Permittivity Measurements for Roasted Ground Coffee Versus Temperature, Bulk Density, and Moisture Content

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Abstract: For a large variety of food products, the moisture content can be indirectly determined by measuring their dielectric properties. In the case of coffee, the permittivity knowledge can be applied to determine the moisture content indirectly or for online moisture meters in automatic control of coffee dryers. However, there is little data on the dielectric properties of roasted ground coffee near the 2.45 GHz ISM band. In this contribution, the permittivity was measured versus temperature, bulk density, and moisture content. A resonant technique based on a coaxial microwave cavity was employed to obtain the complex permittivity as a function of those magnitudes near the 2.45 GHz ISM band. In addition, the permittivity of the coffee particle kernel has been estimated from a complex refractive index mixture equation, thus calculating the permittivity of the coffee particle kernel from the permittivity values of the mixture air-coffee (ground coffee) at different bulk densities. The results showed that both dielectric constant and loss factor increase for increasing temperature, bulk density, and moisture content values. Furthermore, expressions fitting the experimental data were provided, thereby facilitating the estimation of the values throughout the studied temperature, bulk density, and moisture content ranges.

Keywords: coffee; microwave; resonant technique; dielectric constant; loss factor; kernel permittivity

Introduction

The response of the matter exposed to electromagnetic fields is characterized by its dielectric properties. These are quantified by the complex relative permittivity (ε_r) defined by equation (1), which is the absolute permittivity normalized to the permittivity of free space ($\varepsilon_0 = 8.854 \cdot 10^{-12}$ F/m).

$$\varepsilon_r = \varepsilon'_r - j \cdot \varepsilon''_r \qquad (1)$$

where ε_r' is the dielectric constant and ε_r'' is the loss factor. The quantity of electric energy that may be stored inside the irradiated material is determined by the dielectric constant, which is not constant due to its dependence on moisture content (MC), temperature, frequency, and bulk density. The loss factor describes the material's capacity to convert microwave radiation into heat, and it is variable with regard to some parameters, as the dielectric constant is.

The dielectric properties of vegetable materials can be used to estimate their MC e.g., cherry leaves (Dogan et al. 2020), orange and lemon leaves (Genç et al. 2020), or cypress and rockrose (Pérez-Campos et al. 2020). The MC determination becomes crucial as it helps determine the physical properties of materials such as maize (Barnwal 2012), or coffee (Nakilcioğlu-Taş 2019).

Coffee is one of the most well-known and traded commodities on a worldwide scale, valued for its scent and caffeine content. The chemical composition of the roasted beans determines the quality of coffee used in beverages. As a matter of fact, the distinctive coffee flavor is the consequence of the interaction of hundreds of chemical compounds created by roasting processes (Rodrigues et al. 2002).

One of the primary priorities of current commercial coffee producers and coffee researchers is to enhance product quality, and this is indirectly accomplished by regularly measuring its moisture content (Gautz et al. 2008). The state of the product must be assessed during all the actions associated with coffee manufacturing in order to preserve its original quality. The drying stage is considered the most crucial operation in the harvesting to roasting sequence of coffee processing (Ghosh and Venkatachalapathy 2014), given that unappropriated drying is deemed as the major cause of the decay in coffee fragrance, flavor, and taste after brewing. Moreover, the drying of grains is one of the most energy-intensive processes in agriculture (Forbes et al. 1984; Ghosh and Venkatachalapathy 2014). Still, this quality assessment relies on time-consuming and costly artisanal tools or procedures.

Despite the advancement of new techniques for rapid and non-destructive prediction of moisture content (MC) in coffee (Adnan et al. 2017; Setiasih et al. 2019; Tugnolo et al. 2021), the development of an on-line moisture meter capable of providing excellent readings under continuous flow circumstances is an ongoing issue for coffee drying technology (Berbert et al. 2001).

Several methods have been researched with various food products for a similar purpose. Porzuczek presented a method using electrical impedance tomography over a frequency range of 20 Hz to 200 kHz for the online determination of the spatial distribution of the MC in granular material (Porzuczek 2019). Nevertheless, there are still certain issues with this technique that need to be resolved, including the need for a suitable contact between the material and the electrodes as well as the long-term stabilization of the measurement result. Kandala et al. employed a simple impedance meter and a capacitance sensor to estimate the MC of corn samples (Kandala and Sundaram 2009) at frequencies of 1 and 5 MHz.

However, many other authors opted for utilizing a dielectric model so as to predict the material MC given the relationship between the MC and the dielectric properties. Zeng et al. studied the moisture state and migration, inter alia, in ginger slices (Zeng et al. 2022). They reached the conclusion that the MC and the dielectric properties were strongly related, with the biggest influence on the dielectric properties coming from free water. In another contribution, Kim et al. developed an online radio-frequency capacitive-type grain moisture meter that could determine the MC of several varieties of rice and wheat by measuring their dielectric properties (Kim et al. 2003).

The dielectric response has been studied for MC detection (Berbert et al. 2001), as well as the description of water features in green and roasted coffee (Iaccheri et al. 2015). Berbert et al. (2001) studied the permittivity behaviour of three varieties of parchment coffee, for frequencies ranging from 75 kHz to 5 MHz. They also demonstrated how its permittivity varies with MC and bulk density. Finally, they concluded that the relative permittivity should provide less inaccuracy in determining the MC of parchment coffee. The dielectric properties of four coffee stages have been presented in (Velasquez et al. 2018) for frequencies ranging from 0.3 to 6 GHz, and the MC was estimated from the obtained complex permittivity.

Nevertheless, to the best of the authors' knowledge, there are no studies in the literature providing the permittivity of roasted ground coffee under various water content, temperature, and bulk density conditions. Furthermore, the permittivity of coffee granules is also estimated using well-known equations and data from the literature, as well as bulk-density dependent observations.

There are many methods to acquire the dielectric properties of any type of material (Icier and Baysal 2004). In general, the selection of a measurement equipment is conditioned by the material, the required frequency range, and precision, as well as the equipment's price.

The open-ended coaxial probe, transmission line, and resonant cavity methods are the three most prevalent methods for testing dielectric properties in foods and commodities. The coaxial probe approach provides broadband measurements, and it is very easy to use given that it does not require a certain sample shape (Lau et al. 2020). Its main drawback is its limited accuracy, especially for low-loss materials. In addition to that, solids must have a flat surface for a proper measurement.

In the transmission line method, the sample is inserted as a section inside a well-defined transmission line. This method is usually more precise and sensitive than the probe method, but its handling is more complex and requires longer operating times. Furthermore, the measurement accuracy can be severely degraded if the sample does not precisely fill the transmission line cross-section uniformly.

Finally, the resonant cavity approach is based on a differential response analysis over the perturbation produced by a sample on a single-mode resonance electromagnetic pattern, that is the shifting of the resonant frequency (determines the dielectric constant) and the alteration of the quality factor (determines the loss factor) of the cavity. This method offers high accuracy, and it is well-suited for samples with low loss factor values. Nevertheless, it only provides the complex permittivity at a single frequency conditioned by the cavity resonance. The selected device for the measurements in this study is based on a resonant technique that provides results around 2.45 GHz (Gutiérrez et al. 2019).

Materials and Methods

Material

Roasted ground coffee (*Coffea arabica*) was utilized for the tests, produced by UCC Coffee Spain S.L. and commercially accessible at a well-known Spanish supermarket chain. As stated in (Gutierrez et al. 2019), sample containers must be able to fit through the endplate hole and deeper into the center conductor within the cavity to provide concentric alignment. The cylindrical geometry of samples is a requisite for obtaining accurate results, which are conditioned by the cylindrical cavity geometry and the resonant electromagnetic pattern that it produces. Hence, 6-ml quasi-cylindrical polypropylene test tubes (Deltalab Ref. 400400) were used as sample containers. The test tubes' internal diameter and height were 10.3 mm and 86.9 mm, respectively.

Table 1 shows the coffee mass of samples utilized for the three permittivity measurements. The starting conditions of the samples for the temperature, bulk density, and MC relationships examined in this work are also presented in the table.

Table 1. Coffee samples conditions for each permittivity measurement test

Dependence analysis test	No. of samples	Mass (g)	Temperature (°C)	Bulk density (kg/m^3)	MC (%)
Temperature	4	1.69 ± 0.04	[29-87]	371 ± 5	4.8 ± 0.2
Bulk density	3	1.40 ± 0.01	24 ± 2	[310-420]	4.8 ± 0.2
MC	4	1.69 ± 0.04	24 ± 2	363 ± 5	[0-4.8]

Particle Size Measurement Equipment

The particle size distribution was determined using a Mastersizer 2000 analyser (Malvern Instruments) with distilled water as the dispersant medium. Laser diffraction is used to determine particle size. The intensity of light scattered by particles as it passes through the sample is measured to accomplish this. Large particles scatter light strongly at narrow angles, whereas small particles scatter light weakly at wider angles.

Permittivity Measurement Equipment

When selecting the appropriate measuring method to determine the permittivity of materials, it is important to take into consideration several factors, including the geometry and format of the material and how to adapt it into a holder suitable for the measuring technology, a prediction of its electrical losses, and how to configure other parameters of interest (e.g., frequency, temperature, bulk density, moisture content). Since it was anticipated that coffee would have low electrical losses, and keeping in mind the measurement requirements (e.g., preparation and handling of samples, measurement repeatability and accuracy, temperature monitoring, frequency), the transmission line method as waveguide measurement kits, as well as the parallel plate and open-ended coaxial probe methods, were discarded. The resonant coaxial bi-reentrant microwave cavity described in (Gutiérrez-Cano, 2019), in which the substance being tested is housed in a vial, allows for easy temperature monitoring using a regular optical fiber temperature sensor while the permittivity is measured. The handling of granular samples in test tubes simplifies the measurement protocol. In addition, this cavity is commercially available, thereby ensuring the reproducibility of this study.

The relative electric permittivity measurements were conducted using a Dielectric Kit for Vials (DKV), from ITACA research institute of Universidad Politécnica de Valencia (Spain). This device sends a microwave frequency-swept stimulus into a resonant cavity and measures the reflected power. Before measuring the response of the cavity loaded with the sample, the empty cavity must be calibrated. The resonance frequency variation of the response signal i.e., the displacement of its peak location, and its widening due to a decrease in the cavity quality factor when a dielectric material is inserted into its resonant structure (Sheen 2009) are computed to determine the dielectric constant and loss factor of liquid, granular, or powdered materials around 2.45 GHz. As mentioned in (Gutiérrez et al. 2019), the connection between complex permittivity and resonance characteristics is derived using numerical approaches based on mode-matching and circuit analysis.

The DKV's operating frequency spans from 1.5 to 2.6 GHz. It has the ability to characterize materials with dielectric constants of less than 100 and loss factors ranging from 0.001 to 15. This equipment provides a 1% and 5% error in determining the dielectric constant and the loss factor, respectively. The manufacturer's repeatability and linearity values are about 0.2 percent.

The coffee samples had resonance frequencies of 2.40 ± 0.10 GHz. As a result, the relative electric permittivity data presented at various temperature, MC, and bulk density conditions is close to the 2.45 GHz ISM band.

Measurement Procedure for Temperature Dependence of Coffee Permittivity

The permittivity of roasted ground coffee as a function of temperature was measured in a manner similar to that employed in (Pérez-Campos et al. 2020). The temperature evolution of the sample was tracked using an optical fiber sensor and OpSens TempSens signal conditioner equipment. For temperatures above and below 45°C, the TempSens has an accuracy of 0.8°C and 0.3°C, respectively.

The procedure for measuring the permittivity as a function of temperature is shown in figure 1. Initially, each sample was heated in a water bath (Balneum Mariae) to almost 90°C using a 150 mL glass of water pre-heated in a household microwave oven. The heated sample was then placed in the DKV apparatus to be monitored its permittivity while cooling. The temperature over time *T(t)* logging was performed on a computer connected to the TempSens equipment using an in-house LabView code. Simultaneously, the DKV manufacturer's instrument software was utilized to log the sample permittivity over time $\varepsilon_r(t)$. Finally, both datalogs are combined by means of a Matlab script, therefore providing the permittivity dependence on temperature $\varepsilon_r(T)$, as stated in (Fayos-Fernandez et al. 2015).

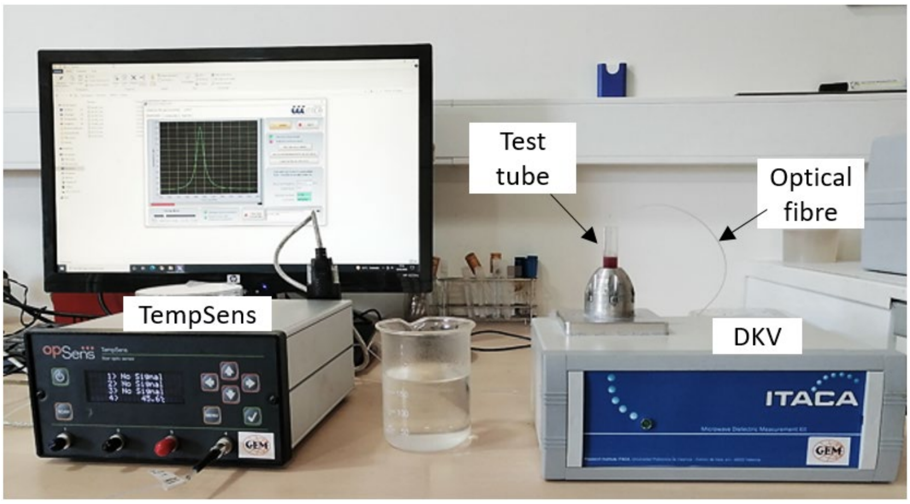


Fig. 1. Methodology and setup for measuring the complex permittivity dependency on temperature.

Every sample was measured once. The average of each samples set with a discretized resolution of ΔT=1°C was used to compute the modelled discrete-temperature dependency of the permittivity data i.e., the permittivity values recorded within the same temperature bin T±ΔT/2 were averaged. As a result, the first discrete-temperature was set to 87°C, matching the bin limits of [86.5, 87.5]°C, while the last discrete-temperature was set to 29°C, matching the bin boundaries of [28.5, 29.5]°C.

As indicated in table 1, the MC and bulk density were kept constant throughout the tests.

Test Protocol for Coffee Permittivity Variation Versus Bulk Density

Another experiment carried out in this paper was evaluating the permittivity dependence on bulk density. The mass of the coffee samples remained unchanged, as shown in table 1, while the volume was lowered from 4.4 to 3.4 cm^3. The mass sample was measured using a Mettler Toledo weighing scale, model XPR56DR, with an accuracy of 0.01 mg. As described in (Fayos-Fernández et al. 2018), the sample volume was obtained using an in-house volumeter developed with a parallax error control.

The findings of permittivity in function of bulk density were computed as the average of three samples set per bulk density value. The average dry-basis MC of the coffee samples used in these density-dependent assays was roughly 5 %. The sample temperature matched the room temperature throughout all bulk density-dependent observations, as previously indicated in table 1.

Measurement Procedure for Moisture Content-Dependent Permittivity

In this study, the dielectric properties of roasted ground coffee were investigated in relation to MC. Four coffee samples were generated. The samples were then progressively dried in a muffle furnace at 90°C for 2 hours at a time. After each drying interval, the samples were extracted and cooled to their ambient temperature. The amount of evaporated water was determined by weighing the samples on a Mettler Toledo weighing scale (model XPR56DR) and measuring their dielectric properties in the DKV.

Because of the weighing scale's high precision (0.01 mg), slight mass decrements were consistently identified between two consecutive readings. As a result, the treatment was declared complete when mass changes were less than 5 mg across two consecutive weigh-ins. This criterion is supported by the fact that no permittivity fluctuation was identified between the two most recent observations. The most recent mass sample collected was used as the dry mass reference.

As indicated in equation (2), the MC used in this study has been represented as a dry basis:

$$MC = \frac{m_i - m_d}{m_d} \quad (2)$$

where m_i and m_d denote the sample mass at a certain MC and the sample mass when totally dried. As a result, *MC* is the ratio of the water mass in the coffee granules to the dried solid mass, because m_i-m_d indicates the water mass in the sample. Averaging the observations from four distinct samples yielded the results of the MC-dependent complex permittivity values.

Calculations for Estimating Coffee Particle Kernel Permittivity

Granular and powdered materials, such as ground coffee, are composed of granular kernels and air that fills the space between them. When measuring the permittivity of these materials in bulk, one have to take into consideration that the observed effective permittivity is the consequence of a combination of grain kernel and air permittivities. As a result, the measurement findings are affected by the bulk density of the granular or powdered material and hence it is critical to establish a reliable relationship between the air-kernel mixture's bulk density and the measured permittivity.

The permittivity-to-bulk density relationship of some granular and powdered materials has already been studied (Nelson 2005). Trabelsi et al. developed a calibration function independent of bulk density that permits permittivity measurements to be used to determine MC in granular materials (Trabelsi et al. 1998). In other investigations, researchers established the material's bulk density before studying its dielectric properties (Torrealba-Meléndez et al. 2015).

In this work, the permittivity of the coffee particle kernel is determined using the dielectric mixture equations for a two-phase mixture, which calculates the permittivity of a solid material (coffee particle) from the permittivity of a granular mixture (particle-air). This requires knowledge of the permittivity of the air-powder combination, its bulk density, and the coffee particle density. The real coffee particle density had been previously calculated in (Nakilcioğlu-Taş and Ötleş 2019), whose value was 0.91 g/cm^3. In this study, the Complex Refractive Index (CRI) mixing equation for two-phase mixtures (Nelson 2005) is used to calculate the permittivity of coffee particles, ε_c (see equation 3).

$$\sqrt{\varepsilon_m} = v_a\sqrt{\varepsilon_a} + v_c\sqrt{\varepsilon_c} \quad (3)$$

Where ε_m, ε_a and ε_c are the air-coffee particle mixture's permittivity, the air permittivity (ε_a = 1) and the coffee particle permittivity, respectively. At the same time, v_a is the volume fraction of air and v_q is that of coffee, so that $v_a + v_c = 1$. Both of these may be calculated using the bulk density of the mixture (ρ_m) and the coffee particle density (ρ_c) e.g., $v_a = \frac{\rho_m}{\rho_c}$.

As a result, equation (3) may be expressed using equations (4) and (5):

$$\varepsilon'_c = \left[\frac{\rho_c}{\rho_m}\left(\sqrt{\varepsilon'_m} - 1\right) + 1\right]^2 \quad (4)$$

$$\varepsilon''_c = \left(\frac{\rho_c}{\rho_m}\right)^2 \cdot \varepsilon''_m \quad (5)$$

Where dielectric constant and the loss factor of the coffee particle are denoted by ε'_c and ε''_c respectively. Similarly, ε'_m is the dielectric constant for the mixture air-coffee and ε''_m its loss factor.

Statistical Analysis

Every permittivity measurement was performed, at least, three times. To calculate error bars for all data points, the standard deviation of the average value of triplicates (or quadruplicates) was used. Matlab (version R2019a, MathWorks software) was used to process and plot the data.

Results

In this section, the particle size distribution is shown as well as the dielectric properties of roasted ground coffee are presented and discussed in relation to temperature, bulk density, and MC. The estimated value for the coffee particle permittivity is also shown in this section. For all the graphics showing permittivity experimental data, the dielectric constant is depicted in blue, whereas the loss factor is represented in red. A dashed line represents the data fittings.

Particle Size Distribution

The particle size analysis results are shown in Figure 2. The particle size distribution of coffee particle kernels was bimodal, with granule sizes (volume mean diameters) of about 0.5 mm. The findings showed that coffee particle kernels did not have a uniform particle size distribution. The average size of particles was 423,1 µm. These findings are similar to those seen in the literature (Khamitova et al. 2020).

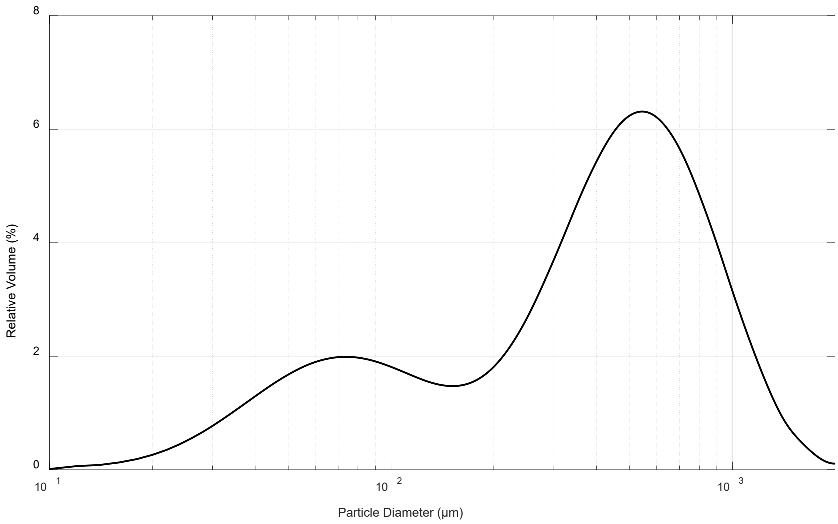


Fig. 2. Particle size distribution of coffee particle kernels.

Permittivity Dependence on Temperature

Figure 3 depicts the average behaviour versus temperature of the dielectric constant and loss factor throughout a temperature range of 29 to 87°C. Figure 3 also shows the standard deviations of both magnitudes and their exponential fitting. The obtained findings show that the dielectric constant and loss factor increased by 13 and 142 % throughout the whole temperature range, respectively. A factor that could account for this rise is the mobility of water dipoles, which might be increased due to the lowering water density as temperature rises, suggesting that some free water is released from its bound state, thus raising the values of the dielectric constant and loss factor. The increase in conductivity in the solid matrix might be another factor explaining the observed behaviour of the dielectric properties. To test these assumptions, however, further research has to be conducted.

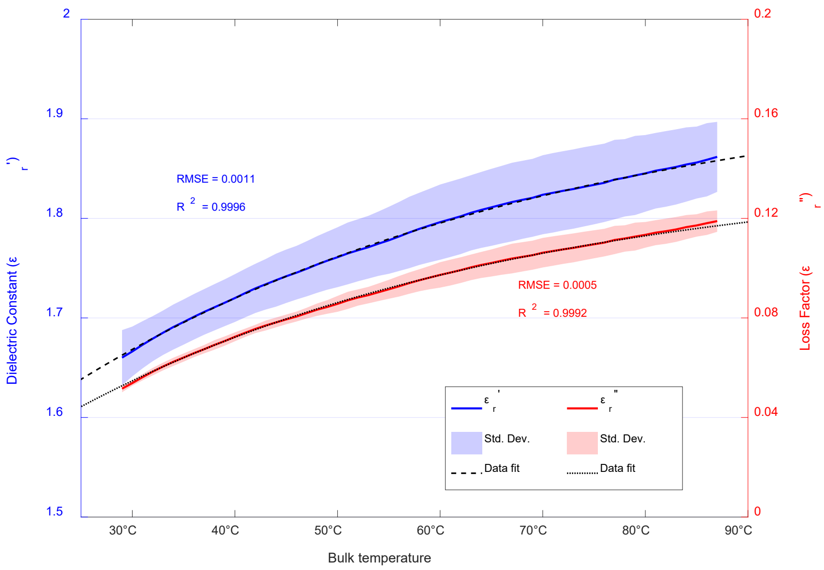


Fig. 3. Coffee permittivity versus temperature and exponential data fitting.
$\rho_m = 0.37$ g/cm^3, $X = 4.8$ %.

Equations (6) and (7) describe the exponential function applied for the dielectric constant and loss factor dependency on temperature data fittings, respectively:

$$\varepsilon'_r(T) = 1.94 - 0.51 \cdot T^{-0.021} \quad (6)$$

$$\varepsilon''_r(T) = 0.14 - 0.17 \cdot T^{-0.023} \quad (7)$$

where T is the sample temperature in degrees Celsius. The dielectric constant's root mean square error (RMSE) and coefficient of determination (R^2) are 0.0011 and 0.9996, respectively. The RMSE for the loss factor is 0.0005 and the R^2 is 0.9992.

Permittivity Dependence on Bulk Density

Figure 4 depicts the average values of the dielectric constant and loss factor versus bulk density. Error bars are used to display standard deviation data. In terms of permittivity fluctuation, the dielectric constant increase for the studied range is roughly 10.5 %, and the loss factor increase is 60.3 %.

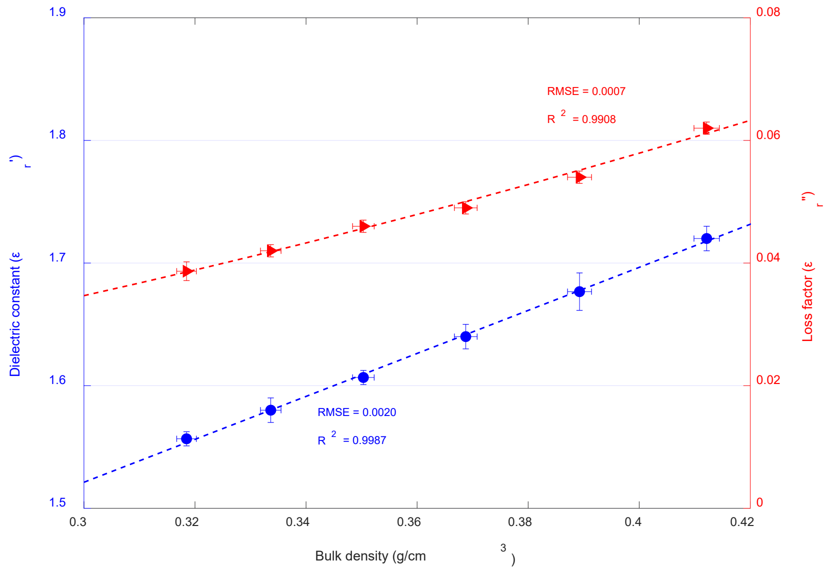


Fig. 4. Coffee permittivity versus bulk density and polynomial data fitting.
$T = 24$°C; $X = 4.8$ %.

As a result, equations (8) and (9) were generated by fitting second-order polynomials to dielectric constant and loss factor data:

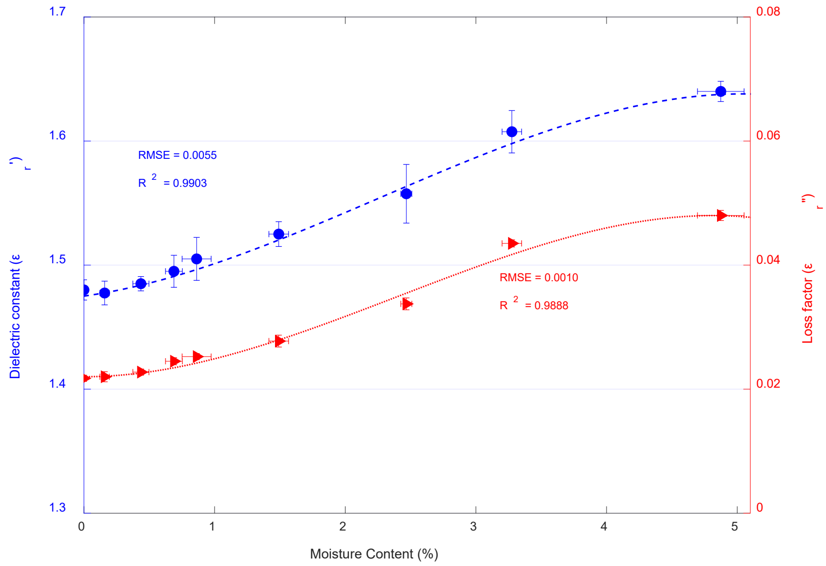
$$\varepsilon'_r(\rho_m) = 0.038 \cdot {\rho_m}^2 + 1.726 \cdot \rho_m + 1 \quad (8)$$

$$\varepsilon''_r(\rho_m) = 0.292 \cdot {\rho_m}^2 + 0.28 \cdot \rho_m \quad (9)$$

where ρ_m is the sample's bulk density (g/cm^3). The RMSE and R^2 for fitting the dielectric constant are 0.0020 and 0.9987, respectively. The RMSE and R^2 for fitting the loss factor are 0.0007 and 0.9908, respectively.

Permittivity Dependence on Dry-Basis Moisture Content

Figure 5 depicts the development of the dielectric constant and loss factor as a function of dry-basis MC. Both the dielectric constant and the loss factor increase with rising MC levels. A possible reason for this behaviour is the fact that when MC grows, so does the amount of water and its mobility, and consequently the loss factor and the dielectric constant. However, different states of water (bound or free) can be perceived by observing the permittivity evolution. For MC values less than 1%, internal water tend to be highly linked to the internal structure of coffee tissue (bound water), resulting in reduced water mobility and very low loss factor values. This behaviour is similar to that found for ginger slices (Zeng et al. 2022): the amount of free water had the greatest influence on dielectric properties.



Fig, 5. Coffee permittivity behaviour versus MC and polynomial data fitting.
ρ_m = 0.36 g/cm^3; T = 24°C

Third order polynomial functions were employed to interpolate the experimental data of permittivity development versus MC, as described by equations (10) and (11):

$$\varepsilon'_r(MC) = 1.475 + 1.47 \cdot MC + 134.2 \cdot MC^2 - 1968 \cdot MC^3 \qquad (10)$$

$$\varepsilon''_r(MC) = 0.022 + 33.6 \cdot MC^2 - 465 \cdot MC^3 \qquad (11)$$

where X is the predicted dry-basis MC from equation (5). The RMSE and R^2 values for fitting the dielectric constant were 0.0055 and 0.9903, respectively, whereas the RMSE and R^2 values for fitting the loss factor were 0.0010 and 0.9888, respectively.

Coffee Particle Kernels Permittivity Estimation

The permittivity of coffee particle kernels was determined using equations (4-5), the average density of the coffee particle kernels presented in (Nakilcioğlu-Taş and Ötleş 2019) e.g., ρ_c = 0.91 g/cm^3, and Figure 4 data of ground coffee permittivity versus bulk density. Figure 6 shows that relatively similar permittivity values of coffee particle kernels are determined while employing varied bulk densities. Modest discrepancies may be explained by small mistakes in bulk density determination and the intrinsic inaccuracy of permittivity measurements. An average value for the dielectric constant and loss factor was obtained and plotted as a constant. In the instance of the dielectric constant of the coffee particle kernel, ε'_c, an average value of 2.87 and a RMSE of 0.0234 were obtained. The estimated average value and RMSE of the coffee particle kernel loss factor, ε''_c, were 0.31 and 0.0076, respectively.

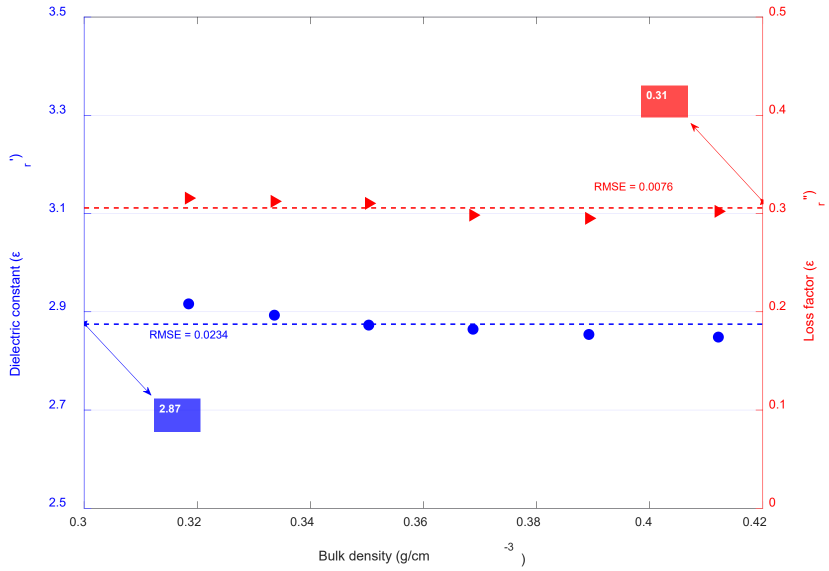


Fig. 6. Estimation of average permittivity of coffee particle assuming ρ_c = 0.71 g/cm^3 and using equations (3-4). T = 24°C; X = 4.8 %.

Conclusions

In this contribution, the dielectric properties of roasted ground coffee have been measured under various temperature, bulk density, and MC conditions. In addition, the permittivity of coffee granules was estimated using well-known equations and data from the literature, as well as bulk-density dependent measurements.

The development of permittivity versus temperature for roasted ground coffee is quite different to that of free water. The permittivity rose with the rising temperature in the first scenario. In the second situation, however, the permittivity declined with increasing temperature. One possible explanation for this difference is the interactions of water with the surrounding structure: the little amount of available water in coffee granules is bound to its internal structure.

Permittivity dependence on bulk density and MC was predicted for roasted ground coffee particle kernels. In both situations, the dielectric constant and loss factor rose in value as the density and MC increased. Furthermore, the average coffee particle kernel permittivity was calculated using the CRI mixing equation and permittivity observations at various bulk densities. The obtained data clearly reveals that the coffee particle kernel permittivity is greater than the permittivity of the ground coffee mixture.

The data presented in this paper will be used to develop sensors for MC determination of roasted ground coffee. The data can also be useful for developing computer models and simulating dielectric heating for microwave processing of roasted ground coffee, as well as providing a theoretical basis for coffee dehydration under dielectric heating. Further investigation is envisaged to develop prediction models capable of accurately estimating the permittivity values throughout a wider range of temperature, bulk density, moisture content, and frequency.

Finally, based on the measurements, one can conclude that the coffee particles under consideration can be processed using microwave technology. However, because permittivity increases with temperature, thermal runaway can occur, particularly at low MC levels where internal water evaporation is almost non-existent.

Acknowledgement

The conference report "Permittivity Measurements for Roasted and Ground Coffee Versus Temperature, Bulk Density, and Moisture Content" had a good reception when it was presented at the Fourth Global Congress on Microwave Energy Applications (4^{th} GCMEA) so the authors were encouraged by the organizers of the congress to prepare this paper solely for being reviewed by the Journal of Microwave Power and Electromagnetic Energy (JMPEE). This paper contains information and details that were not provided in the conference material. The Fourth Global Congress on Microwave Energy Applications (GCMEA) organized by Sichuan University together with The China Association of Microwave Power Applications (CAMPA), was hosted in Chengdu, Sichuan, China on August 17-20, 2022.

Disclosure Statement

The authors report there are no competing interests to declare.

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Table 1. Coffee samples conditions for each permittivity measurement test.

Figure 1. Methodology and setup for measuring the complex permittivity dependency on temperature.

Figure 2. Particle size distribution of coffee particle kernels.

Figure 3. Coffee permittivity versus temperature and exponential data fitting. $\rho_m = 0.37$ g/cm^3, $MC = 4.8$ %.

Figure 4. Coffee permittivity versus bulk density and polynomial data fitting. $T = 24$°C; $MC = 4.8$ %.

Figure 5. Coffee permittivity behaviour versus MC and polynomial data fitting. $\rho_m = 0.36$ g/cm^3; $T = 24$°C

Figure 6. Estimation of average permittivity of coffee particle assuming $\rho_c = 0.71$ g/cm^3 and using equations (3-4). $T = 24$°C; $MC = 4.8$ %.