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Determination of dielectric properties and predictive modeling for designing radio-frequency heating of ground beef

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Dielectric properties of ground beef as affected by the variation of fat content (73/27, 80/20, and 85/15 lean/fat) and temperature (0–90 °C) were determined using a parallel plate LCR meter and liquid test fixture at the radiofrequency (RF) of 27.12 MHz. The values of dielectric constant (ε′) and dielectric loss factor (ε′′) of ground beef significantly increased with temperature ($p < 0.05$) whereas the values of penetration depth (d_p) decreased with temperature ($p < 0.05$) up to the respective points of local extrema. Values of both ε′ and ε′′ were significantly lower ($p < 0.05$) for the leaner blend 85/15 and conversely, penetration depth was significantly higher ($p < 0.05$) for the leaner blend. As temperature increased beyond the point of maximum for ε′ and ε′′ and point of minimum for d_p, there was no significant difference in the dielectric properties between the different lean/fat blends. Predictive equations of second order in temperature and fat content were developed for the dielectric properties which explained 74, 93, and 98% variation in ε′, ε′′, and for d_p respectively, based on R^2 values. The dielectric properties and their fitted models can be utilized for designing pilot and mass scale RF processes for heating ground beef.

KEYWORDS
radiofrecuency, ground beef, dielectric properties, dielectric loss, predictive modeling

Introduction

Radiofrequency (RF) has gained importance in the recent decade as an effective meat processing technology (Zhou & Wang, 2018). It has been utilized in various heating applications for thawing, pasteurizing, and cooking meat products (Guo et al., 2019). RF thawing of different lean: fat beef blends were shown to have an 85 fold reduction in process time compared to conventional air thawing (Farag et al., 2011; Dag et al., 2020) and RF defrosting resulted in significantly lesser drip loss (Farag et al., 2009). RF tempering of beef of different lean/fat compositions had greater endpoint temperature uniformity and a 30-fold reduction in time compared to conventional tempering (Farag K. et al., 2008). RF has been demonstrated to reduce pathogenic microorganisms in ground beef similar to conventional heating but with much shorter cooking times (Guo et al., 2006). More recently, a pilot-scale RF (6 kW) equipment was demonstrated to effectively reduce pathogenic loads in ground beef (Nagaraj et al., 2016) and in non-intact beef steaks (Rincon and Singh, 2016). Thus, RF is a promising technology for meat processing that warrants further exploring of process design, material properties, and effects on physical and chemical qualities of RF-treated meat products (Zhang et al., 2022).The RF heating has been shown to be much more rapid than conventional heating (Traffano-Schiffo et al., 2021). The RF processing has a great potential for commercialization for mass-scale meat processing. A proper understanding of food properties is necessary in order to install, design, and operate continuous processes employing RF. The RF is non-ionizing electromagnetic radiation that produces capacitative or dielectric heating in materials (Ma et al., 2021). Dielectric properties are important in determining how the food molecules couple with the external electromagnetic field, re-align, and generate heat (Llave & Erdogdu, 2020). Muscle foods behave as "lossy" dielectrics or insulating capacitors, i.e., they dissipate the electrical energy from an externally applied electromagnetic field into heat (Gambuteanu & Alexe, 2013). This results from successive charging and discharging of the dielectric material. Two important fundamental properties are used to describe this coupling with the electromagnetic field. ε', the dielectric constant and ε'', the dielectric loss factor is the real and imaginary parts of the complex relative permittivity ε which is defined as $\varepsilon = \varepsilon' - j\varepsilon''$ where j is the square root of negative unity (Tomas-Egea et al., 2022). The dielectric constant is a measure of the ability of the material to get polarized by an external electromagnetic field and store this energy. Species that undergo polarization can be ions, atoms, and dipolar molecules. The loss factor measures the dissipation of the electrical energy into heat. Loss tangent is the ratio of $\varepsilon''/\varepsilon'$ (Tomas-Egea et al., 2022). Power penetration depth (d_p) is defined as the depth within the material in the direction perpendicular to the surface where the power of the electromagnetic wave is reduced to 1/e (e approximately equal to 2.718) or 36.8% of the surface value. The d_p determines the amount of heat generated at a particular location below the surface considering exponential decay of power (Piyasena et al., 2003).

ε' and ε'' are functions of temperature, frequency, and are also affected by the composition of food. Previous research in this domain has focused on determining beef dielectric properties in the thawing temperature range of -18 to 10°C (Farag K. W. et al., 2008), and beef liver and beef meat in the frequency range of 100–2500 MHz (Tran and Stuchly, 1987). Changes in dielectric properties of beef were explored to explain protein denaturation of beef meat in general (Bircan and Barringer, 2002) and of *Biceps femoris* muscle during cooking (Brunton et al., 2006). The effect of temperature and fiber orientation in intact beef *Semitendinosus* muscle was reported at different frequencies (Basaran-Akgul et al., 2008). A series of predictive equations were developed for the dielectric properties of grains, fruits and vegetables, and meat products at microwave frequencies (Calay et al., 1994). Gunasekaran and others (2005) reported the variation of dielectric properties of ground beef with fat content and temperature at the microwave frequencies of 915 and 2450 MHz. Till date, the variation in dielectric properties of ground beef has not been reported at the commercial RF frequency of 27.12 MHz. This information can be utilized to design RF processes of ground beef products for pasteurization or cooking. Predictive equations for dielectric properties can help to account for variation in temperature and fat composition. Hence, the objective of this study is to determine the dielectric properties of ground beef at 27.12 MHz in the temperature range of 0–90°C and develop predictive equations as functions of temperature and fat content.

Materials and methods

Sample preparation

Packaged fresh ground beef of different lean/fat blends (73/27, 80/20, and 85/15) was obtained from a local beef purveyor. The packaged beef was transported on ice to the University of Georgia Food Science Building in Athens, GA. The fresh ground beef was refrigerated at 2 ± 1°C and stored in dark prior to experiments and used within 4 days. The ground beef was thoroughly mixed (homogenized) prior to use to minimize localized fat pockets.

Moisture and ash content determination

The ground beef was homogenized and analyzed separately in triplicate for moisture, protein, fat, and ash contents. The moisture content of the ground beef blends (lean/fat blends: 73/27, 80/20, and 85/15) was determined using AOAC Method (AOAC 934.06) in a vacuum drying oven (National Appliance Co., Skokie, Ill. United States). The ground beef samples of 5 g were evenly spread over bottom of metal dish and tightly covered. The samples were dried at 75°C and 65 mmHg for 6 h. Dish was cooled to room temperature (23±5 °C) in desiccator and final weight was recorded for calculating the moisture content. For the determination of ash content, 2 g of ground beef samples were weighed in crucible and placed in temperature-controlled furnace, heated to 600°C. The temperature was hold at 600°C for 2 h. The crucible was transferred to desiccator to cool and immediately weigh to

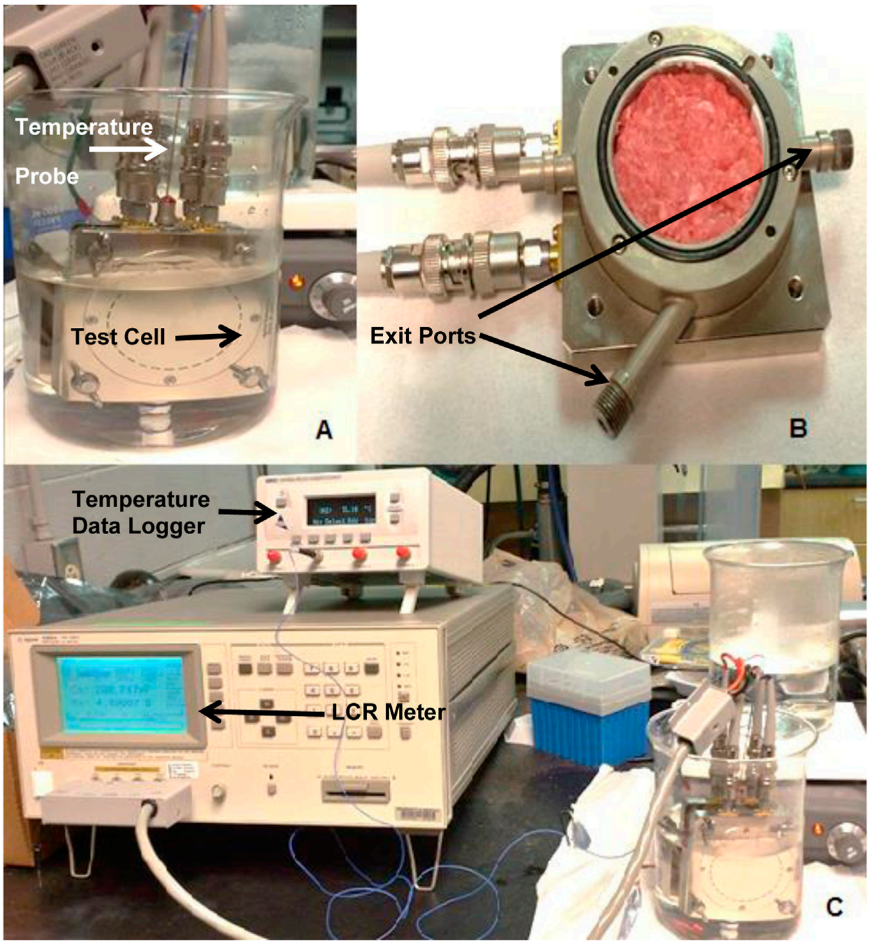

FIGURE 1
(1A): Liquid test cell submerged in a water bath; **(1B)**: Inside of the test cell with the ground beef sample, exit ports sealed with water proof tape; **(1C)**: Instrumentation set up for the experiment.

TABLE 1 Proximate composition of ground beef of different lean and fat blends.

[£]Ground beef blend	Moisture	Protein	Fat	Ash
73/27	58.7^{a}	12.6^{A}	27.2^{A}	1.6^{A}
80/20	67.2^{B}	11.1^{A}	20.5^{B}	1.4^{A}
85/15	70.4^{A}	11.9^{A}	15.4^{C}	1.3^{A}
**SE*	1.1	1.7	0.8	0.6

[A,B,C] Numbers in a column with different letters (a, b) are statistica[a]ly different ($p < 0^{b}05$). All values represent a minimum of three replications.
**SEM, Standard Error°*.
[£]*Ground Beef Blend* = Ground beef blends represents lean to fat ratio (73 lean: 27 fat; 80 lean: 20[b]fat; 85 lean: 15 fat).

get ash content (AOAC Method 942.05). All experiments were replicated a minimum of three times on different occasions and data was averaged for statistical analysis.

Dielectric properties measurement

The dielectric properties of ground beef were analyzed using a custom-built fixture (#4285A; Agilent Technologies, Palo Alto, CA, United States) according to the methods described by (Shrestha and Baik, 2015; Zhang et al., 2004). A custom-built temperature cell connected to an oil bath was used for controlling the ground beef temperature during dielectric property measurement. Prior to experiments, the liquid test cell was cleaned with warm water and a soft detergent, rinsed with double-distilled deionized water, air dried, and standardized using the manufacturer's instructions. A fiber optic temperature probe (Fiso Tech. Inc. Quebec, Canada) was inserted to touch the periphery of the ground beef bed within the test cell as shown in Figure 1A. This probe was connected to a Universal Multichannel Instrument (Fiso Tech. Inc. Quebec, Canada) used to record the temperature. To avoid variations, the system was calibrated before each measurement.

TABLE 2 Fitter equations representing andepsi;', ε'', and d_p including R^2 and root mean square.

Fitted equations	R^2	RMSE
ε' = 10.5956 + 1.508 (10^{-1})T + 1.9417F–1.6277 (10^{-3})T^2—3.7809 (10^{-2})F^2	0.74	1.306
ε'' = -5217.4440 + 124.8693T + 634.552F–0.5760T^2—13.7181F^2	0.93	5.928 (10^2)
dp = 0.04110–3.826 (10^{-4})T—1.200 (10^{-3})F + 2.051 (10^{-6})T^2 + 2.218 (10^{-5})F^2 AA AA + 3.103 (10^{-6})TF	0.98	4.286 (10^{-4})

Least square models for predicting dielectric properties of ground beef as functions of T- Temperature and F-Fat content.

A thin layer of ground beef was spread onto the liquid test cell as shown in Figure 1B. The thickness was adjusted to 1.3 mm using the spacer disk provided by the manufacturer. The ground beef being analyzed served as a dielectric spaced between the parallel plates of the test cell. Two of the three exit ports were sealed with waterproof tape to prevent the beef from escaping the parallel plate assembly. All dielectric measurements were made in a temperature-controlled environment. The dielectric constant (ε′) and loss-factor (ε″) of the ground beef samples were measured and recorded at an RF frequen of 27.12 MHz using a custom-made probe (Capenhurst Technologies, Chester, United Kingdom) connected to a Hewlett Packard 8714 ET Network Analyzer (Agilent Technologies, Palo Alto, CA 94303, United States).

The instrumentation is shown in Figure 1C. The parallel plate capacitance (C_p) and resistance (R_p) measured by the LCR meter were used to calculate the dielectric properties using the following equations according to the manufacturer's instructions (Agilent Technologies, 2000) and reported formulae (Basaran-Akgul et al., 2008).

$$\varepsilon' = \frac{DC_p}{\varepsilon_0 A} \quad (1)$$

$$\varepsilon'' = \frac{D}{2\pi f R_p \varepsilon_0 A} \quad (2)$$

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \quad (3)$$

$$d_p = \frac{c}{2\pi f\sqrt{2\varepsilon'\left(-1+\sqrt{\left(1+(\tan\delta)^2\right)}\right)}} \quad (4)$$

Where D is the gap between the electrodes (1.3×10^{-3} m), C_p and R_p as defined before, ε_0 is the absolute permittivity (8.854×10^{-12} F/m), f is the frequency (27.12 MHz), and ε′, ε″, and d_p, as defined before. The test cell was submerged in an ice slurry or water bath as shown in Figure 1. A to control the temperature. Values of C_p and R_p were noted as the temperature was increased from 0 to 90°C at intervals of 5°C and used to calculate the dielectric properties.

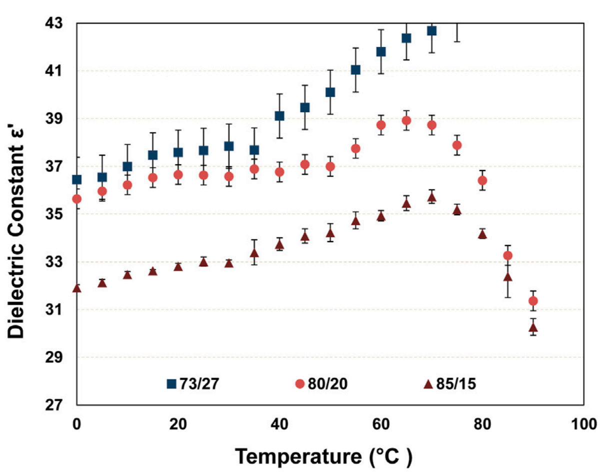

FIGURE 2
Variation of dielectric constant with temperature and lean/fat blends-values represent mean of three replicates with standard deviation.

Statistical analysis

The experiment was replicated three times ($n=3$) and the calculated values were averaged for statistical analysis. The least-square method was employed for multiple regression of response variables, with fat (F) and temperature (T) being the factors. All the predictor coefficients had a significance of <0.05. Model fitting was carried out using R (R Core Team, 2013). The dielectric properties were plotted using MS Excel 2010. Regression coefficients, goodness of fit (R^2), and root mean square of error are reported in Table 2. The three response variables were regressed on F and T in the following form: a + bT + cT^2 + dF + eF^2 + f (T× F). Regression coefficients that were not significant were eliminated when $p > 0.05$.

Results and discussion

Proximate composition analysis of the ground beef revealed that ground beef of different blends varied ($p < 0.05$) with variation in total moisture content (Table 1). More specifically, ground beef blend with higher fat content contained higher moisture level. A similar trend was observed for the total fat content across three ground beef blends. Total ash content was did not differ ($p < 0.05$) among three ground beef blends.

The variation of the dielectric constant with temperature and fat content is shown in Figure 2. For all the three blends, the value of the dielectric constant increased with temperature ($p < 0.05$) as the ground beef was heated above 0°C. The values reached maxima at 65°C for 73/27 and 80/20 ground beef following which they significantly reduced ($p < 0.05$). The maximum was observed at 70°C for the leaner blend 85/15. The numerical value of the dielectric constant was lowest at 90°C for all three blends. Amongst the three blends employed, the values of dielectric constant were significantly lower ($p < 0.05$) for 85/15 ground beef till 80°C. There was no statistical difference between the values obtained for the 73/27 and 80/20 blends in the entire temperature range scanned.

The variation in dielectric constant observed is similar to that reported previously in literature at 27.12 MHz for beef *Biceps femoris* muscle (Brunton et al., 2006) and at microwave frequencies of 915 and 2540 MHz for beef meat (Bircan and Barringer, 2002). However, the maximum in the dielectric constant value was observed at a lower temperature in the present work compared to the cited studies. This trend is similar to the trends observed for dielectric constant values measured at microwave frequencies of 300, 915 and 2540 MHz (Brunton et al., 2006). Current study uses commercial RF frequency of 27.12 MHz that has greater potential of heat generation. It can be assumed that due to higher doses of RF frequency, there would be generation of localized heat that may promote the denaturation of myosin collagen and actin that cumulatively exhibits such increase. Also, in this case, the tendency of denaturation was higher as we have used ground beef having disrupted myofibrillar and connective tissue network that leads to loss of moisture, salts, and water soluble proteins. It also can be pointed out that, the minced beef with different lean/fat blends is prepared by mixing separated lean and fat portion. The fat portion didn't contain the salt part, and minced beef with higher moisture content bears higher leached salt content. This leached salt has a significant negative effect in the dielectric constant. Thus, in minced beef offered a increasing value for dielectric constant with increase in fat content following opposite trend to the reported literature (Lyng et al., 2002), (Lyng et al., 2005). Another interesting observation with respect to fat% and temperature is observed in the current study where after 40°C, the values of dielectric constant increased for all the cases showing maximum for 80/20. With increasing temperature, the disrupted myofibrillar and connective tissue network leads to rapid loss of moisture, salts, and water soluble proteins. As a cumulative effect of leaching of salt, moisture loss and ever evaporation, and denaturation of water soluble proteins exhibited increase in the values of dielectric constant after 40 °C. In ground beef the myofibrillar and connective tissue network is disrupted which results in greater moisture, salts, and water soluble proteins being released.

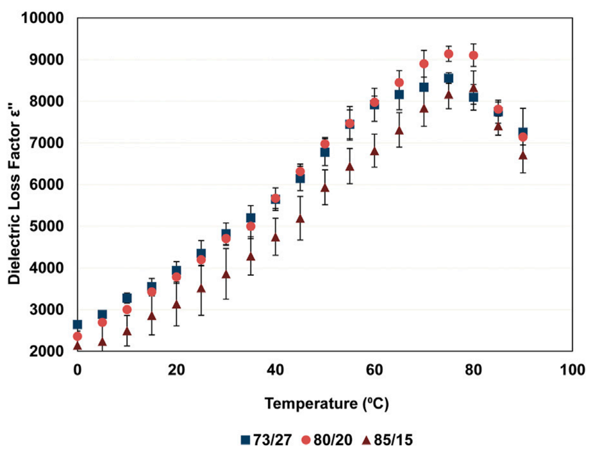

FIGURE 3
Variation of dielectric loss factor with temperature and lean/fat blends-values represent mean of three replicates with standard deviation.

The values of dielectric loss factor significantly increased with temperature ($p < 0.05$) for all the three blends with a maximum appearing at 75°C as seen in Figure 3. A similar trend was previously reported in dielectric loss factor for solid pieces of *Biceps femoris* (Brunton et al., 2006). The dielectric loss factor values observed for the 85/15 blend were significantly lower ($p < 0.05$) than the other two blends up to the point of maxima. There was no statistical difference between the dielectric loss factor values obtained for the 73/27 and 80/20 blends. The values of dielectric constant and loss factor reduced with increasing fat content ($p < 0.05$) and increased with temperature above 0°C ($p < 0.05$).

A similar trend in variation of dielectric loss factor has been previously reported in literature for beef *Biceps femoris* at 27.12 MHz radiofrequency (Brunton et al., 2006) and for ground beef at microwave frequencies (Gunasekaran et al., 2005) although the values were measured only up to 70°C in the latter study. However, the value of dielectric loss factor was lower for high fat percentage in the same study. The difference in this trend is possibly explained by the microwave frequency employed in the cited study on ground beef. Above 50°C myosin denaturation is initiated, and this leads to release of calcium and magnesium ions (Hamm, 1966). At approximately 62°C, collagen denaturation occurs which is accompanied by release of moisture and water-soluble salts. Both mechanisms result in higher ionic mobility by release of fluids and ions (Brunton et al., 2006). Both the increasing temperature and heat induced increase in ionic mobility explain the increase in dielectric loss factor.

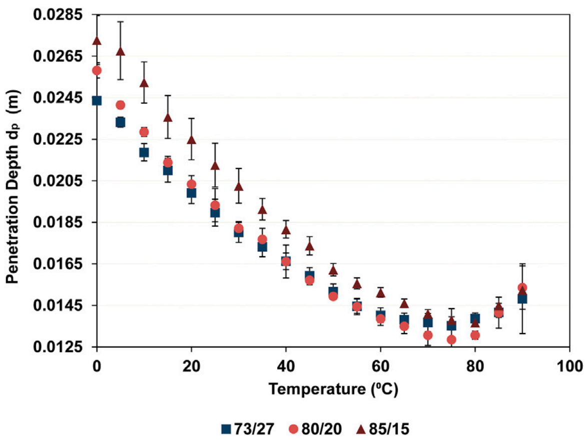

FIGURE 4
Variation of power penetration depth with temperature and lean/fat blends-values represent mean of three replicates with standard deviation.

The variation in penetration depth with temperature and fat content is shown in Figure 4. The penetration depth significantly decreased (p < 0.05) as the temperature increased above 0°C with a minimum appearing for all three blends at 75°C. The penetration depth was significantly higher (p < 0.05) for the leaner blend (85/15) compared to the other two blends up to the point of minimum observed for all three blends. Beyond this temperature, there was no significant difference in the d_p values for the three blends. Thus, interaction of temperature and fat content was observed. This trend closely resembles the variation in penetration depth reported for *Semitendinosus* muscle at RF and microwave frequencies (Basaran-Akgul et al., 2008). Similar values for penetration depth have been reported for ground beef at microwave frequencies up to 75°C (Gunasekaran et al., 2005). However, penetration depth was shown be higher for higher fat content in the cited study. The difference in d_p variation with fat content in this study is possibly explained by a lower frequency compared to microwaves. The reduction in penetration depth of ground beef with temperature and with lean content and signifies a lesser uniform RF heating. This is an important factor to consider while designing RF heating processes.

United States Department of Agriculture–Food Safety and Inspection Services (USDA-FSIS) recommends that research studies using cooking of ground beef products should show that a consistent temperature distributed across the ground beef products that are either partially cooked or cooked from the thawed rather than the frozen state (Berry, 2000). Ground beef products cooked from the frozen state will take longer time and higher temperature to achieve the target endpoint temperature than those that have been thawed (Luchansky et al., 2013). In any case, this research study recommends that in commercial settings, a detailed RF cooking instruction must be provided on the label and commercial establishments should consider conducting additional tests to assess the impact on cooking adequacy. Commercial establishments must consider that consumers generally tend not to fully thaw the frozen product prior to cooking. Alternatively, commercial establish must consider providing two different sets of RF cooking instructions: one for RF heating of thawed ground beef products and additional instruction for RF heating or cooking of frozen raw ground beef products.

As the temperature increased beyond the respective maxima for ε′ and ε″ and minimum for d_p, there was no significant difference between values for the different fat blends. Muscle shrinking, expulsion of moisture, water soluble salts and ions, and protein denaturation with increasing temperature may explain the increase in the values of dielectric constant and dielectric loss factor and conversely the decrease in $d_{p.}$ As the temperature increased beyond the respective extrema values (maxima for ε′ and ε″, and mimimum for d_p) subsequent values of all dielectric properties were not significantly different. This phenomenon may be attributed to tissue shrinkage due to excess protein denaturation.

Second order regression models were fitted for the dielectric constant, dielectric loss factor, and the power penetration depth in Table 2. The goodness of fit (R^2) for ε′ model was only 0.74 with a second order model. Factors other than temperature and fat may be necessary to obtain a model which better explains the variation in ground beef ε′. Perhaps higher order models may yield better R^2 values for ε′ variation. However, the practical interpretation of such higher order models is difficult. The fitted models for ε″ and d_p well had R^2 values close to 1. Thus, there was good agreement between the predicted value and experimentally observed value. The interaction of fat and temperature significantly affected the penetration depth and this interaction explains the trend reported and discussed previously in this study.

Conclusion

Values of all the dielectric properties ε′, ε″, and d_p were determined for ground beef of different fat contents at 27.12 MHz frequency. All the three properties i.e. ε′, ε″, and d_p showed a temperature and fat content dependent variation up to the point of extremum. The values of ε′ and ε" increased with temperature to the point of maximum and then decreased and values of d_p decreased to the point of minimum and then increased. The values of ε′ and ε" were significantly lower for leaner ground beef blend (85/15) up to the point of maximum and values of d_p were significantly lower for the same blend up to the point of minimum. No significant differences in values of all three dielectric properties were observed past the points of extrema among the different fat blends. This may be attributed to protein denaturation, tissue shrinking, and moisture expulsion in ground beef. Models were developed which were 74%, 93%, and 98% effective in explaining the fat and temperature dependent variation in ε', ε'', and d_p respectively based on the R^2 values. The variation in dielectric loss factor and power penetration depth of ground beef is well explained by the developed polynomial equations using temperature and fat content as explanatory variables.

Data availability statement

The datasets presented in this article are not readily available because No data sets were generated for this research. Requests to access the datasets should be directed to AM, anandmohan@uga.edu.

Author contributions

AP: Conceptualization, Methodology, Investigation, Writing—Original draft. AM: Conceptualization, Methodology, Validation, Writing—Original draft, review and editing, Visualization, Project supervision and administration, and Funding acquisition.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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