused noticeable heat loss during the imaging process. Therefore, for subsequent temperature measurements, the fiber-optic sensor could better reflect the actual temperature variation of the moths, and all subsequent analyses were based on the fiber-optic temperature data.During the RF heating process (0–8 min), the heating rates of Indianmeal moth at the egg, young larval, and late-instar larval stages were 3.52, 4.01, and 3.9 °C/min, respectively, indicating that the average heating rate under the RF field followed the order: early-instar larvae > late-instar larvae > eggs. Understanding the heating rates of different developmental stages under the RF field can facilitate precise control of the intensity and duration of RF treatment, thereby achieving efficient disinfestation of Indianmeal moths while minimizing the adverse effects on product quality.

Fig. 12 Comparison of radiofrequency heating rate of the Indianmeal moths under optical fiber temperature measurement and infrared thermal imaging

Effect of temperature and holding time on the mortality of Indianmeal moth

Fig. 13 illustrates the three-dimensional relationship between mortality and temperature and holding time for Indianmeal moth eggs, early-instar larvae, and late-instar larvae, under conditions where the insects were heated to target temperatures in a 27.12 MHz radio frequency (RF) field and then held by a hot-air system. Overall, the mortality of Indianmeal moth at all developmental stages increased with increasing temperature and extended holding time, exhibiting a pronounced temperature–time dependence. As shown in Fig. 13a, the mortality of eggs increased significantly with temperature. At 45 °C, when the holding time was extended from 2 min to 12 min, the mortality increased from 36.67% to

98.67%. At a target temperature of 54 °C, a mortality of 99.33% was achieved within only 2 min, indicating an exponential effect of temperature on the lethal efficiency for eggs. Similarly, temperature was also the most important factor affecting the mortality of early-instar larvae and late-instar larvae. Taking the young larval stage as an example, at 45 °C with a holding time of 12 min, the mortality was only 60%. When the temperature was raised to 51 °C and 54 °C, even at a short holding time of 2 min, the mortality reached 79.33% and 92%, respectively. The effect of temperature on the mortality of Indianmeal moth is mainly attributed to the fact that elevated temperature endows protein molecules with more energy, intensifies thermal motion, and thereby causes protein denaturation; moreover, high temperature suppresses enzyme activity, leading to metabolic dysfunction and loss of viability. This result is consistent with the findings of Liu Qianqian (Liu, 2020) in research on RF disinfestation of milled rice, indicating that higher temperatures produce more significant disinfestation effects.

Fig. 13 Comparison of heat tolerance in different developmental stages of the Indianmeal moths（a-45℃, b-48℃, c-51℃, d-54℃)

Analysis of heat tolerance of Indianmeal moth at different developmental stages

Fig.14 shows the mortality of Indianmeal moth at different developmental stages under the same target temperature and different holding times. As shown in Fig. 14a, at a target temperature of 45 °C, as the holding time increased from 2 min to 12 min, the mortality of eggs increased from 36.7% to 98.7%, while the mortalities of early-instar larvae and late-instar larvae at a holding time of 12 min were 60% and 55.3%, respectively. It can be seen that, at a target temperature of 45 °C, the mortality of eggs was much higher than that of early-instar larvae and late-instar larvae under the same holding time. At 48 °C, eggs were the first to reach complete mortality. At 54 °C with a holding time of 4 min, the young larval stage was completely killed, whereas the late-instar larvae were not completely killed. Therefore, under the same treatment conditions, the mortality of late-instar larvae was lower than that of early-instar larvae, indicating that late-instar larvae possess stronger heat tolerance. Combined with the dielectric property analysis, early-instar larvae are more susceptible to RF heating and exhibit a superior heating effect compared with late-instar larvae. In summary, under RF treatment conditions, the late-instar larval stage of Indianmeal moth is more difficult to control than the young larval stage and the egg stage. The heat tolerance of Indianmeal moth follows the order: late-instar larvae > young larvae > eggs. Therefore, the late-instar larval stage was identified as the key control stage in the RF disinfestation process of dried figs.

Fig. 14 Comparison of heat tolerance in different developmental stages of the Indianmeal moths（a-45℃, b-48℃, c-51℃, d-54℃)

Conclusion

The dielectric property differences between dried figs and Indianmeal moth (Plodia interpunctella) at different developmental stages (eggs, early-instar larvae, and late-instar larvae) were investigated, and the heating rates and heat tolerance of Indianmeal moth at different developmental stages under radio frequency (RF) treatment were analyzed to identify the factors influencing RF disinfestation and optimize the process. The main conclusions are as follows:The dielectric constant and dielectric loss factor of dried figs decreased with increasing frequency but increased with increasing temperature and moisture content. At a temperature of 50 °C, as the moisture content increased from 12% to 20%, the dielectric loss factor of dried figs at 27.12 MHz increased from 1.57 to 40.95, an increase of 39.38. In addition, when the temperature exceeded 60 °C, the dielectric loss factor increased significantly. To control dielectric loss, it is recommended that the material temperature be kept below 60 °C and the moisture content not be excessively high during RF disinfestation.Within the temperature range of 20–80 °C, dried figs with 20% moisture content were used as the representative sample, and their dielectric constant and dielectric loss factor were consistently significantly lower than those of Indianmeal moth at all developmental stages. Moreover, the differences were more pronounced at 27.12 MHz than at 915 MHz. At 50 °C, the difference in loss factor between dried figs with 20% moisture content and late-instar larvae reached 209.04 at 27.12 MHz, whereas it was only 23.45 at 915 MHz. This indicates that the greatest difference in dielectric loss factor between dried figs and Indianmeal moth occurs at 27.12 MHz, suggesting a greater potential for selective heating.During RF heating, early-instar larvae of Indianmeal moth exhibited the highest average heating rate, reaching 4.01 °C/min. At the same lethal temperature, the heat tolerance of different developmental stages differed significantly: at 45 °C with a holding time of 12 min, the mortality of eggs (98.7%) was much higher than that of early-instar larvae (60%) and late-instar larvae (55.3%); at 54 °C, early-instar larvae were completely killed within 4 min, whereas late-instar larvae did not reach 100% mortality, indicating that late-instar larvae possess the strongest heat tolerance. Combined with the dielectric property and heat tolerance analyses, early-instar larvae are more readily heated by RF, while late-instar larvae exhibit the highest heat tolerance.In summary, RF treatment can effectively control storage pests in dried figs. This study provides a theoretical reference and technical basis for further optimizing RF disinfestation technology for storage pests in dried figs.

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Authors' contributions

Yiding Wang: investigation, methodology, formal analysis, validation, data curation, writing-original draft preparation, writing-reviewing and editing. Shuaitao Cao, Ruijie Guan: writing-original draft and writing-reviewing. Xuedong Yao: conceptualization, resources, formal analysis, funding acquisition, project administration. Kelai Cai,Bowen Zhang, Guoshun Yuan : validation, data curation,

investigation, visualization, supervision. Rongguang Zhu, Qiang Wang, and Yong Huang: writing-original draft preparation and writing-reviewing.

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Data availability

The data presented in this study are available on request from the corresponding author.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

All authors agreed to submit this manuscript to this journal for publication.

Competing interests

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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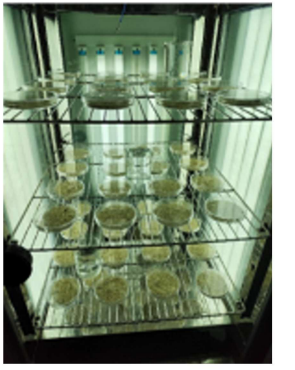
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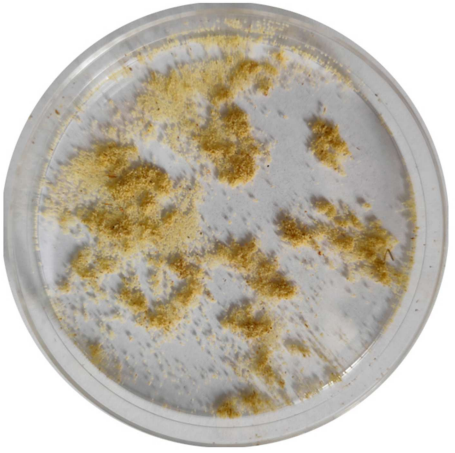


Inoculation



Culture





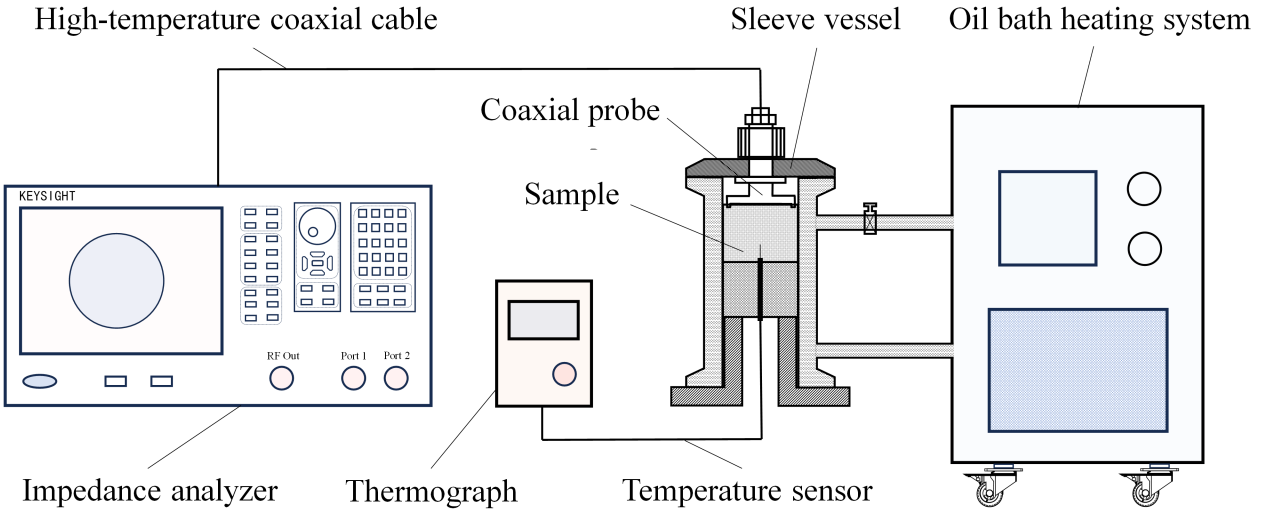
Ovum

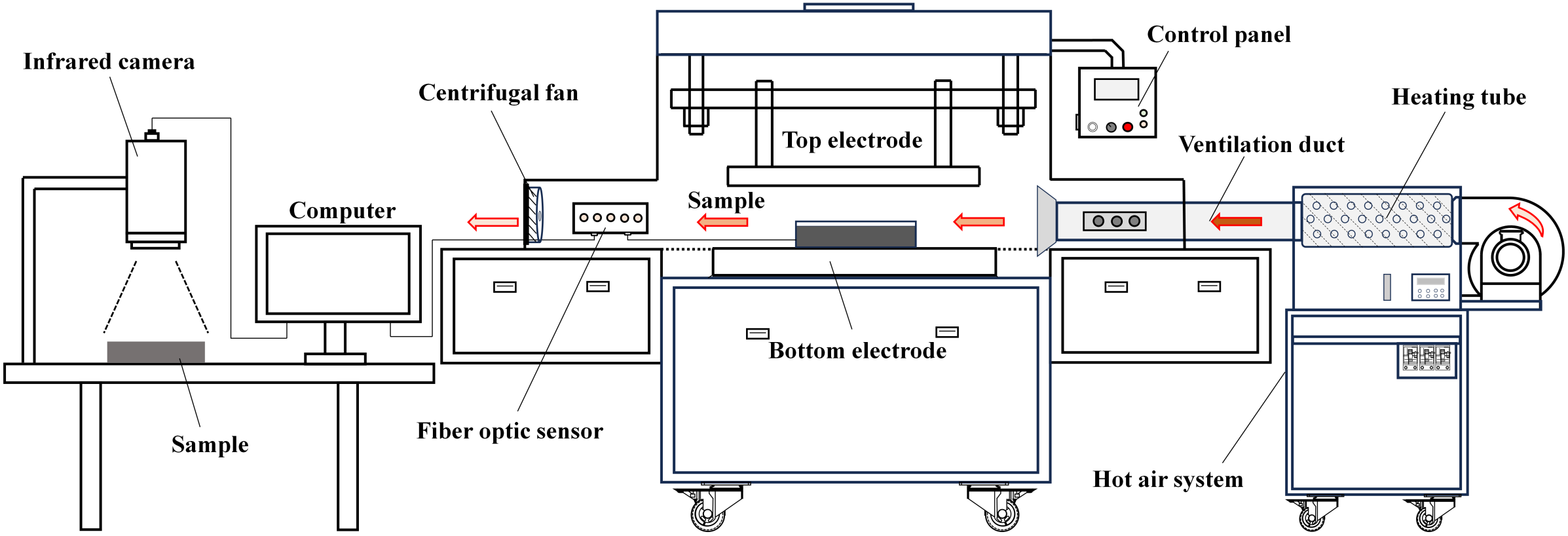


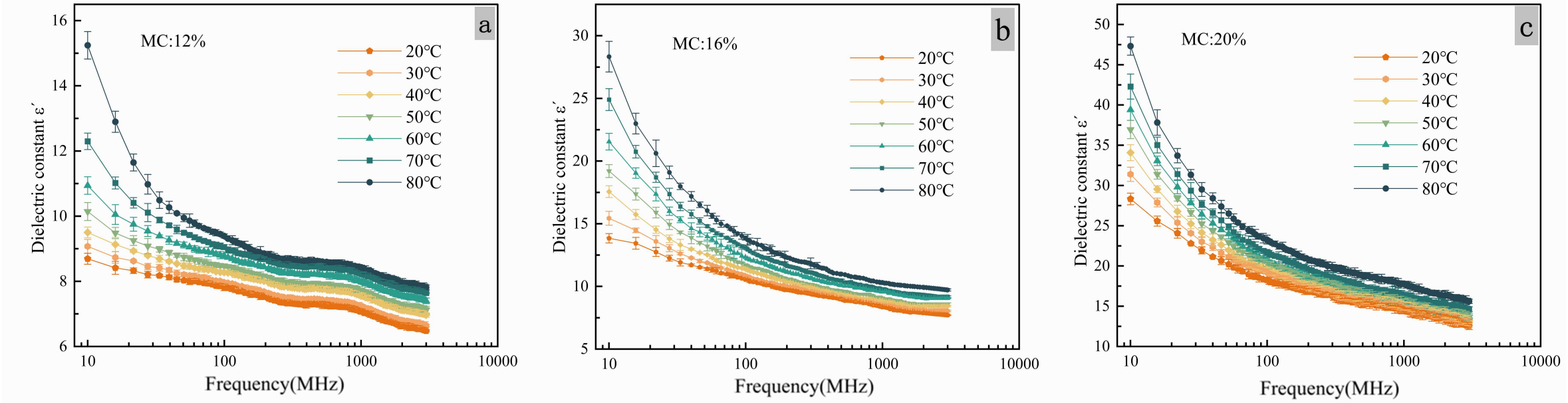
Early instar larvae

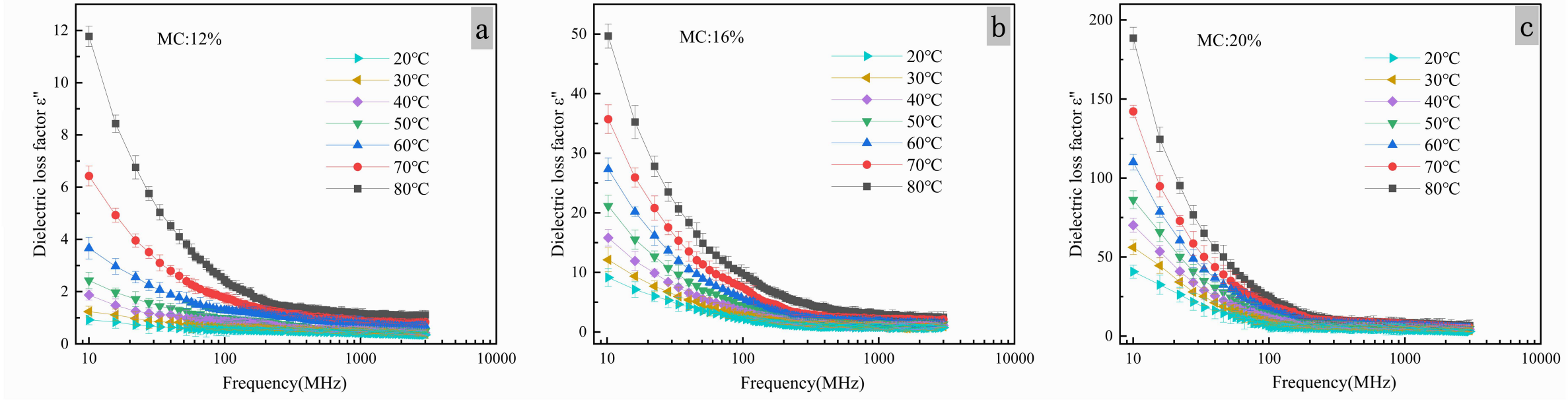


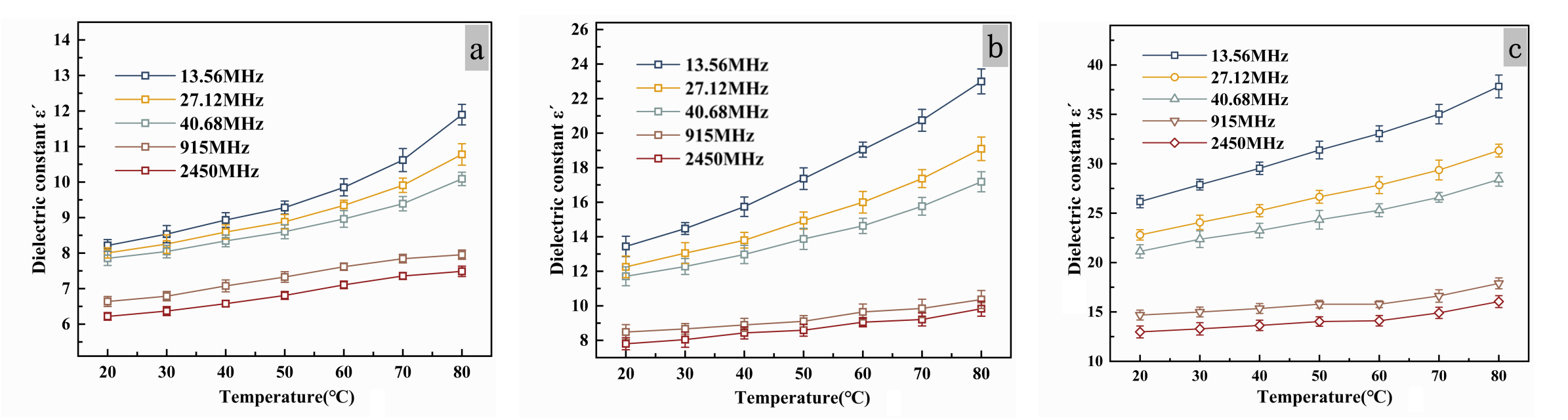
Late instar larvae

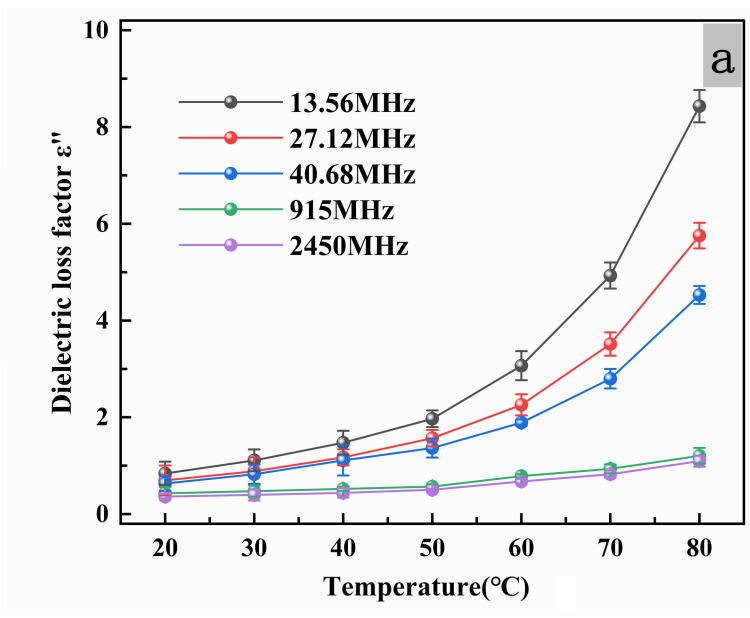

High-temperature coaxial cable
Sleeve vessel
Oil bath heating system
Coaxial probe
Sample
KEYSIGHT
RF Out
Port 1
Port 2
Impedance analyzer
Thermograph
Temperature sensor

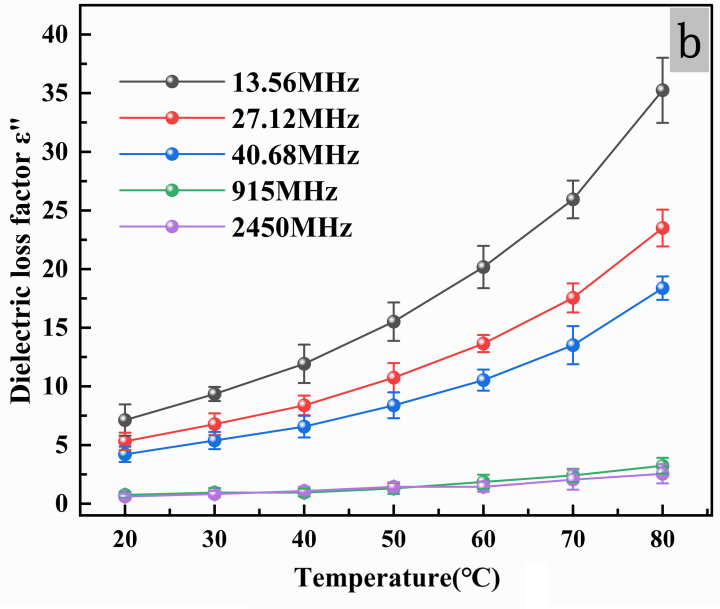

Infrared camera
Computer
Sample
Centrifugal fan
Fiber optic sensor
Top electrode
Sample
Bottom electrode
Control panel
Ventilation duct
Heating tube
Hot air system

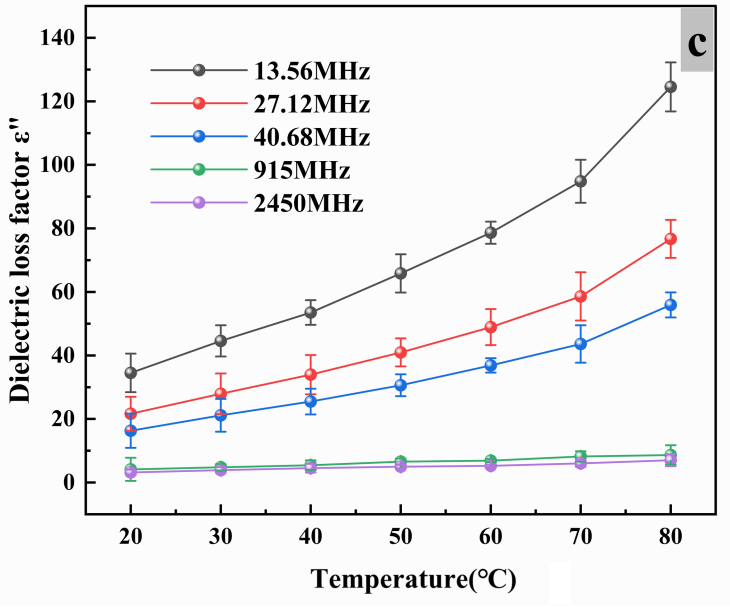

a
MC:12%
20°C
30°C
40°C
50°C
60°C
70°C
80°C
Dielectric constant ε´
Frequency(MHz)
b
MC:16%
c
MC:20%

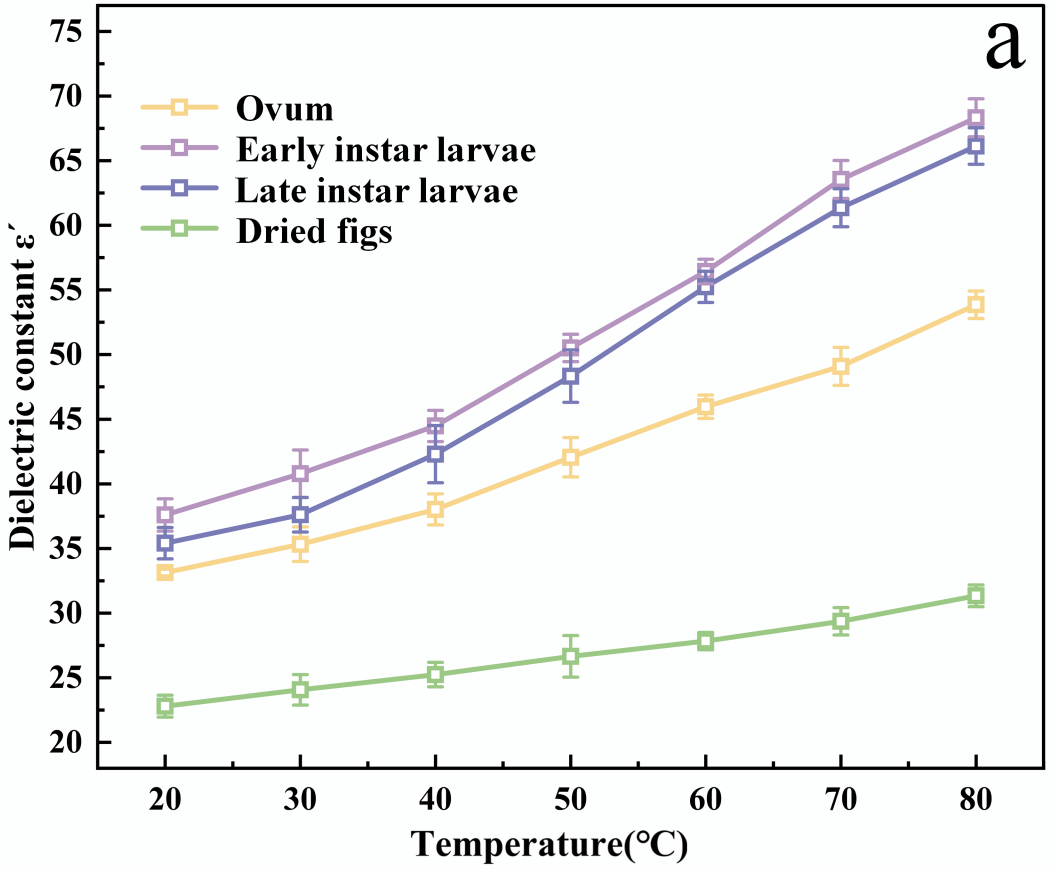

a
MC:12%
20℃
30℃
40℃
50℃
60℃
70℃
80℃
Dielectric loss factor ε"
Frequency(MHz)
b
MC:16%
c
MC:20%

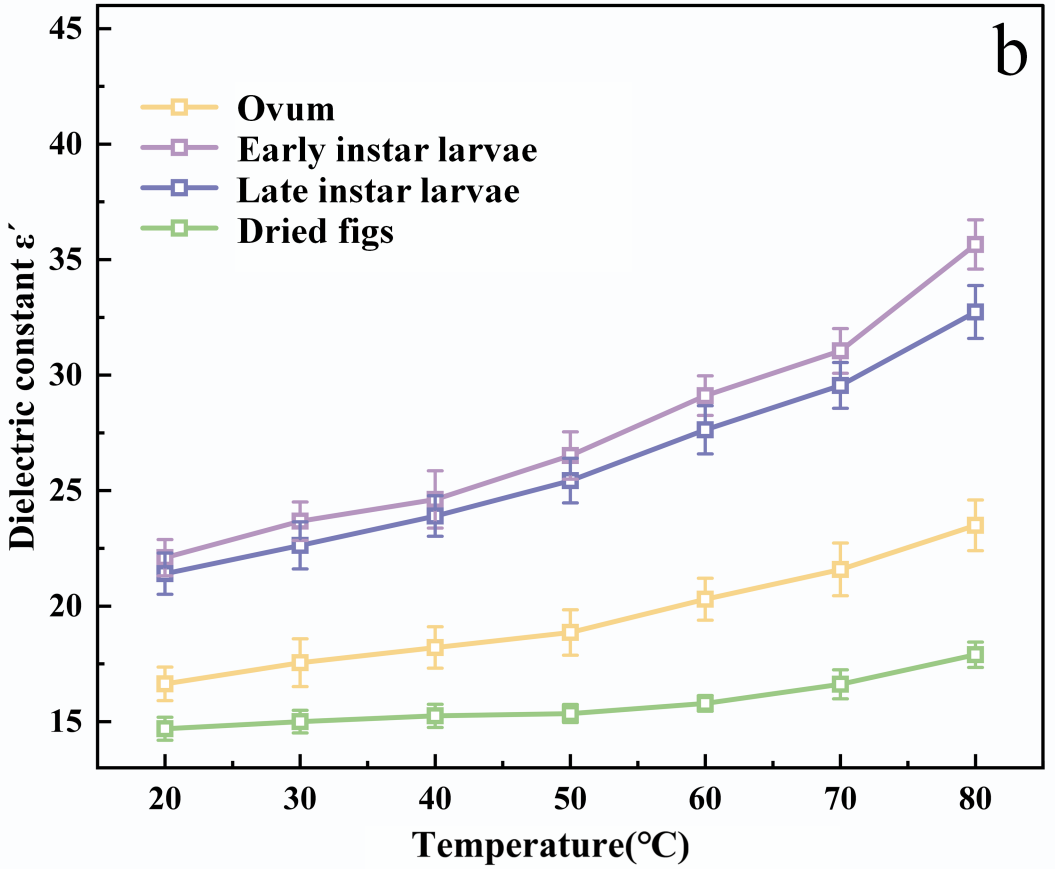

a
b
c
13.56MHz
27.12MHz
40.68MHz
915MHz
2450MHz
Dielectric constant ε´
Temperature(°C)

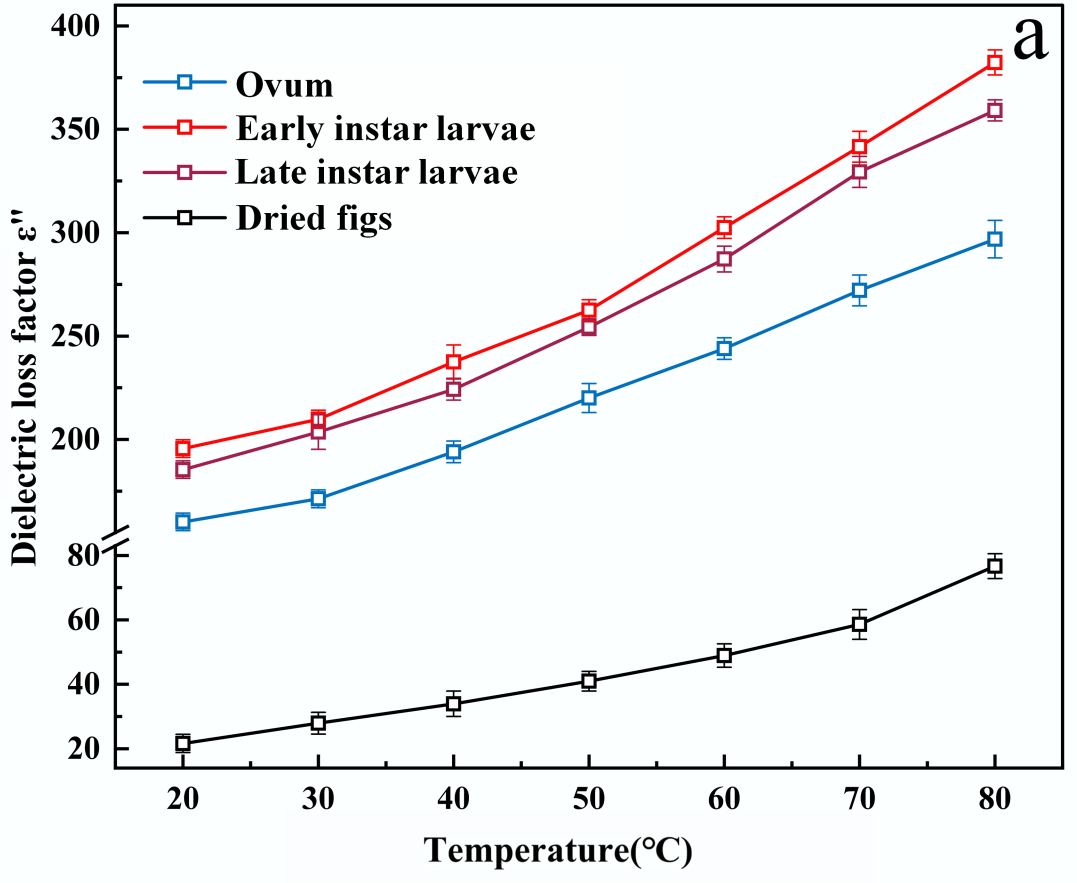

a
13.56MHz
27.12MHz
40.68MHz
915MHz
2450MHz
Dielectric loss factor ε''
Temperature(°C)
0
2
4
6
8
10
20
30
40
50
60
70
80

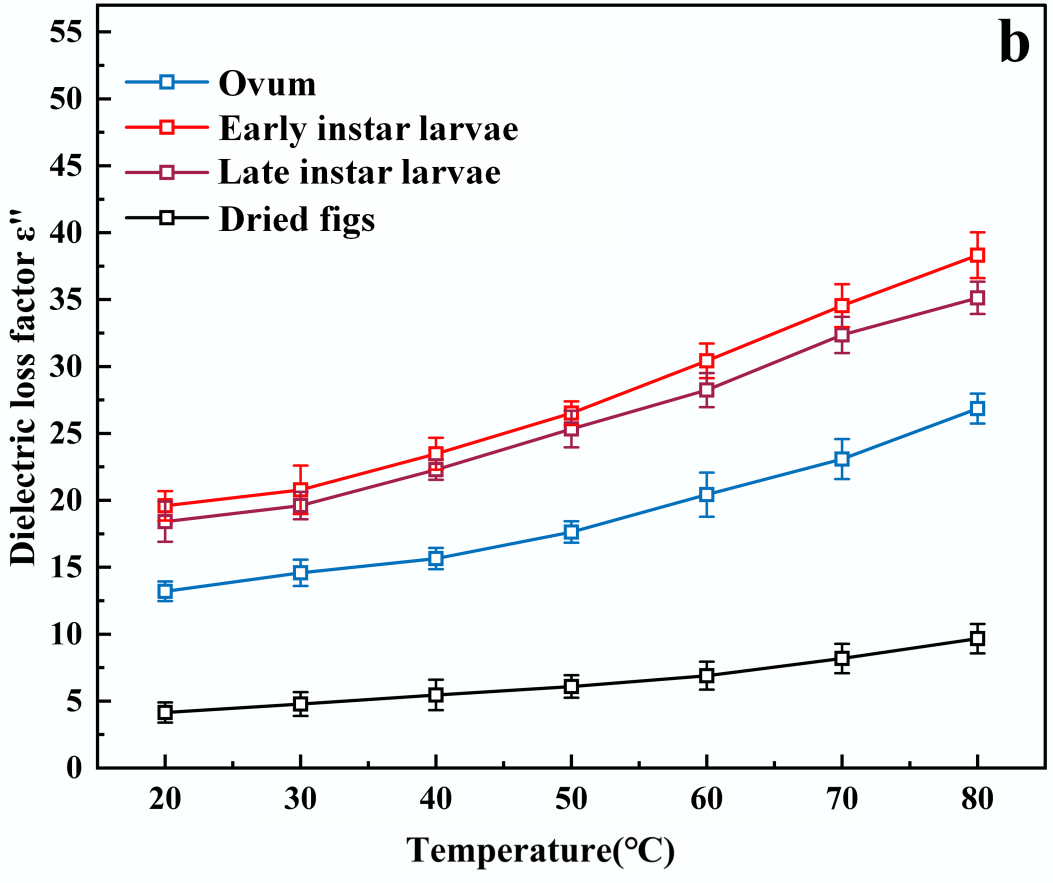

b
13.56MHz
27.12MHz
40.68MHz
915MHz
2450MHz
Dielectric loss factor ε''
Temperature(°C)
0
5
10
15
20
25
30
35
40
20
30
40
50
60
70
80

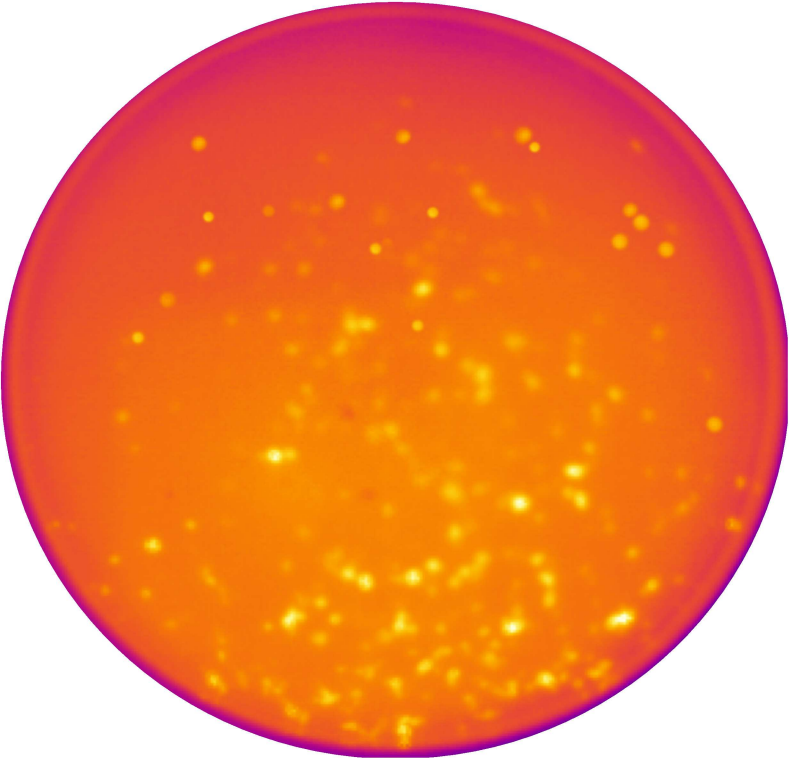
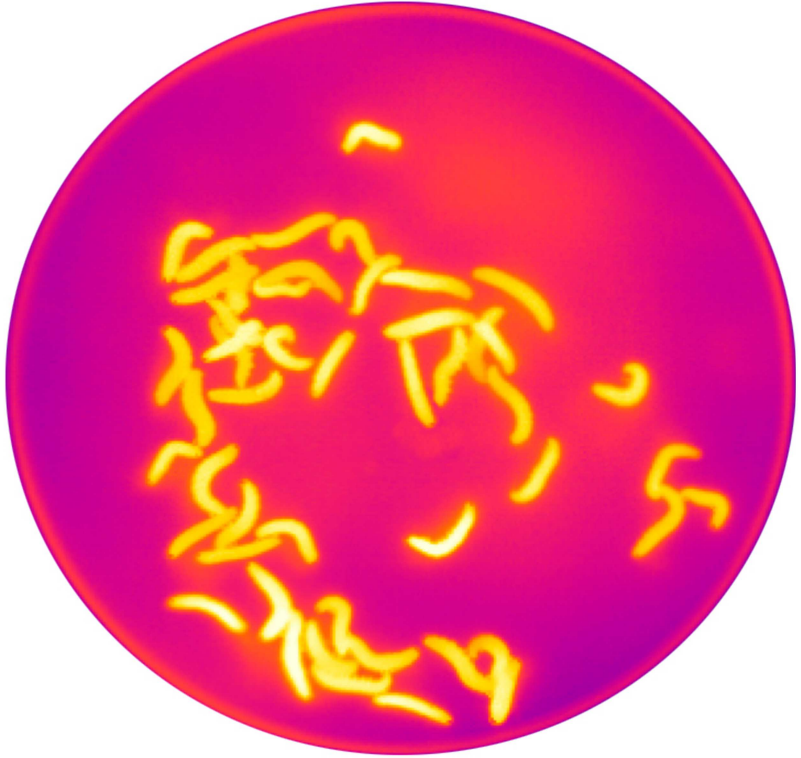
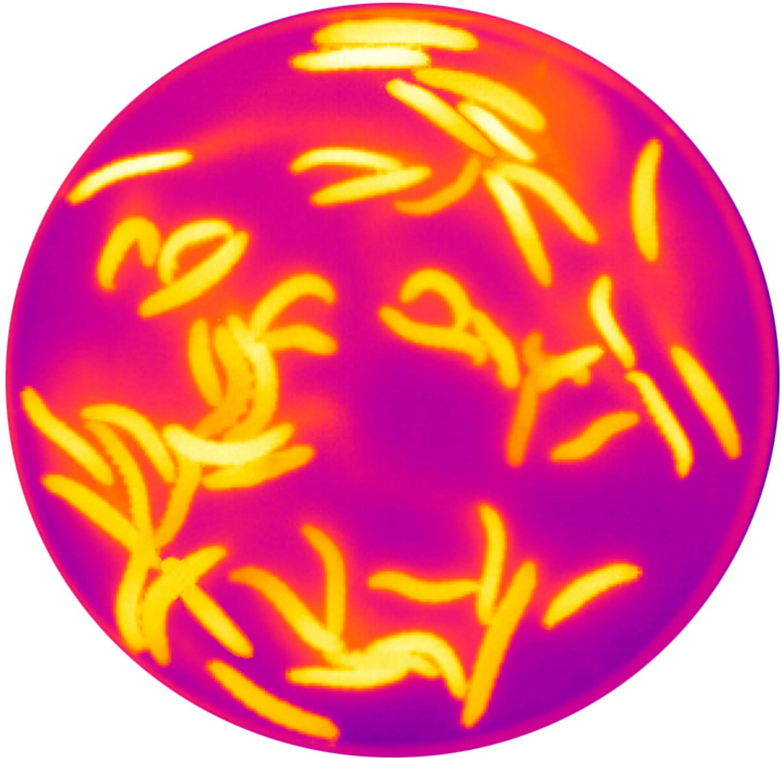

c
13.56MHz
27.12MHz
40.68MHz
915MHz
2450MHz
Dielectric loss factor ε''
Temperature(°C)
0
20
40
60
80
100
120
140
20
30
40
50
60
70
80

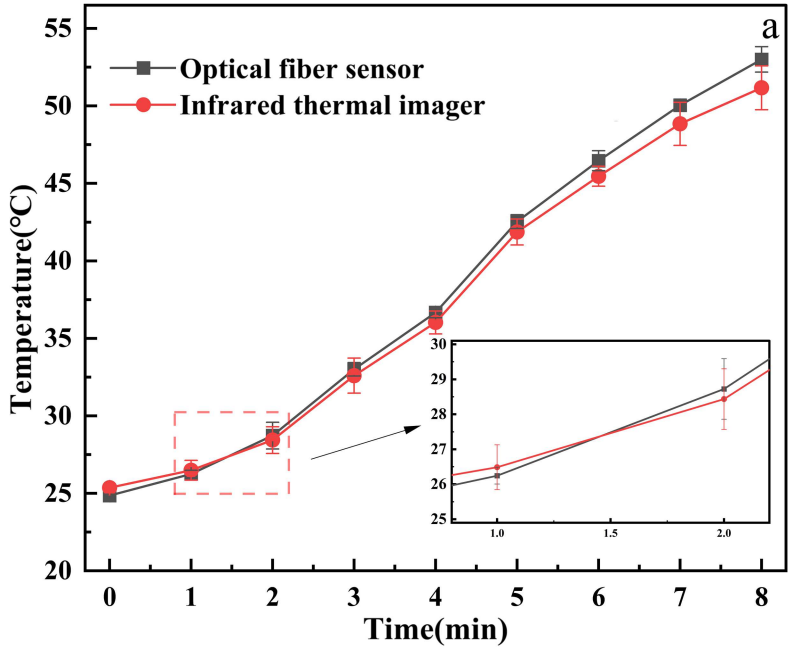

a
Ovum
Early instar larvae
Late instar larvae
Dried figs
Dielectric constant ε´
Temperature(°C)
75
70
65
60
55
50
45
40
35
30
25
20
20
30
40
50
60
70
80

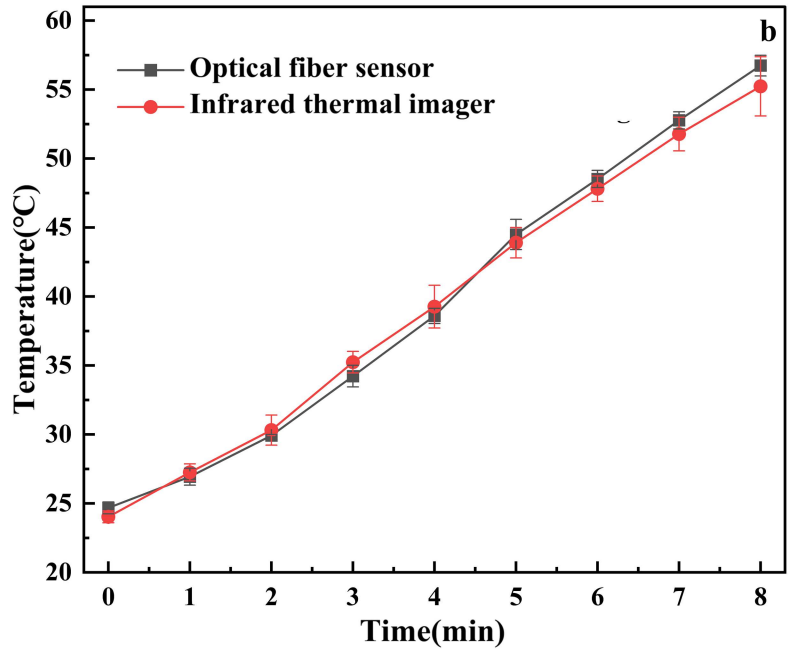

b
Ovum
Early instar larvae
Late instar larvae
Dried figs
Dielectric constant ε´
Temperature(°C)
45
40
35
30
25
20
15
20
30
40
50
60
70
80

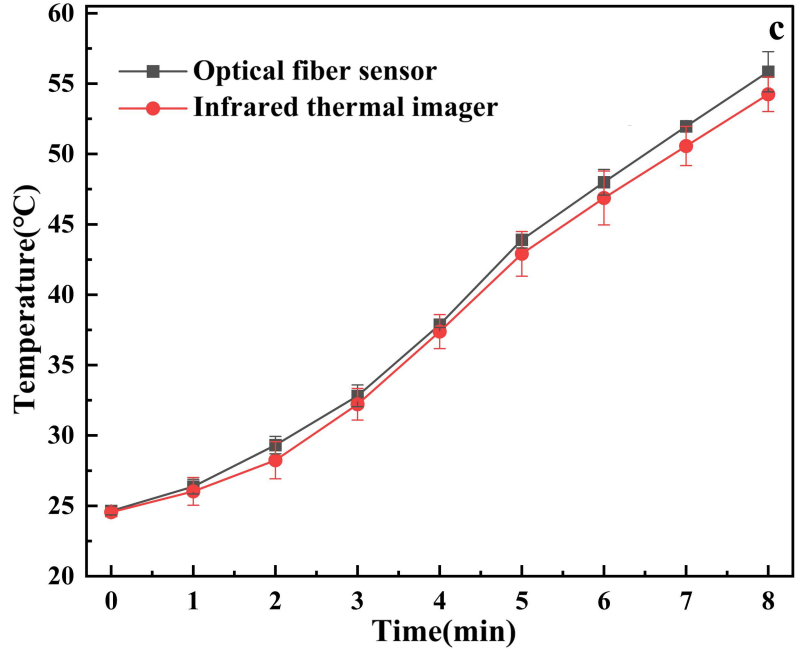

a
Ovum
Early instar larvae
Late instar larvae
Dried figs
Dielectric loss factor ε''
Temperature(℃)
400
350
300
250
200
80
60
40
20
20
30
40
50
60
70
80

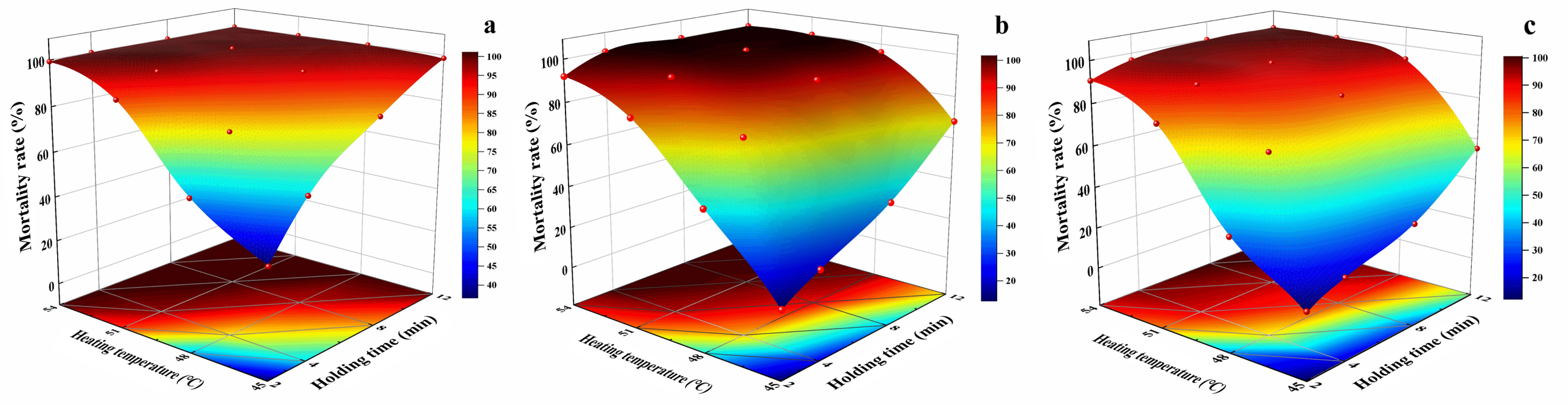

b
Ovum
Early instar larvae
Late instar larvae
Dried figs
Dielectric loss factor ε''
Temperature(℃)
55
50
45
40
35
30
25
20
15
10
5
0
20
30
40
50
60
70
80

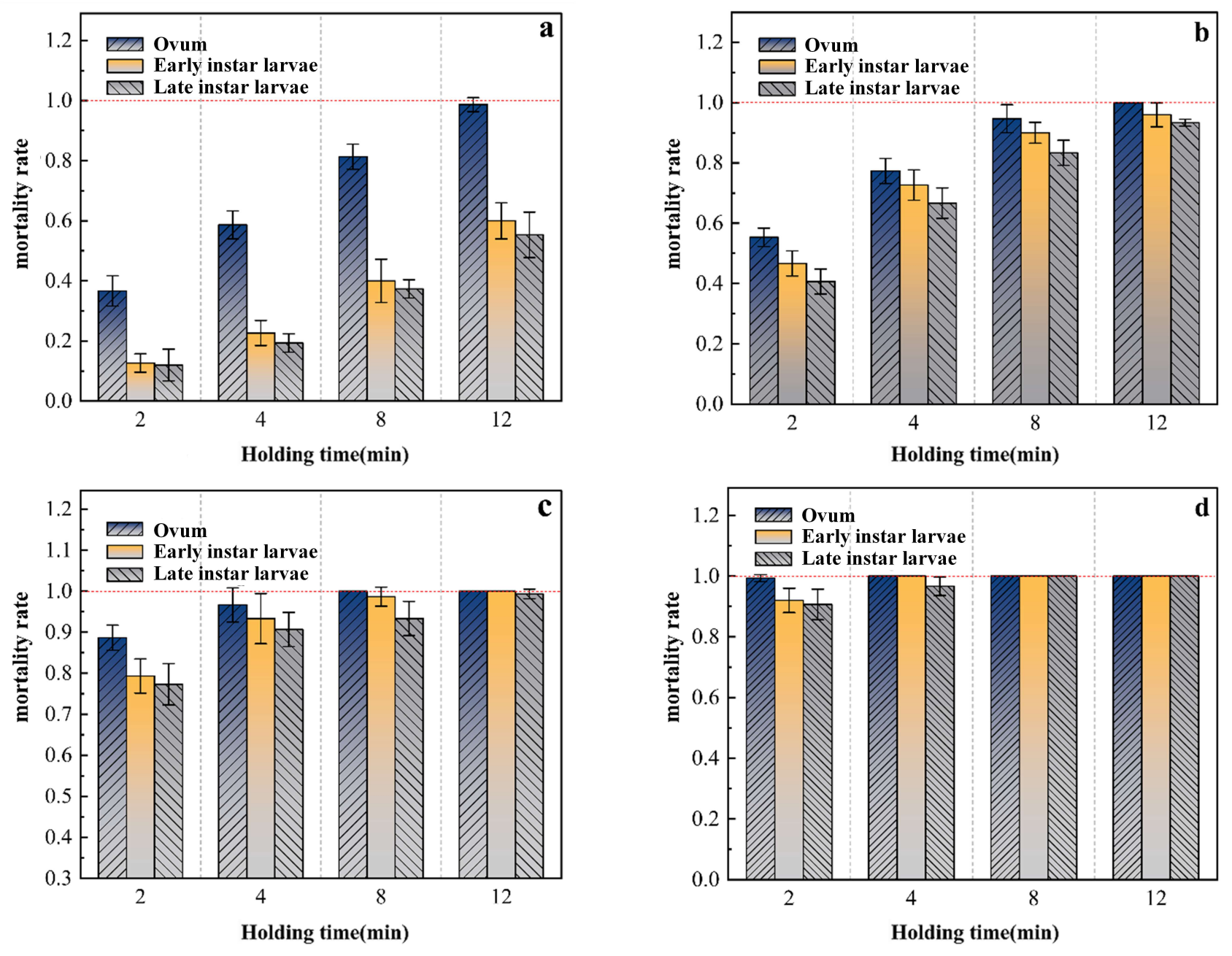





a
Optical fiber sensor
Infrared thermal imager
Temperature(°C)
Time(min)


b
Optical fiber sensor
Infrared thermal imager
Temperature(°C)
Time(min)


c
Optical fiber sensor
Infrared thermal imager
Temperature(°C)
Time(min)


a
b
c
Mortality rate (%)
Heating temperature (℃)
Holding time (min)
100
80
60
40
20
0
45
48
51
54
2
4
8
12


a
Ovum
Early instar larvae
Late instar larvae
mortality rate
Holding time(min)
b
Ovum
Early instar larvae
Late instar larvae
mortality rate
Holding time(min)
c
Ovum
Early instar larvae
Late instar larvae
mortality rate
Holding time(min)
d
Ovum
Early instar larvae
Late instar larvae
mortality rate
Holding time(min)