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# Dielectric properties of edible fungi powder related to radio-frequency and microwave drying

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## Abstract

Edible fungi are rich in nutrition, but they are susceptible to spoilage, and often prolonged by drying. RF and microwave energy drying have the advantages of short drying time, high energy efficiency and good process control. However, to develop an effective dielectric drying method, it is important to understand dielectric properties, the major factor characterizing the interaction between the electromagnetic energy and the food. At present, there is a lack of research on dielectric properties of edible fungi. In this study, a vector network analyzer and an open-ended coaxial-line probe were employed to measure the dielectric parameters. The dielectric parameters were observed at different temperatures (25–85 °C) for edible fungi powder with moisture content ranging from 5 to 30% wet basis over a frequency range of 1–3000 MHz. The relationship between the dielectric properties and frequency, temperature, and moisture content were obtained via regression analysis. Further, the dielectric penetration depth was calculated, and the effects of frequency, moisture content, and temperature on the penetration depth were also analyzed. The results showed that the dielectric properties of edible fungi powder increased with an increase in moisture content and temperature, while they decreased with increasing frequency. At high moisture content and temperature, the increase in dielectric properties was slightly larger than that at low moisture content and temperature. The dielectric properties changed more evidently at lower radio frequencies than at higher radio frequencies. The penetration depth decreased with an increase in temperature, moisture content, and frequency. It can be concluded that a large penetration depth at radio frequencies below 100 MHz could be used to dry edible fungi on a large scale, whereas microwave energy could be employed for drying edible fungi on a small scale.

**Keywords:** Edible fungi, Dielectric properties, Dielectric drying, Dielectric constant, Dielectric loss factor, Mathematical modeling

## Introduction

Edible fungi (mushrooms) have a large fruiting body, taste delicious, and have high edible, medicinal, and economic values (Sun et al. 2019; Xue et al. 2019). Edible fungi are a healthy food with significant therapeutic

effects and are rich in bioactive compounds, including polysaccharides (e.g.,  $\alpha$ - and  $\beta$ -glucan), proteins, peptides, polyphenols, terpenoids, vitamins, and dietary fiber (Khan & Tania, 2012; Reis et al. 2012; Yan et al. 2018). The most reasonable and balanced dietary structure in the twenty-first century is “one meat, one vegetable, and one mushroom,” indicating that edible fungi occupy an extremely important position in human diet (Manzi et al. 2001). At present, China is the world’s largest producer of edible fungi, accounting for more than 70% of

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the world's total production. However, due to the late development of storage and processing technology of edible fungi in China, the technology is relatively backward, restricting the advancement of the edible fungi industry (Sun et al. 2019). Particularly when edible fungi are in season, they are abundant, and the overstocking of products causes extremely heavy economic losses (Walde et al. 2005). Drying processes can be used to reduce the moisture content of edible fungi, preventing the growth and propagation of microorganisms and biological enzyme activity (Su et al. 2020; Tian et al. 2016). The dried product is convenient for long-term storage and transportation. Therefore, research on the drying and storage of edible fungi, methods of drying, and drying conditions is the top priority in the development of the current edible fungi industry.

Drying of edible fungi is a cost-effective and popular processing method (Wang et al. 2017). It has been experimentally shown that the use of radio-frequency (RF) drying is better than conventional heating and drying (Zhao et al. 2018). RF and microwave energy drying have the advantages of short drying time, high energy efficiency, good process control, small footprint, and quick startup and downtime. Microwave-assisted air drying shortened the drying time of mushrooms by four times compared with that of hot air (Ewa et al. 2019). The studies have shown that dielectric drying can significantly improve the drying process of foods in low-moisture foods (Wang et al. 2020; Zhou et al. 2018a, b).

The thermal process of food is a significantly complicated processing, involving various changes and transmissions of calories (Cong et al. 2012). Therefore, attention should be paid to the selection of relevant conditions when using dielectric heating. The most important material characteristic to control dielectric heating is the dielectric permittivity  $\epsilon = \epsilon' - j\epsilon''$  of the material, namely, the dielectric constant,  $\epsilon'$ , and loss factor,  $\epsilon''$  (Lau & Subbiah, 2018). These are influenced by the applied frequency, the material temperature and moisture (Guo et al. 2009; Zhu et al. 2012; Guo & Zhu, 2014). The application of dielectric heating for disinfection, drying, pasteurization, and thawing has been studied by many scholars (Bedane et al. 2017; Li et al. 2018; Ling et al. 2016; Li et al. 2017; Nagaraj et al. 2016; Zheng et al. 2017; Zhou et al. 2017; Zhou et al. 2018a, b). However, there is no specific research on the dielectric properties of edible fungi powder in the frequency range of 1–3000 MHz, and the relationship between the dielectric properties of edible fungi powder and their influencing factors.

To provide useful information for equipment and process design during the deceleration stage of drying edible fungi with dielectric drying, the dielectric properties of five types of edible fungi powder with a moisture

content of 5–30% were measured. For this purpose, an open coaxial probe and vector network analyzer were used, and the temperature and frequency ranges were 25–85 °C and 1–3000 MHz, respectively. Furthermore, mathematical models were used to describe the dependence of the dielectric properties of edible fungi powder on frequency, moisture content, and temperature. The penetration depth of these five types of edible fungi powder was also calculated.

## Materials and methods

### Raw materials

The test materials were selected from five types of edible fungi, including *Pleurotus eryngii*, *Flammulina velutipes*, *Velvet mushroom*, *Agaricus bisporus*, and *Straw mushroom*, which were ordered from the local market. Before the experiment, the edible fungi were washed, diced, and dried in an oven at 55 °C for more than 10 h, and then converted into a powder using a pulverizer. After passing through an 80-mesh sieve, the initial moisture content of the edible fungi powder sample was determined.

### Pretreatment of samples

Samples that were ground into powder and sieved through 80-mesh sieves were weighed and sampled into six parts of approximately 100 g using an electronic balance and placed in evaporating dishes. The powder samples with moisture contents of 5, 10, 15, 20, 25, and 30% were prepared by spraying water on 100-g powder samples with a fine-hole spray pot, and then they were placed in completely sealed bags. The samples were stored in a refrigerator at 4 °C for 24 h, and the bags were shaken four to six times a day to obtain a uniform moisture distribution throughout the sample.

### Determination of moisture content

The initial moisture content of the sample and the actual moisture content of the finished sample were determined via the 105 °C constant weight method. First, a clean aluminum flat weighing dish was placed in a 105 °C drying box to heat for 0.5–1.0 h, and the dish lid was obliquely supported on the side of the dish. Subsequently, the cover was taken out and placed in a desiccator for 0.5 h, and then weighed and recorded (repeated drying was required to obtain constant weight). Next, an accurately weighed 2-g sample (accurate to 0.0001 g) with a thickness of approximately 5 mm was placed into the weighing dish and covered and weighed. The weight was recorded. Subsequently, the weighing dish with sample was placed in a drying oven at 105 °C, weighing dish lid was obliquely supported on the side of the dish. After 4 h of drying, the weighing dish with sample was removed and placed in the desiccator for 0.5 h and

weighed. Then, it was placed in a drying oven at 105 °C for 1 h, taken out, cooled in the desiccator for 0.5 h, and then weighed. The difference in mass between the measurements before and after drying was not more than 0.002 g, which implied a constant weight. Subsequently, the moisture content of the sample was calculated.

**Determination of temperature**

The temperature required for the experiment was set using a constant-temperature water bath to uniformly heat the sample, and the temperature of the sample was calculated using a thermocouple thermometer. In order to accurately determine the temperature change of the sample during the measurement process, the probe of the thermocouple thermometer was inserted inside the sample and fixed.

**Determination of dielectric properties**

The experimental system consisted of a computer, an E5061B vector network analyzer (Agilent Corporation, USA), an open coaxial probe (Agilent Corporation, USA), a constant-temperature water bath, a temperature control unit, and a lifting platform (Jintan Science and Technology Instrument Co., Ltd.). The computer was employed to control the system and record the date and data. The sample temperature was monitored by a T-type thermocouple thermometer with a measurement accuracy of 0.1 °C. The laboratory lifting platform was used to change the water bath height. A schematic diagram of the dielectric properties measurement system is shown in Fig. 1.

Before the measurement experiment, the vector network analyzer was turned on to warm up approximately 30 min. Then, the vector network analyzer and the coaxial probe with an open-end were calibrated. The network analyzer was calibrated using deionized water, air, and short circuit, and the sensitivity of the open coaxial probe was tested as suggested by Lau et al. (2020).

After the calibration, for each moisture level, approximately 15 g of edible fungi powder was put in a stainless-steel cylindrical sample holder (inner diameter 30 mm, height 10 mm) with bulk density about 3.18 g/

cm<sup>3</sup> fixed in a constant-temperature water bath to avoid heat loss as much as possible. It was ensured that the open coaxial probe fitted snugly against the surface of the sample and maintained adequate pressure to avoid air gaps in the measurement process. Further, a thermocouple was inserted in the center of the sample to monitor the temperature of the sample.

The dielectric properties of edible fungi powder at different moisture contents and temperatures were measured. The dielectric constant and dielectric loss factor were read by a computer, and the data were saved. During the experiment, the ambient temperature was controlled as approximately 23 °C, and the height of the water bath was controlled by the laboratory lifting platform. The temperature of the circulating water in the water bath was set to 25, 35, 45, 55, 65, 75, and 85 °C consecutively in intervals of 10 °C. After the sample temperature reached the specified value, the dielectric properties were determined three times in 2 min, and the mean value was calculated.

The mathematical formula proposed by Auksornsri to describe the dielectric constant and dielectric loss factor of pure polar materials could be expressed as follows (Auksornsri et al., 2018):

$$\epsilon' = \epsilon_{\infty} + \frac{\epsilon_s - \epsilon_{\infty}}{1 + (2\pi f)^2 \tau^2} \tag{1}$$

$$\epsilon'' = \frac{(\epsilon_s - \epsilon_{\infty}) \cdot 2\pi f \tau}{1 + (2\pi f)^2 \tau^2} \tag{2}$$

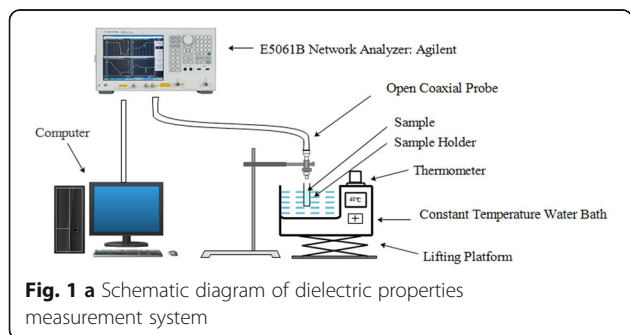
where the dielectric constant  $\epsilon_{\infty}$  indicates that the molecular orientation does not have sufficient time to promote polarization when the frequency is close to infinity,  $\epsilon_s$  stands for the static dielectric constant, i.e., the value at zero frequency,  $f$  represents the frequency (MHz), and  $\tau$  denotes the relaxation time (s), the time when the period related to the dipole time recovers in a random direction after removing the electric field.

**Effect of frequency on dielectric properties**

The sample moisture content was 5–30% with an interval of 5% (a total of six moisture contents) and the temperature range was 25–85 °C with an interval of 10 °C (a total of six temperatures). The moisture content and temperature of the experimental sample were controlled, and the frequency was set to 1–3000 MHz. The effect of the frequency on the dielectric properties was studied.

**Effect of temperature on dielectric properties**

The sample temperature was controlled using a digital constant-temperature water bath. The moisture content was 5–30%, with an interval of 5%, and a total of six moisture content intervals. The frequency was set



to 1–3000 MHz. The moisture content and frequency of the sample were controlled, and the effect of temperature on the dielectric properties was studied from 25 °C to 85 °C in increments of 10 °C.

#### Effect of moisture content on the dielectric properties

The sample moisture content was controlled using a spray pot. The temperature range was 25–85 °C, with a total of seven temperature intervals in increments of 10 °C. The frequency was set to 1–3000 MHz. The temperature and frequency of the sample were controlled, and the effect of moisture content on dielectric properties was studied.

#### Microwave penetration depth

The penetration depth is defined as the distance at which the microwave power is decreased to 1/e ( $e = 2.718$ ) of that at the surface. The penetration depth is an important parameter for evaluating the heating uniformity during microwave heating (Erdogdu et al. 2015). The following equation was used to calculate the penetration depth:

$$d_p = \frac{c}{2\pi f \sqrt{2\epsilon' \left[ \sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} - 1 \right]}} \quad (3)$$

where  $d_p$ ,  $c$ ,  $f$ ,  $\epsilon'$ , and  $\epsilon''$  represent the penetration depth (m), speed of light in free space ( $3 \times 10^8 \text{ m s}^{-1}$ ), frequency of microwave (MHz), measured dielectric constant, and measured dielectric loss factor value, respectively.

#### Statistical analysis

All experiments were repeated at least three times, and the data were expressed as mean  $\pm$  standard deviation. Microcal Origin 9.0 (Microcal Software, Inc., Northampton, USA) software and SPSS 19.0 computer program (SPSS Inc., Chicago, IL, USA) were employed for statistical analysis. Regression analysis was performed to determine the significant probability for moisture content, frequency, and temperature to affect the dielectric constant and dielectric loss constant.

## Results and discussion

#### Effect of frequency on dielectric properties

Figure 2 shows the frequency-dependent dielectric properties ( $\epsilon'$  and  $\epsilon''$ ) of *Pleurotus eryngii* powder with a moisture content of 12.0 and 30.9% at a temperature of 25–85 °C in the frequency range of 1–3000 MHz. From Fig. 2, both  $\epsilon'$  and  $\epsilon''$  are affected by the frequency. In the studied frequency range, the dielectric constant  $\epsilon'$  decreases with frequency, and the trend is more evident at low frequencies. The

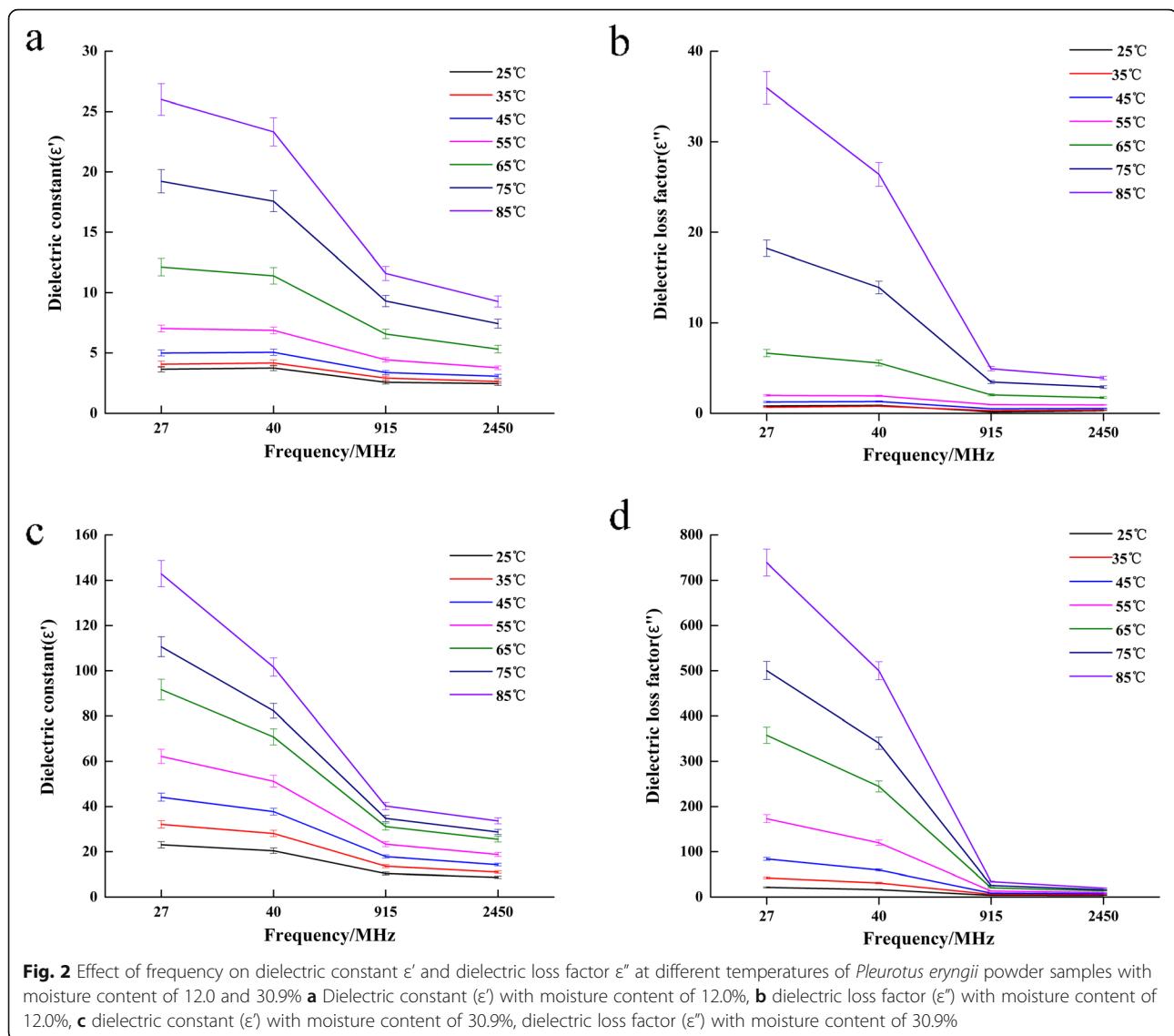
dielectric loss factor  $\epsilon''$  decreases significantly with the increase in frequency. For instance, when the temperature is 75 °C, the frequency increases from 27 MHz to 915 MHz and the dielectric constant of *Pleurotus eryngii* powder with a moisture content of 12.0% decreases from 19.22 to 9.31, which represents a decrease of approximately 51.6%. Similarly, the dielectric loss factor decreases from 18.22 to 2.88, which denotes a reduction of approximately 84.2%. Furthermore, when the frequency continues to increase to 2450 MHz, the dielectric constant reduces from 9.31 to 7.43, which is a decrease of approximately 20.2%, and the dielectric loss factor increases slightly to 3.44. This result is consistent with those reported by Zhang et al. (2016) and Zhou et al. (2018a, b).

At higher temperatures ( $> 45$  °C), the effect of frequency on dielectric constant  $\epsilon'$  and dielectric loss factor  $\epsilon''$  is more prominent than that at lower temperatures. For example, when the frequency is increased from 27 MHz to 2450 MHz, the dielectric constant of *Pleurotus eryngii* powder with a moisture content of 12.0% is reduced from 3.64 to 2.44 at 25 °C, but significantly decreases from 15.99 to 9.27 at 85 °C, respectively. The dielectric loss factor decreases from 0.79 to 0.29 at 25 °C and from 35.94 to 3.90 at 85 °C respectively.

In addition, the effect of frequency on the dielectric constant and dielectric loss factor is more evident at high moisture content than that at low moisture content. For instance, at 25 °C, when the frequency is increased from 27 MHz to 2450 MHz, the dielectric constant of the sample with a moisture content of 12.0% decreases from 3.64 to 2.44, and the dielectric constant of the sample with a moisture content of 30.9% decreases from 23.04 to 8.74, depicting reductions of 33.0 and 62.1%, respectively, and this result is similar to that reported by Auksornsri et al. (2018). Further, the dielectric loss factor value of the sample with a moisture content of 12.0% decreases from 0.79 to 0.29, while the sample with 30.9% moisture content decreases from 21.44 to 3.68, indicating reductions of 63.3 and 82.8%, respectively.

A similar frequency-dependent dielectric constant  $\epsilon'$  and dielectric loss factor  $\epsilon''$  were also found in samples of *Pleurotus eryngii* powder with other moisture contents. As shown in Figs. 3 and 4, the other four edible fungi also have the same frequency-dependent dielectric properties as those of *Pleurotus eryngii*.

Equations (1) and (2) show that  $\epsilon'$  and  $\epsilon''$  are determined by  $\epsilon_s$ ,  $\epsilon_\infty$ ,  $\tau$ , and  $f$ . At a specified temperature,  $\epsilon_s$ ,  $\epsilon_\infty$ , and  $\tau$  are almost constant. Evidently,  $\epsilon'$  and  $\epsilon''$  are negatively correlated with the square of the frequency. This is the reason why  $\epsilon'$  and  $\epsilon''$  of *Pleurotus eryngii* powder decrease with an increase in frequency. The reason that  $\epsilon'$  rises substantially and tends to be gradual at

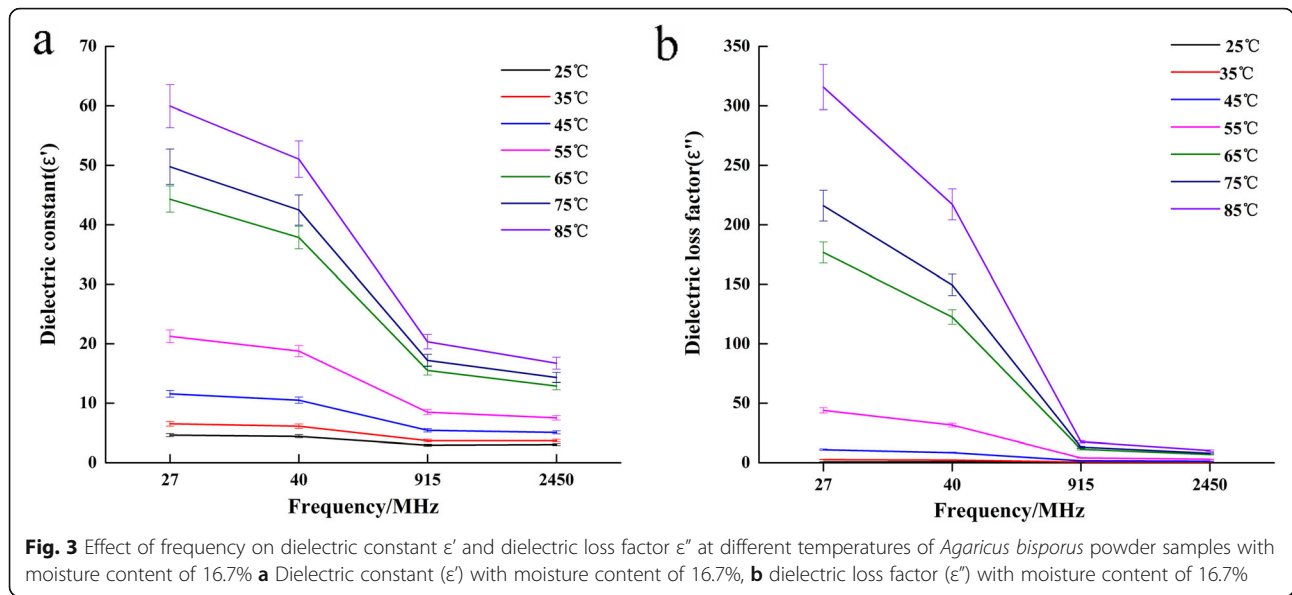


high frequencies is that the negative linear relationship between  $\epsilon'$  and frequency is caused by ion conduction. In the lower RF range and at higher microwave frequencies, ion conduction and dipole polarization are the main loss mechanisms, respectively.

#### Effect of temperature on dielectric properties

The dielectric constant  $\epsilon'$  and the dielectric loss factor  $\epsilon''$  of the *Pleurotus eryngii* powder at temperatures of 25–85 °C, frequencies of 27, 40, 915, and 2450 MHz, and a moisture content of 21.2% are shown in Fig. 5. At the four frequencies, the dielectric constant  $\epsilon'$  and dielectric loss factor  $\epsilon''$  increase with increasing temperature. At high frequencies (915 and 2450 MHz), the dielectric constant and dielectric loss factor vary slightly with temperature, especially the dielectric loss factor. At low

frequencies (27 and 40 MHz), the dielectric constant and the dielectric loss factor change rapidly, especially at temperatures above 45 °C. For example, when the temperature increases from 25 °C to 85 °C, for the sample with a moisture content of 21.2% at 27 MHz, the dielectric constant increases from 8.25 to 70.94, and the dielectric loss factor increases from 2.34 to 368.36, increasing by 88.4 and 99.4%, respectively. At 915 MHz, the dielectric constant and the dielectric loss factor increase from 5.45 and 0.97 to 30.50 and 19.74, increasing by 82.1 and 95.1%, respectively. Similar temperature-dependent dielectric properties were also observed at other moisture levels for *Pleurotus eryngii* powder. From Fig. 6, the other four edible fungi also have the same temperature-dependent dielectric properties as those of *Pleurotus eryngii*.

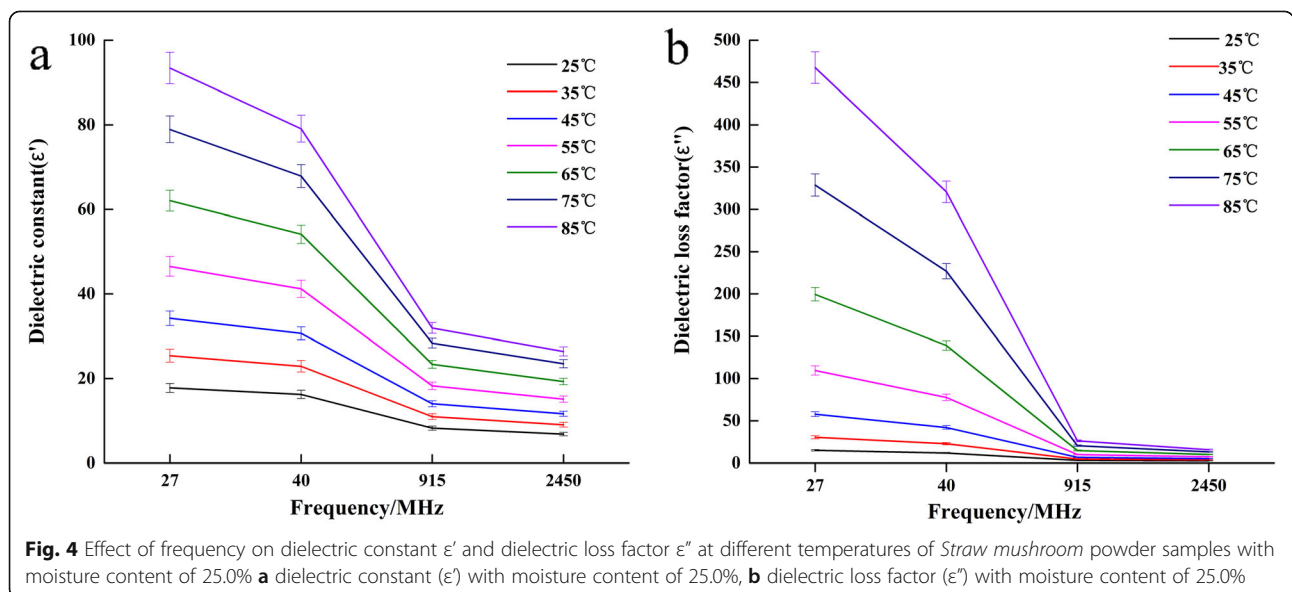


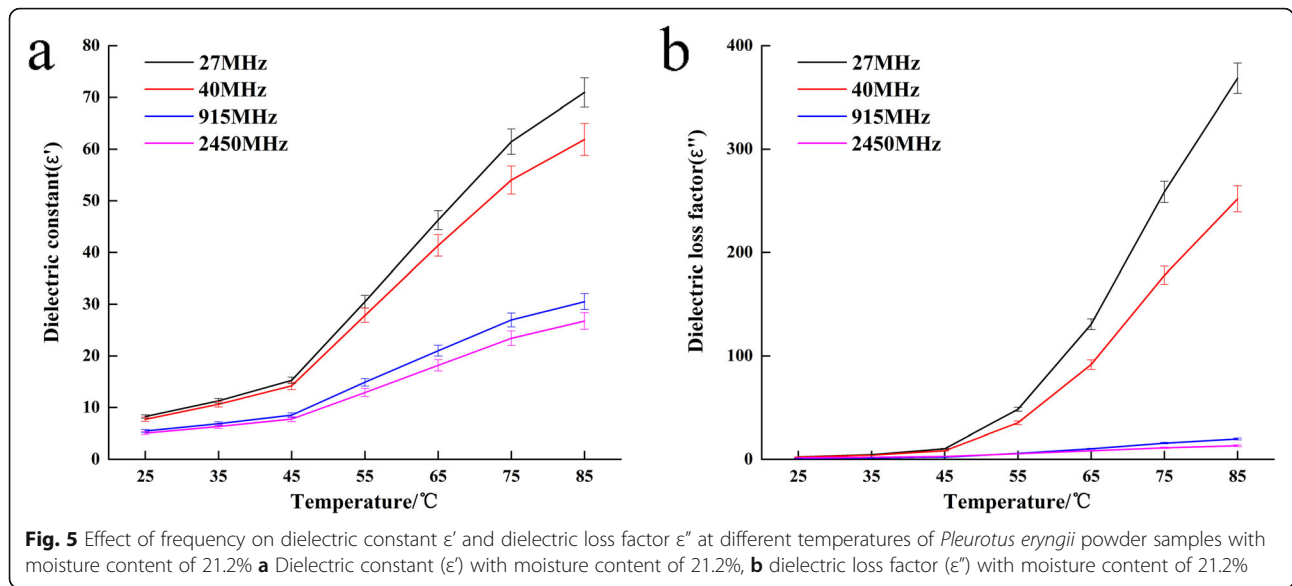
The increase in temperature leads to an increase in Brownian motion and the static dielectric constant, therefore the dielectric constant increases with increasing temperature. The dielectric loss factor is related to the dissolved ions in the sample, and the increase in temperature improves ion mobility and ion conduction, resulting in an increase in the dielectric loss factor in the studied frequency range.

**Effect of moisture content on dielectric properties**

Figure 7 shows the effect of the moisture content of *Pleurotus eryngii* powder on the dielectric constant  $\epsilon'$  and the dielectric loss factor  $\epsilon''$  at seven study temperatures at 915 MHz. Both  $\epsilon'$  and  $\epsilon''$  increase with increasing

moisture content and change rapidly when the moisture content is above 15.0%. In addition, the rate of increase at higher temperatures is slightly larger than that at low temperatures. For instance, at 25 °C, as the moisture content of the sample rises from 9.9 to 30.9%, the dielectric constant  $\epsilon'$  increases from 2.60 to 10.36 and the dielectric loss factor increases from 0.15 to 1.16, which represent increases of 75.0 and 87.0%, respectively. Similarly, at 85 °C, as the moisture content of the sample increases from 9.9 to 30.9%, the dielectric constant  $\epsilon'$  increases from 5.73 to 40.25 and the dielectric loss factor increases from 3.93 to 33.94, which denote increases of 85.8 and 88.4%, respectively. Similar moisture content-dependent dielectric properties were also observed at





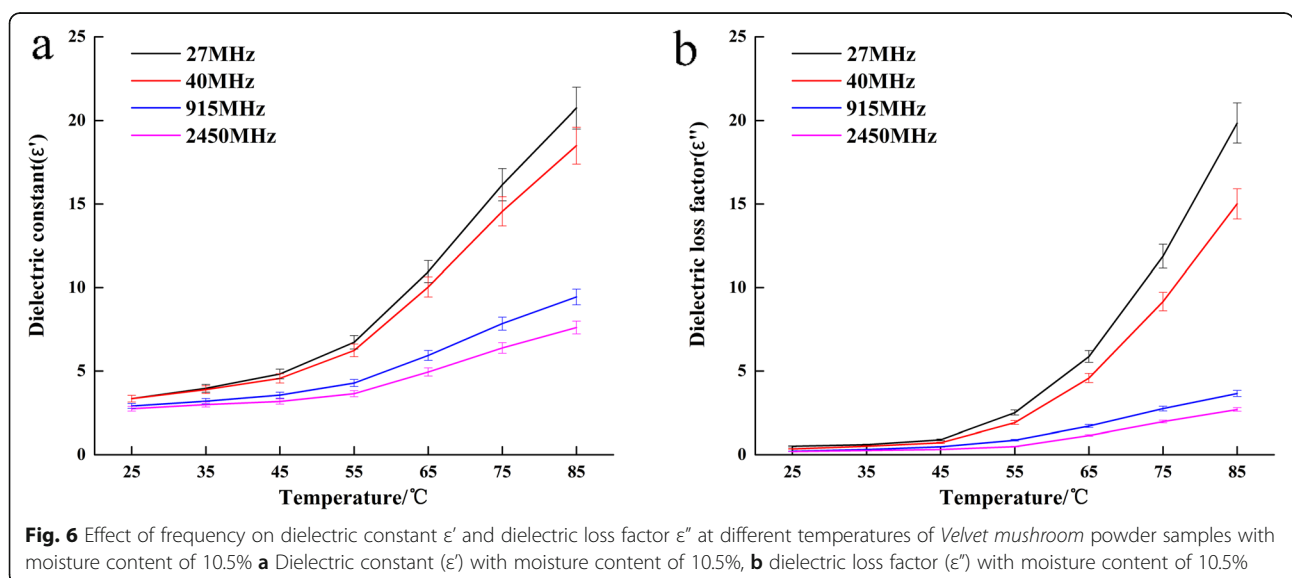
other frequency levels for *Pleurotus eryngii* powder. In addition, Fig. 8 shows that the other four edible fungi have the same moisture content-dependent dielectric properties as those of *Pleurotus eryngii*.

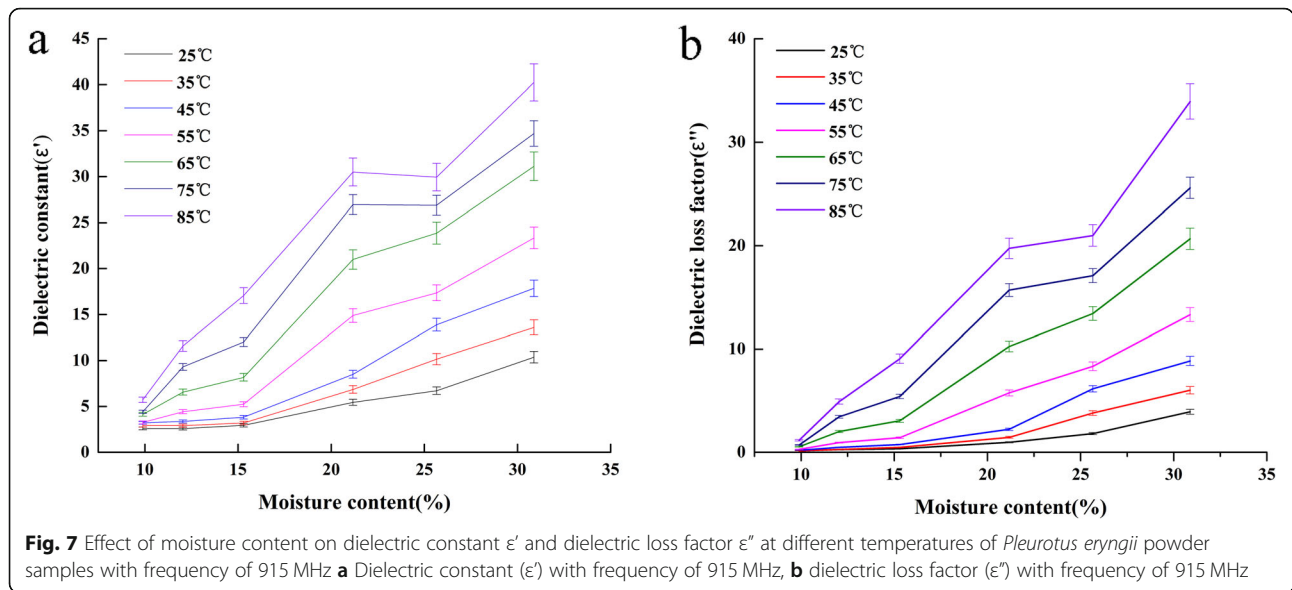
The effect of moisture content on dielectric properties depends on the free water and combined moisture content in food (Ozturk et al. 2016). With an increase in moisture content, the water molecules in the material gradually come close together to form multi-layered combined water (Li et al. 2019), or even become free water, which accelerates the overall metabolism of *Pleurotus eryngii* powder and enhance the activity of internal ions. Consequently, the dielectric constant and the dielectric loss factor

increase with increasing moisture content (Ahmed et al. 2020).

**Regression analysis**

Table 1 shows the regression models used in this study to describe the dielectric properties of the five types of edible fungi powder as a function of temperature and moisture content at frequencies of 27, 40, 915, and 2450 MHz. Table 2 shows the regression equations and the correlation coefficient  $R^2$  for the relationship between the dielectric constant and dielectric loss factor and moisture content and temperature at different frequencies.

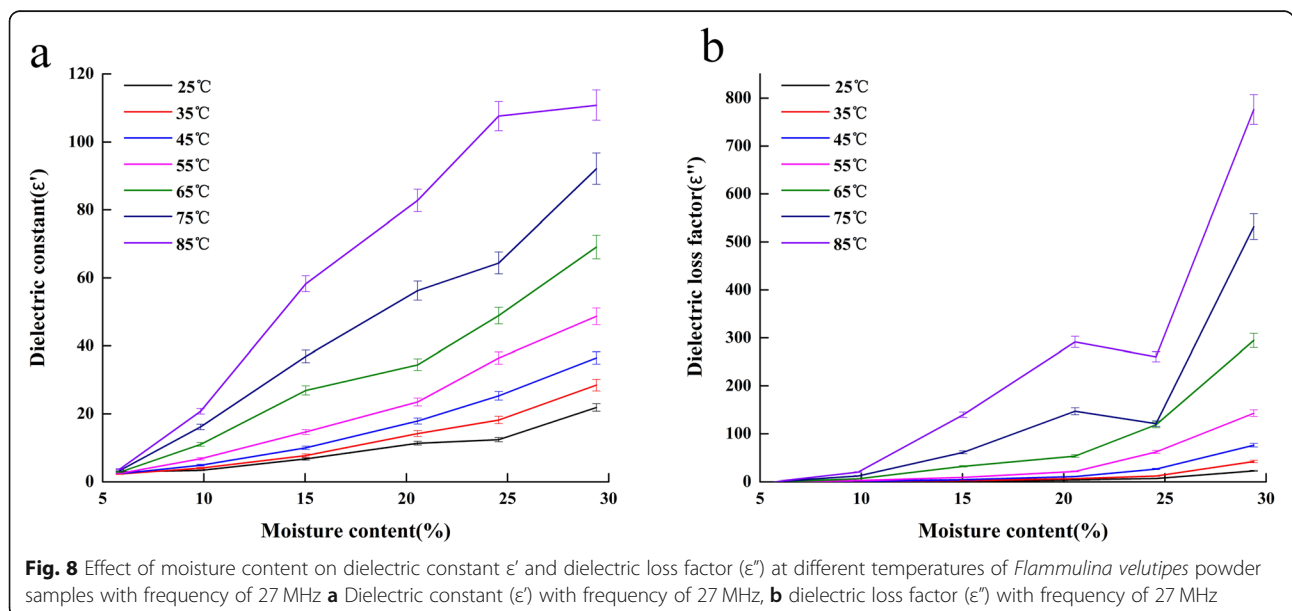




According to the regression equation model established using regression analysis, the dielectric constant and dielectric loss factor of any moisture content and temperature can be obtained at a known frequency. Simultaneously, the moisture content of the sample can also be obtained through the equation model under the conditions of known temperature and dielectric properties. This equation model provides basic data for the online monitoring of sample moisture content and serves as guidance for the research and production of equipment to measure/monitor sample moisture content.

**Determination of power penetration depth**

According to the dielectric constant and dielectric loss factor of *Pleurotus eryngii* powder obtained under different moisture contents, temperatures, and frequencies, the penetration depths of *Pleurotus eryngii* and *Agaricus bisporus* powder were calculated using formula (3) in Tables 2 and 3, respectively. Both tables show that the penetration depth decreases as the temperature, moisture content, and frequency increase. Considering *Pleurotus eryngii* with a moisture content of 12.0% as an example, at a frequency of 27 MHz, the penetration





**Table 1** Regression equations and correlation coefficients of dielectric properties for five edible fungi powders ( $R^2$ )

Frequency (MHz)	Dielectric constant ( $\epsilon'$ )	Dielectric loss factor ( $\epsilon''$ )
<b><i>Pleurotus eryngii</i></b>		
27	$\epsilon' = -74.9158 + 0.8672 T + 297.5579 W (R^2 = 0.9495)$	$\epsilon'' = -392.792 + 4.4708 T + 1266.036 W (R^2 = 0.9424)$
40	$\epsilon' = -56.9852 + 0.6875 T + 231.8879 W (R^2 = 0.9457)$	$\epsilon'' = -266.215 + 3.03976 T + 859.9247 W (R^2 = 0.9454)$
915	$\epsilon' = -22.9905 + 0.3017 T + 99.70858 W (R^2 = 0.9684)$	$\epsilon'' = -20.0743 + 0.23216 T + 72.4287 W (R^2 = 0.9869)$
2450	$\epsilon' = -18.6761 + 0.2496 T + 81.7795 W (R^2 = 0.9546)$	$\epsilon'' = -12.3889 + 0.14357 T + 48.7449 W (R^2 = 0.9627)$
<b><i>Flammulina velutipes</i></b>		
27	$\epsilon' = -60.3683 + 0.8701 T + 235.3554 W (R^2 = 0.944)$	$\epsilon'' = -299.52 + 3.7894 T + 970.2958 W (R^2 = 0.919)$
40	$\epsilon' = -47.1171 + 0.6826 T + 193.8688 W (R^2 = 0.949)$	$\epsilon'' = -205.114 + 2.6039 T + 667.2806 W (R^2 = 0.9318)$
915	$\epsilon' = -17.0753 + 0.2668 T + 80.9498 W (R^2 = 0.9276)$	$\epsilon'' = -16.6038 + 0.2195 T + 60.9836 W (R^2 = 0.9024)$
2450	$\epsilon' = -12.971 + 0.2077 T + 63.0395 W (R^2 = 0.9203)$	$\epsilon'' = -10.2345 + 0.1329 T + 40.946 W (R^2 = 0.9868)$
<b><i>Agaricus bisporus</i></b>		
27	$\epsilon' = -65.3171 + 0.9818 T + 235.9902 W (R^2 = 0.9362)$	$\epsilon'' = -416.175 + 6.2894 T + 1112.254 W (R^2 = 0.9791)$
40	$\epsilon' = -52.1488 + 0.7962 T + 193.9608 W (R^2 = 0.9434)$	$\epsilon'' = -283.77 + 4.2883 T + 763.7767 W (R^2 = 0.9337)$
915	$\epsilon' = -18.3079 + 0.2903 T + 76.3639 W (R^2 = 0.9556)$	$\epsilon'' = -21.1307 + 0.3157 T + 65.1009 W (R^2 = 0.978)$
2450	$\epsilon' = -13.6822 + 0.2265 T + 58.1319 W (R^2 = 0.9489)$	$\epsilon'' = -11.8995 + 0.1744 T + 39.834 W (R^2 = 0.9119)$
<b><i>Velvet mushroom</i></b>		
27	$\epsilon' = -55.9134 + 0.8158 T + 201.5411 W (R^2 = 0.9171)$	$\epsilon'' = -261.638 + 3.5709 T + 712.8062 W (R^2 = 0.9673)$
40	$\epsilon' = -42.0661 + 0.6263 T + 158.5781 W (R^2 = 0.9338)$	$\epsilon'' = -179.433 + 2.4546 T + 532.6113 W (R^2 = 0.9732)$
915	$\epsilon' = -13.4923 + 0.2249 T + 58.3516 W (R^2 = 0.944)$	$\epsilon'' = -14.1945 + 0.1977 T + 47.0965 W (R^2 = 0.9736)$
2450	$\epsilon' = -10.0243 + 0.1784 T + 44.9965 W (R^2 = 0.9335)$	$\epsilon'' = -8.1648 + 0.1133 T + 29.5383 W (R^2 = 0.9134)$
<b><i>Straw mushroom</i></b>		
27	$\epsilon' = -64.6363 + 0.8826 T + 253.2708 W (R^2 = 0.9162)$	$\epsilon'' = -349.441 + 4.6281 T + 1092.099 W (R^2 = 0.9693)$
40	$\epsilon' = -53.3488 + 0.7265 T + 216.0695 W (R^2 = 0.9272)$	$\epsilon'' = -239.195 + 3.1689 T + 752.551 W (R^2 = 0.9749)$
915	$\epsilon' = -19.4398 + 0.2747 T + 87.3258 W (R^2 = 0.9462)$	$\epsilon'' = -19.2365 + 0.2528 T + 68.4678 W (R^2 = 0.9654)$
2450	$\epsilon' = -14.9895 + 0.2196 T + 68.7421 W (R^2 = 0.9373)$	$\epsilon'' = -11.175 + 0.1469 T + 42.8537 W (R^2 = 0.907)$

depth is reduced from 430 cm to 29 cm during the temperature rise from 25 °C to 85 °C. Under a constant temperature and frequency, such 915 MHz and 35 °C, the moisture content increases from 9.9 to 30.9%, and the penetration depth of *Pleurotus eryngii* decreases from 58 cm to 3.3 cm. Simultaneously, the penetration depth decreases from 95 cm to 2.8 cm with the frequency increasing from 27 MHz to 2450 MHz under a constant temperature and moisture content, such as a 25 °C and 25.7%. Table 2 indicates that the relationships between the dielectric properties and penetration depths of the other four edible fungi were similar to those of *Pleurotus eryngii*. In addition, in some studies on wheat flour and soybean flour, the same penetration depths with respect to frequency, temperature, and moisture content as those of *Pleurotus eryngii* powder were obtained (Wang et al. 2006).

It is also evident from Tables 2 and 3 that the penetration depth at lower frequencies (< 100 MHz) is significantly greater than that at higher frequencies.

This implies that the uniformity of RF heating at lower frequencies is substantially greater than that at higher frequencies. Compared with the lower RF, the power penetration depth of *Pleurotus eryngii* is smaller under the effect of higher microwave frequencies, indicating that more heat is on the surface of the material in the microwave heating process. Foods with higher moisture contents have higher dielectric properties and correspondingly lower energy penetration depths, and the majority of foods have a smaller power penetration depth under the effect of short-wavelength electromagnetic waves such as microwaves. It indicates that when drying *Pleurotus eryngii*, radio frequencies of 27 and 40 MHz can be used for large depth processing, while radio frequencies of 915 and 2450 MHz can be used for small-depth processing.

It is worth noting that the penetration depth of electromagnetic waves acting on materials is different. In the study of the dielectric properties of bread, the relation

**Table 2** The calculated penetration depths of *Pleurotus eryngii* powder under different moisture contents and temperatures

Moisture content	Frequency (MHz)	Penetration depth (m)						
		Temperature						
		25 °C	35 °C	45 °C	55 °C	65 °C	75 °C	85 °C
9.9%	27	124.61 ± 0.05	67.28 ± 0.03	12.04 ± 0.02	11.01 ± 0.09	16.82 ± 0.13	7.95 ± 0.09	2.66 ± 0.04
	40	37.61 ± 0.04	20.14 ± 0.05	33.89 ± 0.06	25.23 ± 0.11	4.25 ± 0.05	3.04 ± 0.04	1.57 ± 0.03
	915	0.57 ± 0.01	0.58 ± 0.01	0.47 ± 0.08	0.32 ± 0.12	0.20 ± 0.12	0.16 ± 0.05	0.11 ± 0.03
	2450	0.22 ± 0.01	0.13 ± 0.07	0.089 ± 0.02	0.074 ± 0.09	0.054 ± 0.17	0.05 ± 0.25	0.033 ± 0.11
12.0%	27	4.30 ± 0.01	5.58 ± 0.03	3.24 ± 0.12	2.42 ± 0.05	0.96 ± 0.01	0.46 ± 0.03	0.29 ± 0.12
	40	2.74 ± 0.05	3.18 ± 0.01	2.11 ± 0.02	1.66 ± 0.04	0.75 ± 0.01	0.38 ± 0.01	0.24 ± 0.19
	915	0.48 ± 0.07	0.33 ± 0.12	0.20 ± 0.05	0.12 ± 0.08	0.067 ± 0.15	0.047 ± 0.19	0.037 ± 0.12
	2450	0.11 ± 0.14	0.091 ± 0.11	0.066 ± 0.15	0.042 ± 0.18	0.027 ± 0.11	0.019 ± 0.07	0.016 ± 0.07
15.3%	27	6.96 ± 0.03	5.12 ± 0.15	2.72 ± 0.01	1.03 ± 0.06	0.47 ± 0.15	0.25 ± 0.09	0.15 ± 0.05
	40	4.67 ± 0.21	3.39 ± 0.02	2.02 ± 0.08	0.86 ± 0.14	0.39 ± 0.12	0.21 ± 0.17	0.12 ± 0.03
	915	0.26 ± 0.11	0.20 ± 0.01	0.14 ± 0.05	0.086 ± 0.17	0.050 ± 0.24	0.034 ± 0.17	0.025 ± 0.11
	2450	0.089 ± 0.19	0.066 ± 0.11	0.044 ± 0.12	0.036 ± 0.11	0.020 ± 0.03	0.014 ± 0.15	0.011 ± 0.19
21.2%	27	2.19 ± 0.05	1.34 ± 0.07	0.71 ± 0.03	0.24 ± 0.11	0.13 ± 0.16	0.088 ± 0.29	0.072 ± 0.15
	40	1.51 ± 0.15	0.96 ± 0.16	0.56 ± 0.01	0.20 ± 0.18	0.11 ± 0.01	0.074 ± 0.05	0.060 ± 0.14
	915	0.13 ± 0.24	0.095 ± 0.34	0.069 ± 0.33	0.036 ± 0.14	0.024 ± 0.34	0.018 ± 0.14	0.015 ± 0.11
	2450	0.028 ± 0.34	0.023 ± 0.16	0.020 ± 0.18	0.013 ± 0.15	0.010 ± 0.17	0.009 ± 0.15	0.008 ± 0.16
25.7%	27	0.95 ± 0.01	0.41 ± 0.04	0.25 ± 0.05	0.18 ± 0.08	0.11 ± 0.27	0.081 ± 0.21	0.068 ± 0.16
	40	0.76 ± 0.13	0.34 ± 0.14	0.21 ± 0.05	0.15 ± 0.15	0.089 ± 0.17	0.068 ± 0.18	0.057 ± 0.17
	915	0.076 ± 0.11	0.044 ± 0.26	0.032 ± 0.02	0.027 ± 0.01	0.020 ± 0.06	0.017 ± 0.06	0.014 ± 0.01
	2450	0.028 ± 0.05	0.018 ± 0.05	0.013 ± 0.04	0.011 ± 0.03	0.009 ± 0.02	0.0084 ± 0.1	0.0077 ± 0.2
30.9%	27	0.43 ± 0.03	0.27 ± 0.05	0.18 ± 0.04	0.11 ± 0.06	0.075 ± 0.08	0.062 ± 0.11	0.051 ± 0.24
	40	0.35 ± 0.14	0.23 ± 0.15	0.15 ± 0.08	0.09 ± 0.01	0.062 ± 0.02	0.052 ± 0.05	0.042 ± 0.05
	915	0.044 ± 0.27	0.033 ± 0.29	0.026 ± 0.06	0.020 ± 0.09	0.015 ± 0.01	0.013 ± 0.03	0.010 ± 0.01
	2450	0.016 ± 0.04	0.013 ± 0.09	0.0103 ± 0.03	0.0085 ± 0.05	0.0072 ± 0.1	0.0067 ± 0.02	0.0059 ± 0.01

between the penetration depth and temperature, frequency, and moisture content is the same as the variation in penetration depth of electromagnetic waves on *Pleurotus eryngii* (Liu et al. 2009). The study of the penetration depth of electromagnetic waves on mashed potatoes showed an opposite trend as those of bread and *Pleurotus eryngii* (Guan et al. 2004).

When RF waves reach the inside of food, their electromagnetic energy will decay, and the power penetration depth is an important indicator for measuring their heating effect. When the penetration depth is small, more electromagnetic waves act on the surface of the food, resulting in an abnormal temperature rise on the surface of the food. This also indicates that the uniformity of the medium drying is greater at lower radio frequencies than that at the microwave frequency. Therefore, for evenly dried food materials, the thickness should not exceed two to three times the penetration depth (Jiao et al. 2011).

## Conclusions

The findings of this study indicated that the dielectric properties ( $\epsilon'$  and  $\epsilon''$ ) of edible fungi were closely related to their moisture content, frequency, and temperature. The dielectric constant  $\epsilon'$  and loss factor  $\epsilon''$  of edible fungi powder increased with moisture content and temperature and decreased with increasing frequency. At higher temperatures ( $>45^\circ\text{C}$ ), the effect of frequency on dielectric constant  $\epsilon'$  and dielectric loss factor  $\epsilon''$  was more prominent than at lower temperatures; the effect of frequency on dielectric constant  $\epsilon'$  and dielectric loss factor  $\epsilon''$  was more evident at higher moisture content; the variation of frequency on dielectric constant  $\epsilon'$  and dielectric loss factor  $\epsilon''$  is more noticeable at lower frequencies. The regression analysis polynomial equation model can be used to characterize the values of the dielectric constant and dielectric loss factor as a function of temperature and moisture content at a certain

**Table 3** The calculated penetration depths of *Agaricus bisporus* powder at different moisture contents and temperatures

Moisture content	Frequency (MHz)	Penetration depth (m)						
		Temperature						
		25 °C	35 °C	45 °C	55 °C	65 °C	75 °C	85 °C
6.2%	27	6.80 ± 0.05	4.98 ± 0.03	4.75 ± 0.01	4.26 ± 0.15	5.11 ± 0.28	5.93 ± 0.23	20.17 ± 0.32
	40	4.01 ± 0.04	3.31 ± 0.04	3.30 ± 0.05	3.07 ± 0.12	3.40 ± 0.18	4.00 ± 0.19	8.44 ± 0.21
	915	0.51 ± 0.11	0.57 ± 0.01	0.57 ± 0.02	0.51 ± 0.01	0.46 ± 0.04	0.39 ± 0.06	0.27 ± 0.15
	2450	1.20 ± 0.24	1.72 ± 0.11	1.82 ± 0.04	7.28 ± 0.25	3.50 ± 0.08	0.88 ± 0.03	0.30 ± 0.11
11.0%	27	156.26 ± 0.11	18.64 ± 0.23	3.29 ± 0.09	0.79 ± 0.05	0.28 ± 0.12	0.14 ± 0.03	0.11 ± 0.05
	40	25.96 ± 0.17	25.30 ± 0.03	2.50 ± 0.07	0.65 ± 0.04	0.23 ± 0.06	0.12 ± 0.01	0.09 ± 0.02
	915	1.02 ± 0.04	0.50 ± 0.15	0.22 ± 0.01	0.09 ± 0.04	0.04 ± 0.01	0.03 ± 0.01	0.02 ± 0.01
	2450	0.28 ± 0.05	0.15 ± 0.01	0.07 ± 0.09	0.04 ± 0.01	0.02 ± 0.01	0.013 ± 0.01	0.011 ± 0.01
16.7%	27	4.66 ± 0.03	1.71 ± 0.01	0.59 ± 0.04	0.24 ± 0.01	0.11 ± 0.01	0.10 ± 0.01	0.08 ± 0.01
	40	2.98 ± 0.16	1.31 ± 0.01	0.49 ± 0.17	0.20 ± 0.01	0.09 ± 0.04	0.08 ± 0.01	0.06 ± 0.01
	915	0.32 ± 0.17	0.16 ± 0.04	0.08 ± 0.01	0.04 ± 0.01	0.019 ± 0.01	0.017 ± 0.01	0.014 ± 0.01
	2450	0.08 ± 0.18	0.06 ± 0.01	0.03 ± 0.01	0.02 ± 0.01	0.0104 ± 0.03	0.0095 ± 0.01	0.008 ± 0.01
20.4%	27	1.09 ± 0.01	0.73 ± 0.01	0.41 ± 0.01	0.22 ± 0.01	0.13 ± 0.01	0.08 ± 0.01	0.05 ± 0.01
	40	0.86 ± 0.13	0.59 ± 0.05	0.35 ± 0.01	0.18 ± 0.01	0.11 ± 0.01	0.07 ± 0.01	0.04 ± 0.01
	915	0.10 ± 0.11	0.09 ± 0.01	0.06 ± 0.01	0.03 ± 0.01	0.02 ± 0.01	0.014 ± 0.01	0.010 ± 0.01
	2450	0.04 ± 0.17	0.034 ± 0.01	0.026 ± 0.01	0.016 ± 0.01	0.011 ± 0.01	0.008 ± 0.01	0.006 ± 0.01
25.9%	27	0.42 ± 0.17	0.30 ± 0.01	0.18 ± 0.01	0.12 ± 0.01	0.08 ± 0.01	0.06 ± 0.01	0.05 ± 0.01
	40	0.35 ± 0.11	0.26 ± 0.02	0.15 ± 0.02	0.10 ± 0.01	0.07 ± 0.01	0.05 ± 0.01	0.04 ± 0.01
	915	0.05 ± 0.18	0.04 ± 0.01	0.03 ± 0.01	0.02 ± 0.01	0.015 ± 0.01	0.011 ± 0.01	0.0103 ± 0.01
	2450	0.02 ± 0.19	0.02 ± 0.01	0.014 ± 0.01	0.010 ± 0.01	0.008 ± 0.01	0.0064 ± 0.01	0.0059 ± 0.01
31.2%	27	0.22 ± 0.17	0.18 ± 0.01	0.15 ± 0.01	0.11 ± 0.01	0.09 ± 0.01	0.07 ± 0.01	0.054 ± 0.01
	40	0.18 ± 0.19	0.15 ± 0.02	0.12 ± 0.01	0.09 ± 0.01	0.07 ± 0.01	0.05 ± 0.01	0.044 ± 0.01
	915	0.032 ± 0.17	0.028 ± 0.02	0.024 ± 0.01	0.019 ± 0.01	0.015 ± 0.01	0.012 ± 0.01	0.010 ± 0.01
	2450	0.015 ± 0.21	0.013 ± 0.02	0.011 ± 0.01	0.009 ± 0.01	0.008 ± 0.01	0.007 ± 0.01	0.006 ± 0.01

frequency. The establishment of this equation model provides basic data for online monitoring of sample moisture content and also offers a reference for the research and production of equipment to measure/monitor sample moisture content. The penetration depth of electromagnetic waves decreases with increasing frequency, temperature, and moisture content of the sample. Therefore, radio frequencies below 100 MHz and higher microwave frequencies can be used for large-scale and small-scale processing of edible fungi, respectively. This study provides useful information for drying edible fungus with radio-frequency or microwave energy and designing dielectric drying equipment.

#### Abbreviation

RF: Radio-frequency

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Authors contributed equally to the reported work. The author read and approved the final manuscript.

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#### Availability of data and materials

The datasets used or analysed during the current study are available from the corresponding author on reasonable request.

#### Declarations

#### Ethics approval and consent to participate

Not applicable.

#### Consent for publication

Not applicable.

**Competing interests**

Not applicable.

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