

Article

Use of Modern Regression Analysis in the Dielectric Properties of Foods

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Abstract: The dielectric properties of food materials is used to describe the interaction of foods with electromagnetic energy for food technology and engineering. To quantify the relationship between dielectric properties and influencing factors, regression analysis is used in our study. Many linear or polynomial regression equations are proposed. However, the basic assumption of the regression analysis is that data with a normal distribution and constant variance are not checked. This study uses sixteen datasets from the literature to derive the equations for dielectric properties. The dependent variables are the dielectric constant and the loss factor. The independent variables are the frequency, temperature, and moisture content. The dependent variables and frequency terms are transformed for regression analysis. The effect of other qualitative factors, such as treatment method and the position of subjects on dielectric properties, are determined using categorical testing. Then, the regression equations can be used to determine which influencing factors are important and which are not. The method can be used for other datasets of dielectric properties to classify influencing factors, including quantitative and qualitative variables.

Keywords: dielectric properties; frequency; moisture content; temperature; regression analysis

1. Introduction

The dielectric properties of foods are the basic information for the interaction of foods with electromagnetic energy. These properties are used to determine the effect of heating and pasteurization treatments. The frequencies that are used are 13.56, 27.12, and 40.68 MHz for radio frequency and 915 and 2450 MHz for microwave electric fields. Then, the dielectric properties of foods are used to design successful treatments [1].

The property that is used to describe the dielectric properties of a material is the relative complex property, ϵ^* .

The relative complex property is expressed as in Equation (1):

$$\epsilon'' = \epsilon' - j\epsilon'' \quad (1)$$

where ϵ' is the dielectric constant and ϵ'' is the loss factor.

The dielectric constant ϵ' is the measure of the ability of a material to store energy, which is affected by the electric field. The dielectric loss factor ϵ'' is the measure of the ability of a material to dissipate energy. The thermal energy of the material is converted as in Equation (2):

$$P_v = E^2 \sigma = 55.63 \times 10^{-12} f \times E^2 \times \epsilon'' \quad (2)$$

where P_v is the energy that is developed per unit volume in W/m^3 , f is the frequency in Hz, and E is the electric field strength inside the load in V/m.

Several techniques are developed to determine the dielectric properties of foods [2–4]. Detailed reviews of this topic and the relationship between the dielectric properties have been undertaken [1,5–7]. Studies have been published on the dielectric properties of foods such as egg with powder [8], egg whites and whole eggs [9,10], chickpea flour [11], cowpea weevil, black-eyed peas and mung beans [12], butter [13], bread [14], cheese [15], salmon and sturgeon [16], salmon fillets [17], macadamia nuts [18], and pecan kernels [19].

To develop thermal treatments for post-harvest insect control, the dielectric properties of five fruits, two nuts, and four insect larvae at four frequencies and five temperatures were tested and reported [20].

Recently, Routray and Orsat [21] mention the challenges of the application for dielectric properties of foods. The nonuniform heating limits the microwave application of the large-scale processing. The prediction equations of low moisture products such as spices are required to develop the in-package pasteurization technique. The finite element method provides a way to observe the heating patterns, and the prediction equations of dielectric properties are the basic information. The dielectric properties of complex food equations are the concern of food engineers [21]. The development of the prediction equation for the dielectric properties of multi-component foods by their components and its individual prediction equation would be very useful for the food industry.

The factors that affect the dielectric properties of foods include the applied frequency, the temperature, the bulk density, and the concentration and constituents of foods [1,4–7]. The equations for dielectric properties describe the relationship between the dielectric properties and influencing factors. Calay et al. [22] described three types of prediction equations (Equations (3)–(6)):

1. Variables including temperature, moisture content, and frequency

$$y_1 = a_0 + a_1 T + a_2 X + a_3 f \quad (3)$$

where y_1 is the dielectric constant or the dielectric loss factor, T is the temperature in °C, X is the moisture content (wet basis, w.b. or dry basic, d.b.) in %, and f is the applied frequency in MHz.

2. Variables including temperature and moisture content

$$y_2 = b_0 + b_1 T + b_2 X + b_{12} T \times X \quad (4)$$

$$y_3 = c_0 + c_1 T + c_2 X \quad (5)$$

3. Only one variable with other factors fixed

$$y_4 = c_0 + c_1 T + c_2 T^2 \text{ at fixed moisture content and frequency} \quad (6)$$

Calay et al. [22] used the coefficient of determination R^2 as the sole criterion to determine the fitting agreement for these equations.

The published models using data that involve more variables are listed in Table 1. Most of these equations are multiple regression equations. Many linear or polynomial regression equations are established at a fixed frequency for other factors [8,13,14,17,23]. Everard et al. [15] used a partial least square regression to establish empirical equations to predict moisture content. However,

the assumption of the partial least square regression in terms of the multi-collinearity was not considered. Guo et al. [10] proposed prediction equations that use the logarithmic form of dielectric properties (dependent variable) and the logarithmic form of influencing factors (independent variable).

Simple linear regression is used widely. These equations proposed by Kannan et al. [24] involved a higher-order polynomial equation with an inverse form of the frequency and an exponential function for other variables. Multiple linear regression models involving the influencing factors, the interaction between these factors, and the density at fixed frequency were used by Zhu et al. [25]. Boldor et al. [26] adopted the power form of dielectric properties to quantify the effect of the moisture content and temperature at fixed frequency. Zhu and Guo [29] proposed a simple linear equation to describe the relationship between dielectric properties and the logarithmic form of the frequency at fixed conditions of the moisture content and temperature for potato starch. Yu et al. [27] proposed a multiple regression model with three factors as independent variables (temperature, moisture content, and frequency) and their interactions between factors.

Most studies use R^2 as the sole criterion. Some studies used the p -value to assess the utility of a model [7,19,26,28,29,31]. However, these criteria (R^2 and p -value) are used for the classical regression, not for the modern regression. Using only the R^2 or p -value does not decide the applicability of regression models [31–33].

Modern regression expresses the quantitative relationship between dependent variables and influencing factors for a biological system [34–36]. In this study, this modern regression technique is used to determine the effect of various factors on the dielectric properties. Modern regression techniques, such as the normal test, the constant variance test, tests on a single regression coefficient, and categorical testing are applied in the study of dielectric properties of foods.

To the best knowledge of the authors, modern regression equations have not been used in a study of dielectric properties. This study determines the usefulness of the modern analysis to determine the influencing factors for the dielectric properties of foods using data from previous studies.

Table 1. Published models of dielectric constants for foods.

| Study | Food Type | Frequency (MHz) | Temperature (°C) | Moisture Content (% w.b. or d.b.) | Equations | Statistics Criteria | | | |
|---------------------------|-----------------------|-----------------|------------------|-----------------------------------|---|---------------------|---------|-------------|------------------------|
| | | | | | | R ² | p-Value | Normal Test | Constant Variance Test |
| Calay et al. (1995) [22] | Fruit and vegetable | 900–3000 | 0–70 | 50–90 | Equation (1-1) | yes | no | no | no |
| | Meat | 2000–3000 | 0–70 | 60–80 | Equation (1-2) | yes | no | no | no |
| | Fish | 2450 | 0–70 | >70 | Equation (1-3) Equation (1-4) | yes | no | no | no |
| Guo et al. (2007) [10] | Eggs | 10–1800 | 24 | – | Equation (1-5) | yes | no | no | no |
| Ahmed et al. (2007) [13] | Butter | 500–3000 | 30–80 | 17–19 | Equation (1-6) at fixed temperature | yes | no | no | no |
| Wang et al. (2007) [17] | Fish (salmon fillets) | 27–1800 | 20–120 | 74.97–76.14 | Equation (1-3) | yes | no | no | no |
| Dev et al. (2008) [23] | Eggs | 20–10,000 | 0–62 | | Equation (1-7) | yes | no | no | no |
| Liu et al. (2009) [14] | Bread | 13.56–1800 | 25–85 | 34–38.6 | Equation (1-8) at fixed temperature and moisture | yes | no | no | no |
| | | | | | Equation (1-9) at fixed temperature and frequency | | | | |
| | | | | | Equation (1-3) at fixed frequency and moisture | | | | |
| Wang et al. (2009) [9] | Eggs | 27–1800 | 20–120 | | Equation (1-3) at fixed frequency | yes | no | no | no |
| Kannan et al. (2013) [24] | Eggs | 10–3000 | 5–56 | | Egg white: ϵ' : Equation (1-10) | yes | no | no | no |
| | | | | | Egg white: ϵ'' : Equation (1-11) | | | | |
| | | | | | Egg yolk: ϵ' : Equation (1-12) | | | | |
| | | | | | Egg yolk: ϵ'' : Equation (1-13) | | | | |

Table 1. Cont.

| Study | Food Type | Frequency (MHz) | Temperature (°C) | Moisture Content (% w.b. or d.b.) | Equations | Statistics Criteria | | | |
|--------------------------------|------------------|-----------------|------------------|-----------------------------------|---|---------------------|---------|-------------|------------------------|
| | | | | | | R ² | p-Value | Normal Test | Constant Variance Test |
| Zhu et al. (2013) [25] | Wheat seeds | 1–1000 | 5–40 °C | 11.1–17.1 | Equation (1-14) | yes | no | no | no |
| Boldor et al. (2014) [26] | Peanuts | 300–3000 | 23–50 | 18–23 | Equation (1-4) at fixed frequency | yes | no | no | no |
| Yu et al. (2015) [27] | Canola seeds | 500–3000 | 30–70 | 5–11 | Equation (1-15) | yes | no | no | no |
| Zhang et al. (2016) [28] | Peanut kernels | 10–4500 | 25–85 | 10–30 | Equation (1-16) | yes | no | no | no |
| Boreddy and Subbiah (2016) [8] | Egg white powder | 10–3000 | 20–100 | 5.5–13.4 | Equation (1-17) at fixed frequency | yes | no | no | no |
| Zhu and Guo (2017) [29] | Potato Starch | 20–4500 | 25–75 | 15.1–43.1 | Equation (1-18) at fixed moisture and temperature | yes | no | no | no |
| Ling et al. (2018) [30] | Rice bran | 300–3000 | 25–100 | 10.36–24.69 | Equation (1-19) | yes | no | no | no |
| Zhang et al. (2019) [19] | Pecan Kernels | 27–2450 | 5–65 | 10–30 | Equation (1-20) | yes | no | no | no |

Equation (1-1): $y_i = a_0 + a_1 T + a_2 X + a_3 f$; Equation (1-2): $y_i = b_0 + b_1 T + b_2 X + b_{12} T \times X$; Equation (1-3): $y_i = c_0 + c_1 T + c_2 T^2$; Equation (1-4): $y_i = d_0 + d_1 T + d_2 X$; Equation (1-5): $\log y_i = e_0 + e_1 \log f$; Equation (1-6): $y_i = f_0 + f_1 f + f_2 f^2$; Equation (1-7): $y_i = g_0 + g_1 T + g_2 f$; Equation (1-8): $y_i = h_0 + h_1 f$; Equation (1-9): $y_i = i_0 + i_1 X$; Equation (1-10): $y_i = (c_0 + c_1 T + c_2 T^2) \times \exp(j_0 + j_1 T/f)$; Equation (1-11): $y_i = (k_0 + k_1 T + k_2 T^2) + (n_0 + n_1 T + n_2 T^2)/f$; Equation (1-12): $y_i = (l_0 + l_1 T + l_2 T^2 + l_3 T^3 + l_4 T^4) \times \exp[(m_0 + m_1 T + m_2 T^2 + m_3 T^3 + m_4 T^4)/f]$; Equation (1-13): $y_i = (n_0 + n_1 T + n_2 T^2 + n_3 T^3 + n_4 T^4) + (o_0 + o_1 T + o_2 T^2 + o_3 T^3 + o_4 T^4)/f$; Equation (1-14): $y_i =$ Multiple linear regression model, variables involved: $(X, T, \rho X, T, X \times \rho, T \times \rho, X^2, \rho^2, T^2, X \times T \times \rho, X^2 \times T, X^2 \times \rho, X \times T^2, X \times \rho^2, T^2 \times \rho, T^2 \times \rho^2, X^3, T^3, \rho^3$ at fixed frequency (ρ is density); Equation (1-15): $y_i = \rho_0 + \rho_1 F + \rho_2 X + \rho_3 T + \rho_4 f \times X + \rho_5 f \times T + \rho_6 X \times F + \rho_7 T \times X \times f$; Equation (1-16): $y_i =$ Multiple linear regression model, variables involved $T, X, T \times X, T^2 \times X^2, T^2 \times X, T \times X^2, T^3, X^3$; Equation (1-17): $y_i = q_0 + q_1 X + q_2 T + q_{11} X^2 + q_{12} T^2 + q_{12} X \times T$; Equation (1-18): $y_i = r_0 + r_1 \log f$; Equation (1-19): $y_i =$ Multiple linear regression model, variables involved $T, X, X \times T, X^2, T^2, X^2 \times T, X \times T^2, X^3, T^3$; Equation (1-20): $y_i = t_0 + t + t_2 T + t_{11} X^2 + t_{22} T^2 + t_{12} T \times X$; R^2 is the coefficient of determination.

2. Materials and Methods

2.1. Regression Analysis

A typical multiple linear regression model involves three variables (Equation (7)):

$$y_i = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1 \times x_2 + b_{13}x_1 \times x_3 + b_{23}x_2 \times x_3 + b_{123}x_1 \times x_2 \times x_3 + \varepsilon_i \quad (7)$$

where y_i is the dielectric constant or loss factor, $b_0, b_i, b_j, b_k, b_{ii}, b_{ij}, -b_{ijk}$, are the parameters, x_i is an independent variable, such as frequency, temperature, or moisture content, and ε_i is a model random error.

The nonstandard conditions for a linear regression model include the model misspecification, the non-constant variance, and a non-normal distribution [31–33]. These conditions can be identified using modern regression analysis. The diagnostic techniques are described as follows:

2.1.1. Residual Plots

The distribution between residuals and the predicted values of a model is called a residual plot. A residual plot is a graph that present the residuals on the longitudinal axis and the predicted value of the model on the horizontal axis. If the data exhibit a uniform distribution along the $y_i = 0$ line, this regression model is an appropriate model. If there is a fixed pattern for the data distribution, this model is not suitable [32,37–39].

2.1.2. Normality Test

A normal distribution of the data is verified using the Kolmogorov–Smirnov test. The Kolmogorov–Smirnov statistic calculates the distance between the empirical distribution function of the sample and the cumulative distribution function of the normal distribution. The criterion is a p -value to determine the probability of being incorrect in concluding the data [32,37–39].

2.1.3. Constant Variance Test

A constant variance test is performed by calculating the Spearman rank correlation between the observed values of dependent variables and the absolute residual values. The statistic is used to evaluate the strength and direction of the association that exists between two variables. The p -value is used to determine the significance of any correlation between these variables [37–39].

2.1.4. Transformation

If the assumption of a normal distribution and constant variance are violated, data with independent or dependent variables are transformed to stabilize the error variances and to achieve a normal distribution of the data. The ordinary forms of the transformation are logarithmic ($\ln y$), inverse power ($1/y$), and square root (\sqrt{y}) [31,32,37–39].

In this study, two forms of the combination of independent variables are used (Equation (8) and Equation (9)):

$$f(T, X, f) = b_0 + b_1T + b_2X + b_3f + b_{11}T^2 + b_{22}X^2 + b_{33}f^2 + b_{12}T \times X + b_{13}T \times f + b_{23}X \times f + b_{123}T \times X \times f. \quad (8)$$

The term f is transformed into logarithmic form as $\ln(f)$:

$$g(T, X, \ln f) = c_0 + c_1T + c_2X + c_3 \ln f + c_{11}T^2 + c_{22}X^2 + c_{33} \ln f^2 + c_{12}T \times X + c_{13}T \times \ln f + c_{23}X \times \ln f + c_{123}T \times X \times \ln f. \quad (9)$$

Four forms of independent variables are used: y , \sqrt{y} , $\ln y$ and $1/y$.

The statistical analysis involved multiple linear regression. The parameters were estimated with the use of SigmaPlot v. 14.0 (SPSS Inc., Chicago, IL, USA).

2.2. The Effect of the Storage Time

To determine the effect of the storage time on the dielectric properties, storage time is assumed as a variable and is incorporated into the regression model. If the relationship between a dielectric property (y) and the logarithmic form of the frequency presented in Equation (10) is:

$$\ln(y) = d_0 + d_1 \ln f + d_2 \ln f^2 \quad (10)$$

then, the equation (Equation (11)) to determine the effect of the storage time on the dielectric property is:

$$\ln(y) = e_0 + e_1 \ln f + e_2 St + e_{11} \ln f^2 + e_{22} St^2 + e_{12} \ln f \times St \quad (11)$$

where St is the storage time in weeks.

The effect of the storage time is tested by validating three parameters: e_2 , e_{22} , and e_{12} . If these three parameters are invalid and are not significantly different from zero, the effect of the storage time on dielectric properties is neglected.

2.3. Categorical Testing

To determine the effect of categorical variables, such as treatment (e.g., unsalted or salted) [13,16], position of the sample (e.g., anterior, middle, tail, and belly) [17], moisture conditions (e.g., low, medium, and high) [15], or concentration (e.g., no salted, light salted, medium salted, and heavy salted) [19], a categorical test is used.

1. Two categories:

$z = 0$, if the observation is from level A.

$z = 1$, if the observation is from level B.

If the equation (Equation (12)) linking the independent variable and two variables is:

$$y_i = b_0 + b_1 x_1 + b_{11} x_1^2 + b_2 x_2 + b_{22} x_2^2 + b_{12} x_1 x_2 + \varepsilon_i \quad (12)$$

then, the equation (Equation (13)) to determine the significance of two levels of a factor is

$$y_i = c_0 + c_3 z + c_1 x + c_{13} x_1 z + c_{11} x_1^2 + c_{113} x_1^2 z + c_2 x_2 + c_{23} x_2 z + c_{22} x_2^2 + c_{223} x_2^2 z + c_{12} x_1 x_2 + c_{123} x_1 x_2 z + \varepsilon_i \quad (13)$$

where c_3 , c_{13} , c_{113} , c_{23} , c_{323} , and c_{113} are constants and z is the categorical variable.

The effect of a factor is determined by testing the significance of c_3 , c_{13} , c_{113} , c_{23} , c_{323} , and c_{113} values.

2. Three categories:

$z_1 = 0, z_2 = 0$, if the observation is from level A.

$z_1 = 1, z_2 = 0$, if the observation is from level B.

$z_1 = 0, z_2 = 1$, if the observation is from level C.

Equation (12) pertains to factors with three levels.

The equation to determine the significance of the levels of a factor is (Equation (14)):

$$y_i = d_0 + d_1 x_1 + d_2 x_2 + d_{11} x_1^2 + d_{22} x_2^2 + d_{12} x_1 x_2 + d_3 z_1 + d_4 z_2 + d_{13} x_1 z_1 + d_{14} x_1 z_2 + d_{113} x_1^2 z_1 + d_{114} x_1^2 z_2 + d_{23} x_2 z_1 + d_{24} x_2 z_2 + d_{223} x_2^2 z_1 + d_{224} x_2^2 z_2 + d_{123} x_1 x_2 z_1 + d_{124} x_1 x_2 z_2 + \varepsilon_i \quad (14)$$

The effect of factors is determined by testing the significance of $d_3, d_4, d_{13}, d_{14}, d_{113}, d_{114}, d_{223}, d_{224}, d_{123},$ and d_{124} values.

3. Four categories:

$z_1 = 0, z_2 = 0, z_3 = 0,$ if the observation is from level A.

$z_1 = 1, z_2 = 0, z_3 = 0,$ if the observation is from level B.

$z_1 = 0, z_2 = 1, z_3 = 0,$ if the observation is from level C.

$z_1 = 0, z_2 = 0, z_3 = 1,$ if the observation is from level D.

The equation to determine the significance of these factors is (Equation (15)):

$$y_i = e_0 + e_1x_1 + e_2x_2 + e_{11}x_1^2 + e_{22}x_2^2 + e_{12}x_1x_2 + e_3z_1 + e_4z_2 + e_5z_3 + e_{13}x_1z_1 + e_{14}x_1z_2 + e_{15}x_1z_3 + e_{113}x_1^2 + e_{114}x_1^2z_2 + e_{115}x_1^2z_3 + e_{23}x_2z_1 + e_{24}x_2z_2 + e_{25}x_2z_3 + e_{223}x_1^2z_1 + e_{224}x_1^2z_2 + e_{225}x_1^2z_3 + e_{123}x_1x_2z_1 + e_{124}x_1x_2z_2 + e_{125}x_1x_2z_3 + \varepsilon_i \tag{15}$$

2.4. Criterion of the Model Comparison

In this study, the dependent variables have different forms, such as $y, \sqrt{y}, \ln y,$ and $1/y.$ The best equation could not only be determined using the R^2 value of each equation. The R^2 value is calculated as [31,32] (Equation (16)):

$$R^2 = \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2} \tag{16}$$

where \hat{y}_i is the predicted value for the equation, \bar{y} is the average value of the dependent variable, and y_i is the dependent variable.

The numerical values for the dependent variable are different because of its transformation form. The R^2 value for model y is calculated using the values of $\hat{y}_i, \bar{y},$ and $y_i.$ The R^2 of $\ln(y)$ is calculated using $\hat{y}_i, \ln \bar{y},$ and $\ln y_i.$ It is meaningless to compare the R^2 values of these models.

The error variance or error mean square s^2 is used to determine the fitting agreement for several models [31–33]. However, the transformed response value must be transformed back to the natural variable.

The calculation of s^2 is for the y_i (Equation (17)):

$$s^2 = \frac{\sum(y_i - \bar{y})^2}{n - p} \tag{17}$$

For the $\ln(y)$ form equation, all predicted values using regression are in the form of $\ln \hat{y}_i.$ The s^2 value is calculated as (Equation (18)):

$$s^2 = \frac{\sum(y_i - \text{Exp}(\ln \hat{y}_i))^2}{n - p} \tag{18}$$

The same process is used for the $1/y$ form of the equation, where all predicted values for regression are $(1/\hat{y}_i),$ and the s^2 value is calculated as (Equation (19)):

$$s^2 = \frac{\sum(y_i - (1/\hat{y}_i) - 1)^2}{n - p} \tag{19}$$

2.5. Literature Survey

Sixteen sets of data for dialectical properties and the experimental values for frequency, temperature, and moisture content are presented in Table 2.

Table 2. Published data for dielectric properties in the literature.

| Items | | Frequency (MHz) | | | | | | Temperature (°C) | | | | | | Moisture Content (%) | | | | | | Literature | |
|-----------------|--|-----------------|-------|-------|------|------|------|------------------|----------------------------------|-----|--------|------|--------|----------------------|------|--------|------|------|--------|------------|------|
| Egg | White powder | 13.56 | 27.12 | 40.68 | 915 | 2450 | 20 | 40 | 60 | 80 | 100 | 8 | % d.b. | | | | | [8] | | | |
| | | 27.12 | 915 | 20 | 40 | 60 | 80 | 100 | 5.5 | 6.6 | 8.0 | 9.8 | 13.4 | % d.b. | [9] | | | | | | |
| Whites | Liquid | 27 | 40 | 915 | 1800 | 20 | 40 | 60 | 70 | 80 | 100 | 120 | | | | | | [9] | | | |
| Egg | Precooked Albumen Yolk | 10 | 27 | 40 | 100 | 915 | 1800 | 24 | | | | | | | | | | | [10] | | |
| | | 10 | 27 | 40 | 100 | 915 | 1800 | 24 | Storage time (0,1,2,3,4,5) weeks | | | | | | | | | | | | |
| Vegetables | Chickpea flour Black-eyed peas | 27 | 40 | 100 | 915 | 1800 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 7.9 | 11.4 | 15.8 | 20.9 | % w.b. | [11] | |
| | | 27 | 40 | 915 | 20 | 30 | 40 | 50 | 60 | 8.8 | 12.7 | 16.8 | 20.9 | % w.b. | [12] | | | | | | |
| Fruits | Apple(GD) Apple(RD) Cherry Grape-fruit Orange | 27 | 40 | 915 | 1800 | 20 | 30 | 40 | 50 | 60 | | | | | | | | | | | [20] |
| Butter | Unsalted Salted | 915 | 2,450 | 30 | 40 | 50 | 60 | 70 | 80 | | | | | | | | | | | [13] | |
| Bread | | 13.56 | 27.12 | 40.68 | 915 | 1800 | 25 | 40 | 55 | 70 | 85 | 34.0 | 34.6 | 37.1 | 38.6 | % w.b. | [14] | | | | |
| Cheese | | 270 | 500 | 800 | 1200 | 1900 | 3000 | 5 | 45 | 55 | 65 | 75 | 85 | | | | | | [15] | | |
| Fish | | | | | | | | | | | | | | | | | | | | | |
| Sturgeon caviar | Unsalted Salted | 27 | 915 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | | | | | | [16] | | | | | |
| Salmon fillets | Anterior Middle Tail Belly | 27 | 40 | 915 | 1800 | 20 | 40 | 60 | 80 | 100 | 120 | | | | | | [17] | | | | |
| Nut | Almond Walnut | 27 | 40 | 915 | 1800 | 20 | 30 | 40 | 50 | 60 | | | | | | [20] | | | | | |
| | | 27 | 40 | 915 | 1800 | 20 | 30 | 40 | 50 | 60 | | | | | | [20] | | | | | |
| | Macadamia nut kernels | 27.12 | 40.68 | 915 | 1800 | 25 | 40 | 60 | 80 | 100 | 3 | 6 | 12 | 18 | 24 | % w.b. | [18] | | | | |
| Pecan | Unsalted | 27 | 40 | 915 | 2450 | 5 | 25 | 45 | 65 | 15 | % w.b. | | | | | [19] | | | | | |
| | Light salted | | | | | | | | | | | | | | | | | | | | |
| | Medium salted Heavy salted | | | | | | | | | | | | | | | | | | | | |
| Insect | Codling moth Indian-meal moth Mexican fruit fly Navel arrange worm | 27 | 40 | 915 | 1800 | 20 | 30 | 40 | 50 | 60 | | | | | | [20] | | | | | |

3. Results

3.1. The Dielectric Equations with Three Variables

3.1.1. Egg White Powder

Two datasets are used for this literature [8]. The first dataset shows the dielectric content and loss factor data at 8.0% d.b. moisture content for five temperatures from 20 to 100 °C and five frequencies (13.56, 29.12, 40.68, 951, and 2450 MHz). The second dataset shows the dielectric properties at temperatures from 20 to 100 °C, two frequencies (27.12 and 915 MHz), and five moisture contents (5.5, 6.6, 8.0, 9.8, and 13.4% d.b.). Both datasets are pooled to derive the equations for this study. The dielectric properties of the egg white powder at 8.0% (Figure 1a) and 13.4% d.b. (Figure 1b) are showed in Figure 1.

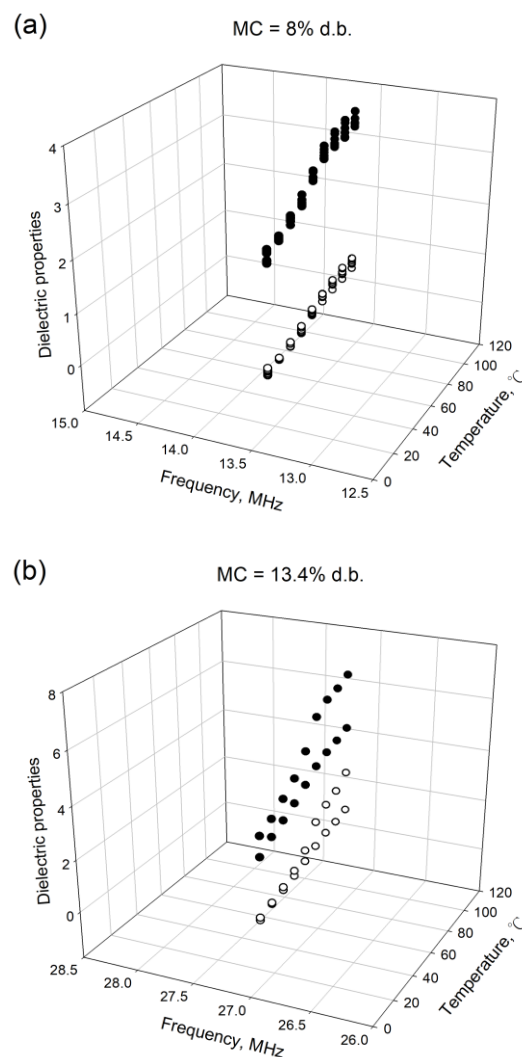


Figure 1. The dielectric properties of the egg white powder at 8.0% moisture content (MC) (a) and 13.4% d.b. moisture content (MC) (b); ○ is the dielectric constant; ● is the loss factor.

The results for the dielectric content using modern regression analysis are listed in Table 3 (Equation (3-1) to Equation (3-8)). Four equations fulfill the criteria for the regression check. They have normally distributed data and a constant variance. The results are $\ln(\epsilon') = f_1(f)$, $1/\epsilon' = f_2(f)$, $\ln(\epsilon') = g_1(\ln f)$ and $1/\epsilon' = g_2(\ln f)$.

Table 3. The relationship between the dielectric constant and the influencing factors and statistical criteria established by regression analysis for egg white powder.

| |
|--|
| Equation (3-1): $\varepsilon' = 2.928 - (0.0154 \times T) - (0.000173 \times f) - (0.274 \times X) - (0.0000923 \times T^2) + (0.0151 \times X^2) + (0.0000353 \times T \times f) + (0.00558 \times T \times X) + (0.00000654 \times f \times X) - (0.00000439 \times T \times f \times X)$ |
| $R^2 = 0.980$ |
| Normality Test (Kolmogorov–Smirnov): Passed ($p = 0.590$) |
| Constant Variance Test (Spearman Rank Correlation): Failed ($p = 0.041$) |
| Equation (3-2): $\sqrt{\varepsilon'} = 1.432 - (0.000287 \times T) + (0.0000403 \times f) - (0.0340 \times X) - (0.0000334 \times T^2) + (0.00279 \times X^2) + (0.00000750 \times T \times f) + (0.00116 \times T \times X) - (0.00000899 \times f \times X) - (0.000000906 \times T \times f \times X)$ |
| $R^2 = 0.980$ |
| Normality Test: Passed ($p = 0.398$) |
| Constant Variance Test: Failed ($p = 0.048$) |
| Equation (3-3): $\ln \varepsilon' = 0.488 + (0.00361 \times T) + (0.000120 \times f) + (0.00237 \times X) - (0.0000460 \times T^2) + (0.00175 \times X^2) + (0.00000640 \times T \times f) + (0.000944 \times T \times X) - (0.0000194 \times f \times X) - (0.000000743 \times T \times f \times X)$ |
| $R^2 = 0.976$ |
| Normality Test: Passed ($p = 0.160$) |
| Constant Variance Test: Passed ($p = 0.497$) |
| Equation (3-4): $1/\varepsilon' = 0.678 - (0.00330 \times T) - (0.0000699 \times f) - (0.0219 \times X) + (0.0000203 \times T^2) + (0.000155 \times X^2) - (0.00000121 \times T \times f) - (0.000123 \times T \times X) + (0.0000102 \times f \times X) + (0.000000119 \times T \times f \times X)$ |
| $R^2 = 0.990$ |
| Normality Test: Passed ($p = 0.151$) |
| Constant Variance Test: Passed ($p = 0.467$) |
| Equation (3-5): $\varepsilon' = 2.954 - (0.0456 \times T) + (0.0186 \times \ln f) - (0.282 \times X) - (0.0000926 \times T^2) - (0.00778 \times \ln f^2) + (0.0150 \times X^2) + (0.00928 \times T \times \ln f) + (0.00920 \times T \times X) + (0.00273 \times \ln f \times X) - (0.00113 \times T \times \ln f \times X)$ |
| $R^2 = 0.980$ |
| Normality Test: Passed ($p = 0.459$) |
| Constant Variance Test: Failed ($p = 0.003$) |

Table 3. Cont.

| |
|---|
| Equation (3-6): $\sqrt{(\varepsilon')} = 1.390 - (0.00697 \times T) + (0.0246 \times \ln f - (0.0291 \times X) - (0.0000335 \times T^2) - (0.00231 \times \ln f^2) + (0.00280 \times X^2) + (0.00203 \times T \times \ln f + (0.00193 \times T \times X) - (0.00181 \times \ln f \times X) - (0.000236 \times T \times \ln f \times X)$ |
| $R^2 = 0.980$ |
| Normality Test: Passed ($p = 0.355$) |
| Constant Variance Test: Failed ($p = 0.031$) |
| Equation (3-7): $\ln(\varepsilon') = 0.400 - (0.00242 \times T) + (0.0434 \times \ln f + (0.0140 \times X) - (0.0000462 \times T^2) - (0.00271 \times \ln f^2) + (0.00180 \times X^2) + (0.00181 \times T \times \ln f + (0.00159 \times T \times X) - (0.00422 \times \ln f \times X) - (0.000197 \times T \times \ln f \times X)$ |
| $R^2 = 0.977$ |
| Normality Test: Passed ($p = 0.370$) |
| Constant Variance Test: Passed ($p = 0.349$) |
| Equation (3-8): $1/\varepsilon' = 0.720 - (0.00196 \times T) - (0.0199 \times \ln f) - (0.0280 \times X) + (0.0000204 \times T^2) + (0.000905 \times \ln f^2) + (0.000118 \times X^2) - (0.000389 \times T \times \ln f) - (0.000238 \times T \times X) + (0.00227 \times \ln f \times X) + (0.0000342 \times T \times \ln f \times X)$ |
| $R^2 = 0.964$ |
| Normality Test: Passed ($p = 0.020$) |
| Constant Variance Test: Passed ($p = 0.574$) |

Four residual plots are shown in Figure 2a–d. The distribution between residual and predicted values for ε' vs. f (Figure 2a) and ε' vs. $\ln f$ (Figure 2b) show a scatter and an inflated distribution for the residual. This demonstrates a non-constant variance for the data. The uniform distributions for residuals in Figure 2c $\ln \varepsilon'$ vs. $\ln f$ and Figure 2d ($1/\varepsilon'$ vs $\ln f$) show that two equations are appropriate.

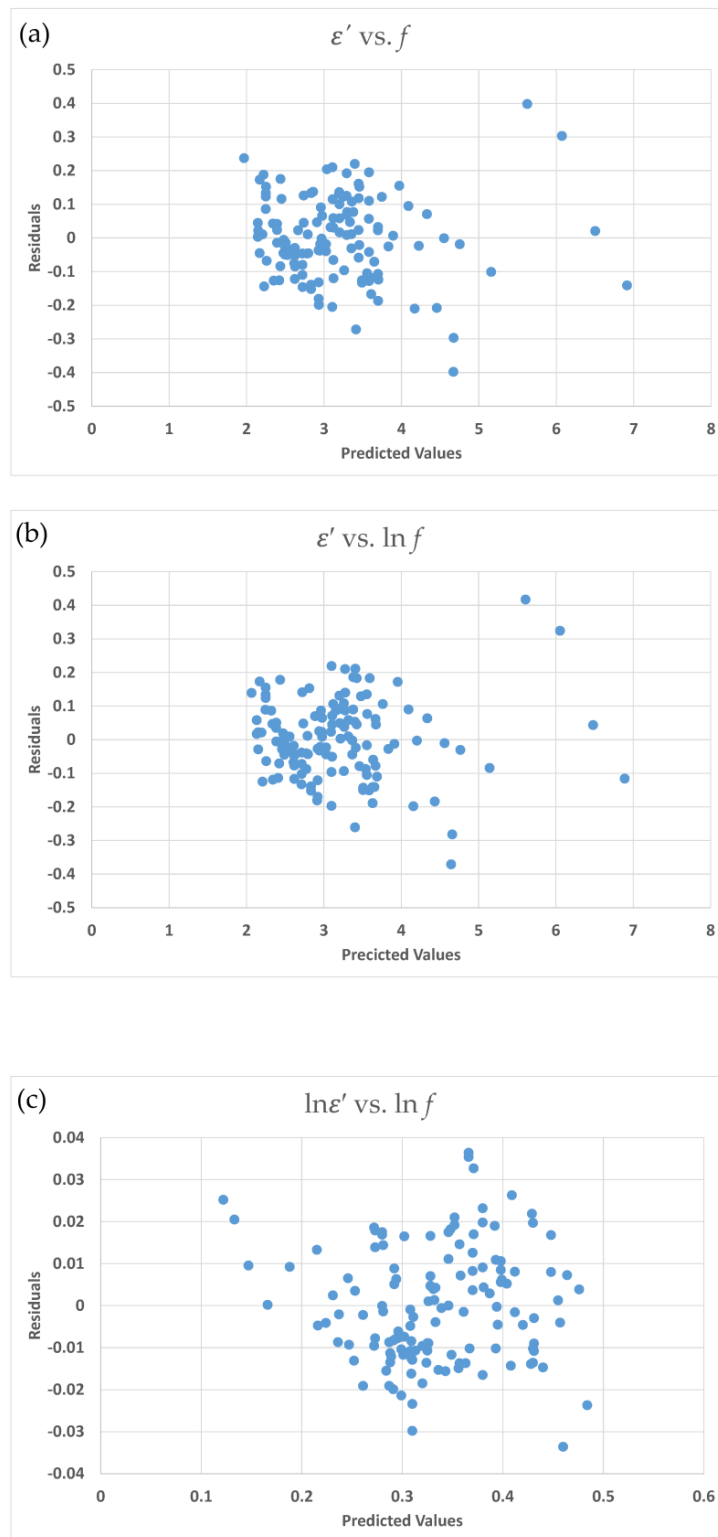


Figure 2. Cont.

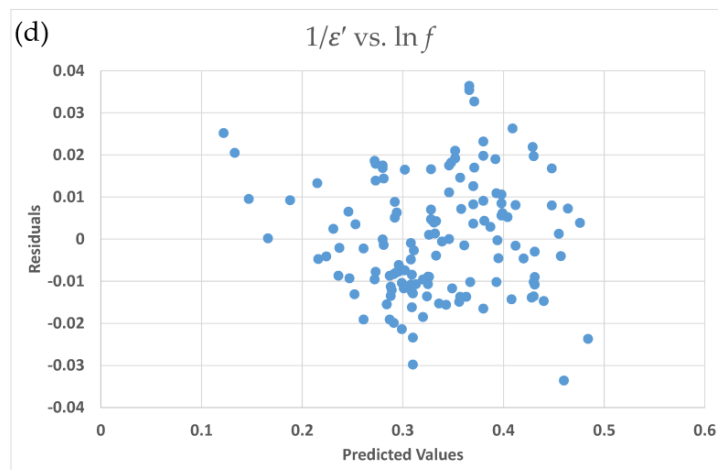


Figure 2. Residual plots for the dielectric constant ε' equation for egg white powder (Boreddy and Subbich data [8]); (a) ε' vs. f ; (b) ε' vs. $\ln f$, (c) $\ln \varepsilon'$ vs. $\ln f$; (d) $(1/\varepsilon')$ vs. $\ln f$.

The respective s^2 values are 0.165, 0.201, 0.125, and 0.195 for the Equation (3-3) ($\ln(\varepsilon')$ vs. $f_1(f)$), Equation (3-4) ($1/\varepsilon'$ vs. $f_2(f)$), Equation (3-7) ($\ln(\varepsilon')$ vs. $g_1(\ln f)$), and Equation (3-8) ($1/\varepsilon'$ vs. $g_2(\ln f)$). Equation (3-7) has the smallest s^2 value and is the most appropriate equation for the dielectric constant.

The results of the regression analysis for the loss factor for egg white powder are listed in Table 4.

Only Equation (4-5) passes the normal test and the constant variance test. The residual plots of ε'' vs. f and the ε'' vs. $\ln f$ are shown in Figure 3. Figure 3a shows the scatter data distribution and the scatter conditions for non-constant variance. The uniform distribution of data in Figure 3b presents that this equation is appropriate in terms of a t -test for each coefficient. The terms X^2 and $\ln f^2$ have no significant effect on the loss factor. The final equation for the relationship between the loss factor and the influencing factors is shown in Equation (4-9).

The distribution of residual plots are lookalike for Figure 3a,b. However, the results of the normality test and the constant variance test are different. The adequateness of the model fitting cannot be verified only with visual methods of residual plots.

In the literature of the dielectric properties of egg white powder [8], the multiple regression variables were moisture constant and temperature. Each frequency had a specific equation. For our study, frequency is a variable, and only two equations (dielectric constant and loss factor) are required.

Table 4. The relationship between the loss factor and the influencing factors and statistical criteria established with regression analysis for egg white powder.

| |
|--|
| Equation (4-1): $\varepsilon'' = 1.279 - (0.0230 \times T) - (0.000605 \times f) - (0.257 \times X) - (0.00000381 \times T^2) + (0.00862 \times X^2) + (0.0000280 \times T \times f) + (0.00431 \times T \times X) + (0.0000899 \times f \times X) - (0.00000363 \times T \times f \times X)$ |
| $R^2 = 0.965$ |
| Normality Test: Passed ($p = 0.132$) |
| Constant Variance Test: Failed |
| Equation (4-2): $\sqrt{\varepsilon''} = 0.124 + (0.00225 \times T) + (0.0000236 \times f) - (0.0289 \times X) - (0.0000489 \times T^2) + (0.00175 \times X^2) + (0.00000957 \times T \times f) + (0.00144 \times T \times X) + (0.00000852 \times f \times X) - (0.00000123 \times T \times f \times X)$ |
| $R^2 = 0.967$ |
| Normality Test: Failed ($p = 0.006$) |
| Constant Variance Test: Passed ($p = 0.064$) |
| Equation (4-3): $\ln(\varepsilon'') = -5.742 + (0.0599 \times T) + (0.00112 \times f) + (0.318 \times X) - (0.000316 \times T^2) - (0.00583 \times X^2) + (0.00000753 \times T \times f) + (0.000485 \times T \times X) - (0.000104 \times f \times X) - (0.000000957 \times T \times f \times X)$ |
| $R^2 = 0.955$ |
| Normality Test: Failed ($p = < 0.001$) |
| Constant Variance Test: Failed ($p = < 0.001$) |
| Equation (4-4): $1/\varepsilon'' = 46.309 - (0.612 \times T) - (0.0100 \times f) - (4.452 \times X) + (0.00259 \times T^2) + (0.116 \times X^2) + (0.0000895 \times T \times f) + (0.0238 \times T \times X) + (0.00114 \times f \times X) - (0.0000109 \times T \times f \times X)$ |
| $R^2 = 0.712$ |
| Normality Test: Failed ($p = < 0.001$) |
| Constant Variance Test: Failed ($p = < 0.001$) |
| Equation (4-5): $\varepsilon'' = 1.667 - (0.0463 \times T) - (0.336 \times X) - (0.0688 \times \ln f) - (0.00000442 \times T^2) - (0.0105 \times \ln f^2) + (0.00875 \times X^2) + (0.00720 \times T \times \ln f) + (0.00728 \times T \times X) + (0.0234 \times \ln f \times X) - (0.000923 \times T \times \ln f \times X)$ |
| $R^2 = 0.963$ |
| Normality Test: Passed ($p = 0.01$) |
| Constant Variance Test: Passed ($p = 0.919$) |

Table 4. Cont.

| |
|--|
| Equation (4-6): $\sqrt{\varepsilon''} = 0.115 - (0.00627 \times T) - (0.0442 \times X) + (0.0458 \times \ln f) - (0.0000494 \times T^2) - (0.00647 \times \ln f^2) + (0.00197 \times X^2) + (0.00259 \times T \times \ln f) + (0.00247 \times T \times X) + (0.00300 \times \ln f \times X) - (0.000319 \times T \times \ln f \times X)$ |
| $R^2 = 0.964$ |
| Normality Test: Failed ($p = 0.004$) |
| Constant Variance Test: Passed ($p = 0.098$) |
| Equation (4-7): $\ln(\varepsilon'') = -6.414 + (0.0504 \times T) + (0.369 \times X) + (0.342 \times \ln f) - (0.000317 \times T^2) - (0.0153 \times \ln f^2) - (0.00495 \times X^2) + (0.00264 \times T \times \ln f) + (0.00143 \times T \times X) - (0.0229 \times \ln f \times X) - (0.000278 \times T \times \ln f \times X)$ |
| $R^2 = 0.944$ |
| Normality Test: Failed ($p = < 0.001$) |
| Constant Variance Test: Failed ($p = < 0.001$) |
| Equation (4-8): $1/\varepsilon'' = 52.229 - (0.658 \times T) - (5.242 \times X) - (2.207 \times \ln f) + (0.00259 \times T^2) + (0.0108 \times \ln f^2) + (0.114 \times X^2) + (0.0173 \times T \times \ln f) + (0.0312 \times T \times X) + (0.269 \times \ln f \times X) - (0.00250 \times T \times \ln f \times X)$ |
| $R^2 = 0.952$ |
| Normality Test: Failed ($p = < 0.001$) |
| Constant Variance Test: Failed ($p = < 0.001$) |
| Equation (4-9): $\varepsilon'' = 1.975 - (0.0471 \times T) - (0.347 \times X) - (0.178 \times \ln f) + (0.00932 \times X^2) + (0.00723 \times T \times \ln f) + (0.00729 \times T \times X) + (0.0236 \times \ln f \times X) - (0.000924 \times T \times \ln f \times X)$ |
| $R^2 = 0.962$ |
| Normality Test: Passed |
| Constant Variance Test: Passed ($p = 0.823$) |

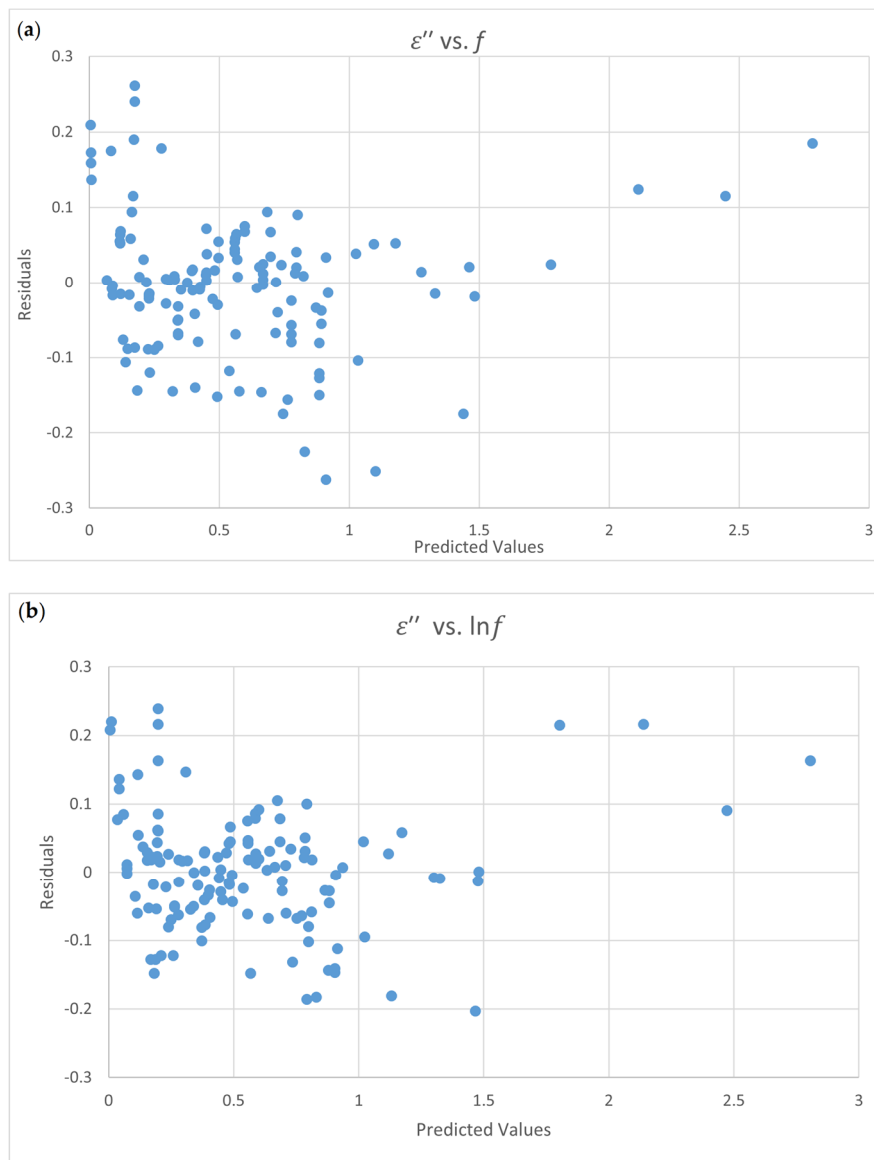


Figure 3. Residual plots for the loss factor ϵ'' equation for egg white power (Boreddy and Subbich data [8]); (a). ϵ'' vs. f ; (b). ϵ'' vs. $\ln f$.

3.1.2. Chicken Flour

The dielectric properties of chicken flour are determined for moisture contents from 7.8% to 20.9% w.b., temperature from 20 to 90 °C, and frequencies of 27, 40, 100, 915, and 1800 MHz [11]. No regression models are presented in the literature [11].

The relationship between dielectric constant and the influencing factors (moisture content, temperature, and frequency) was established using regression analysis, and the results are listed in Supplementary Materials Tables S1 and S2.

The adequate equations are listed as the following (Equation (20) and Equation (21)):

$$\begin{aligned}
 1/\epsilon' = & 0.560 - (0.00263 \times T) + (0.0000684 \times f) - (0.0161 \times X) - (0.0000110 \times T^2) - \\
 & (0.000000260 \times f^2) + (0.000117 \times X^2) + (0.000000459 \times T \times f) + (0.00000309 \times T \times X) \\
 & + (0.00000239 \times f \times X) - (0.000000544 \times T \times f \times X)
 \end{aligned} \tag{20}$$

$$\ln(\varepsilon'') = 3.935 - (0.268 \times T) - (0.339 \times X) - (0.595 \times \ln f) + (0.00300 \times T^2) + (0.0584 \times \ln f^2) + (0.00903 \times X^2) + (0.00888 \times T \times \ln f) + (0.0122 \times T \times X) - (0.000623 \times T \times \ln f \times X) - (0.0000115 \times T^3) - (0.00000589 \times (T \times f)^2) - (0.00000191 \times (T \times X)^2). \quad (21)$$

In Supplementary Materials Table S1, the only adequate equation, $1/\varepsilon'$, is a dependent variable, and moisture content, temperature, and frequency are independent variables (Equation (20)). Other models cannot pass the normal test or the constant variance test. The residual plots for ε' vs. f and $1/\varepsilon'$ vs. f show the data distribution of errors. Figure 4a shows a funnel-type data distribution and a non-constant variance error. Figure 4b shows a uniform distribution for predicted errors.

Only the equation, $\ln(\varepsilon'')$ vs. $g(X, T, \ln f)$, is an appropriate model. These variables have a more complex form, e.g., T^3 , $(T \times \ln f)^2$ and $(T \times X)^2$. The residual plots for ε'' vs. $\ln f$ are shown in Figure 5a. The funnel effect shows a heterogeneous variance. In Figure 5b, the $\ln \varepsilon''$ vs. $\ln f$ model has a uniform distribution for residual data.

There is a heterogeneous variance for dielectric properties in the standard deviations for each measurement [11]. The standard deviation is calculated using three sets of measurements. Two typical data distributions are shown in Figure 6. Figure 6a shows the standard deviations for the dielectric constant for different temperatures and frequencies at 11.4% w.b. The standard deviation increases as temperature increases. The lower the frequency, the greater the standard deviation. The numerical values for 915 and 1800 MHz are similar.

The standard deviation of the loss factor at 20.9% w.b. is shown in Figure 6b. The greatest value is for 80 °C. Lower frequencies have greater standard deviations. The non-even values of standard deviations show the origin of the heterogeneous variance.

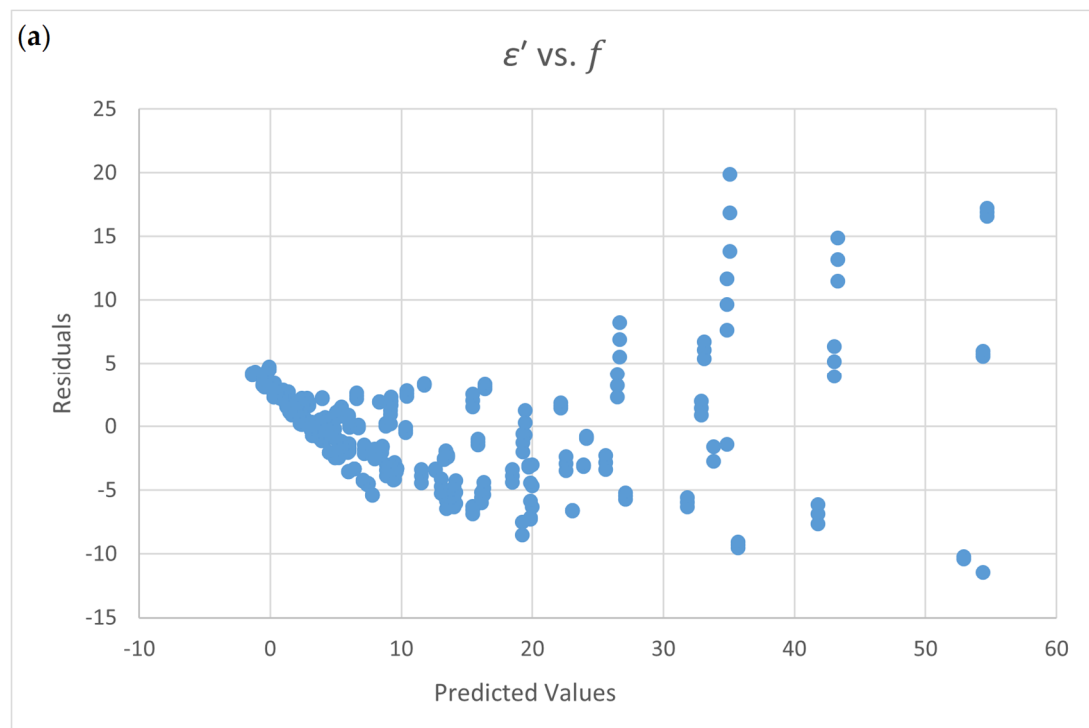


Figure 4. Cont.

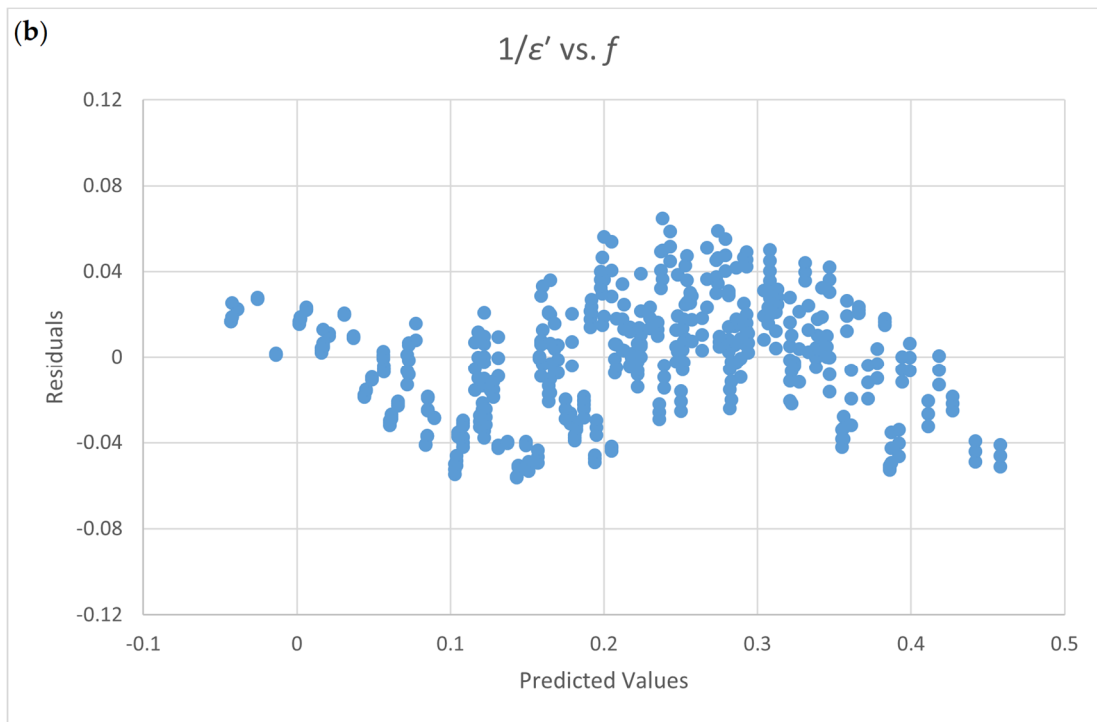


Figure 4. Residual plots for the dielectric constant ϵ' equation for chicken flour (Guo et al. data [11]); (a). ϵ' vs. f ; (b). $1/\epsilon'$ vs. f .

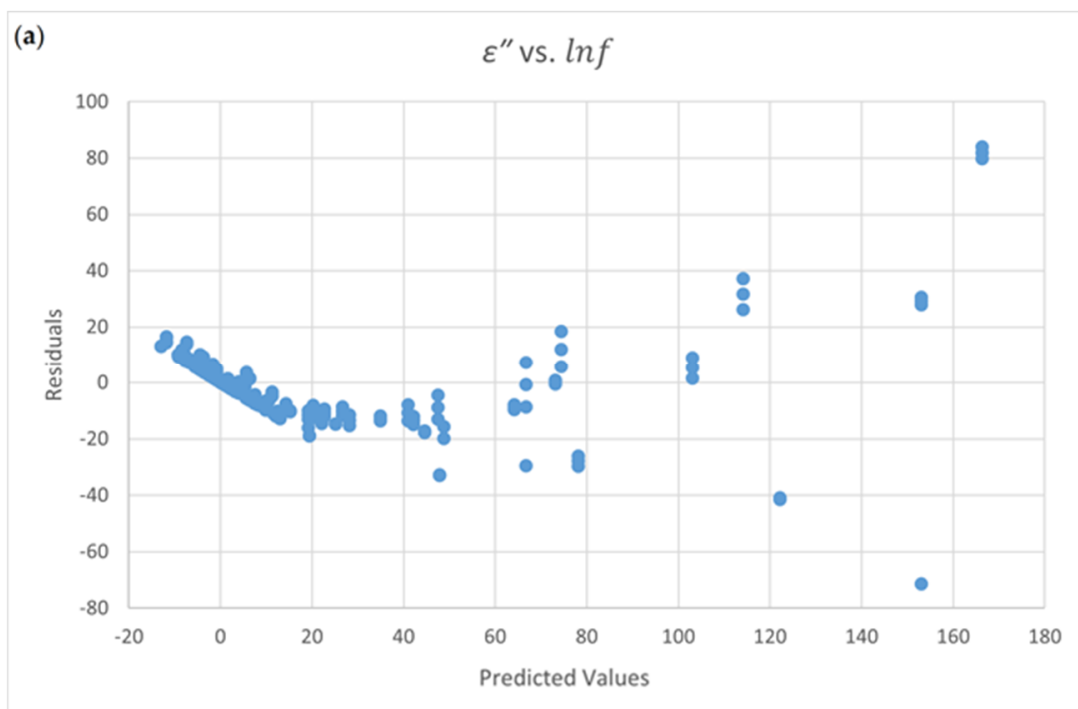


Figure 5. Cont.

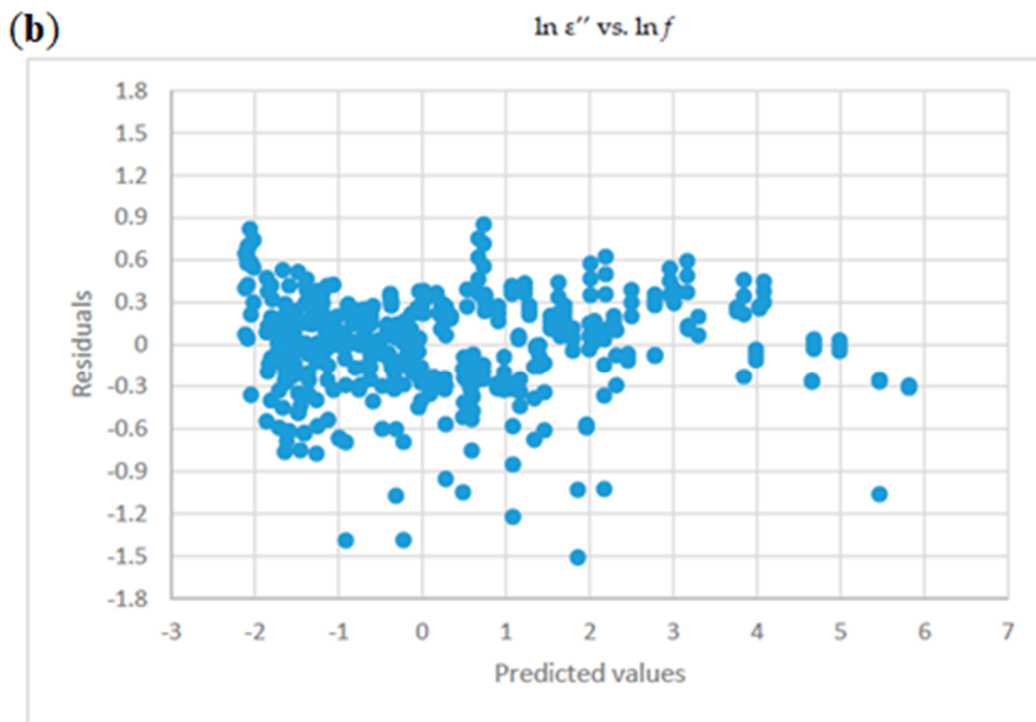


Figure 5. Residual plots for the loss factor ϵ'' equation for chicken flour (Guo et al. data [11]); (a). ϵ'' vs. $\ln f$; (b) $\ln \epsilon''$ vs. $\ln f$.

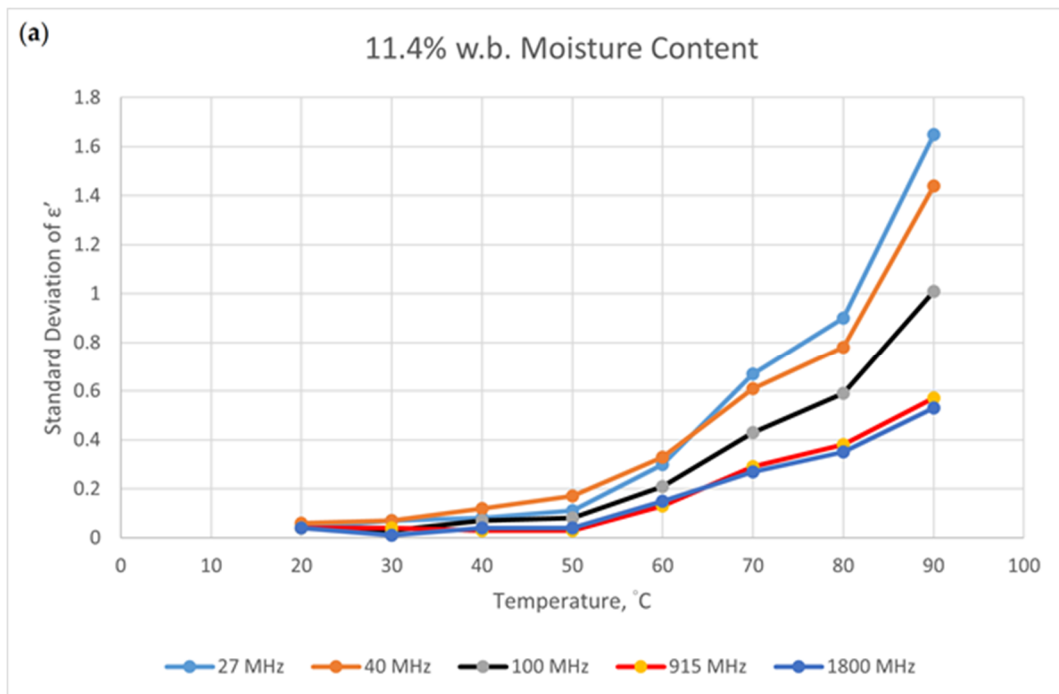


Figure 6. Cont.

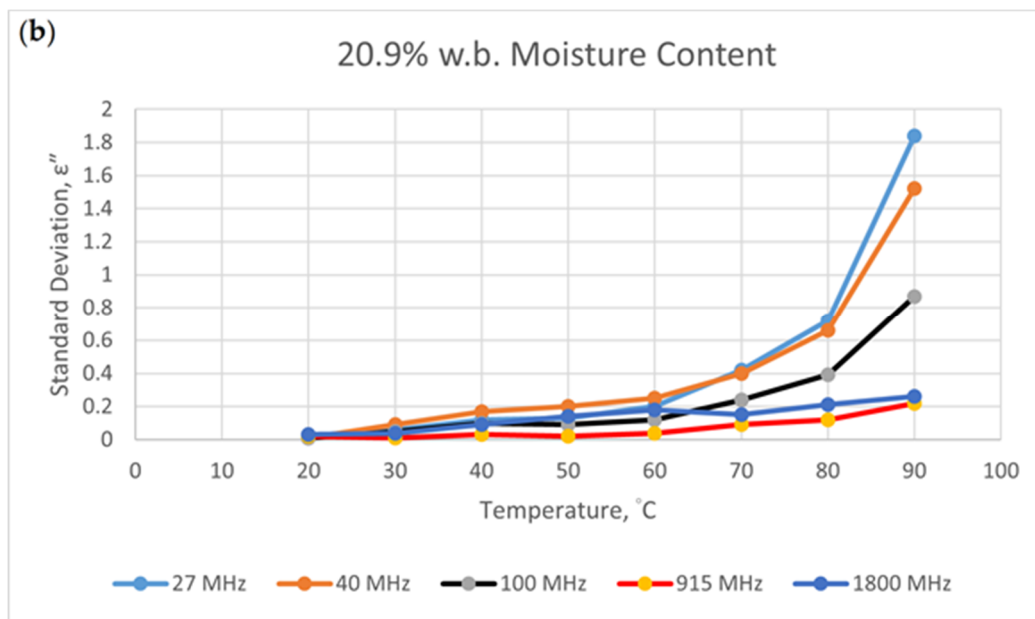


Figure 6. The relationship between the standard deviation of the measured data and the temperature at different frequencies for two moisture contents; (a). 11.4% w.b. moisture content; (b). 11.4% w.b. moisture content.

3.1.3. Bread

The dielectric properties for white bread with different moisture contents (34.0, 34.6, 37.1, and 38.6% w.b.) were determined at frequencies of 13.56, 27.12, 40.68, 915, and 1800 MHz and at temperature of 25 to 85 °C [14]. The results for regression are listed in Supplementary Materials Table S3. The relationship between response $1/\epsilon'$ and the three variables (X , T , $\ln f$) is the only appropriate equation for the dielectric constant (Supplementary Materials Table S3). Further analysis indicates that T^2 and $\ln f^2$ do not have a significant effect on response. The best equation is listed as follows (Equation (22)):

$$1/\epsilon' = 1.236 - (0.0136 \times T) - (0.0289 \times X) + (0.0959 \times \ln f) - (0.00626 \times \ln f^2) + (0.000194 \times T \times \ln f) + (0.000307 \times T \times X). \quad (22)$$

The relationship between $\ln(\epsilon'')$ and X , T and $\ln f$ is the only model that passes the normal test and the constant variable test (Equation (23)).

$$\ln(\epsilon'') = -8.366 + (0.136 \times T) + (0.336 \times X) - (0.716 \times \ln f) + (0.0000507 \times T^2) + (0.0793 \times \ln f^2) - (0.00369 \times T \times \ln f) - (0.00291 \times T \times X) - (0.0137 \times \ln f \times X) \quad (23)$$

The literature of the dielectric properties of bread [11] uses three equations. For 37.1% w.b. and five temperatures, the ϵ' and ϵ'' response is described as $b_0 + b_1/f$. At a fixed temperature of 25 °C and five frequencies, the dielectric properties have a linear relationship with moisture constant: $c_0 + c_1X$. At a fixed frequency of 27.12 MHz and four moisture contents, the relationship between the dielectric properties and temperature is a 2nd order polynomial equation: $d_0 + d_1T + d_2T^2$.

In our study, the independent variables are influencing factors (moisture content, temperature, and frequency) and are incorporated into a multiple regression equation. This is a more useful and convenient method to derive the equations for the dielectric properties of bread.

3.1.4. Black-Eyed Peas

The predicted equations for dielectric properties of black-eyed peas were studied using regression analysis (Table 5). The dataset from the literature [12] applies to four moisture contents (8.8, 12.7, 16.8, and 20.3% w.b.), three frequencies (27, 40, and 915 MHz) and five temperatures (20–60 °C). For the dielectric content, two equations (Equations (5-1) and (5-2)) pass the normal test and the constant variance test.

The transformations of the responses are $\ln \varepsilon'$ and $1/\varepsilon'$. A comparison of the error mean square for two models shows that the fitting-agreement for $\ln \varepsilon'$ is better than that for $1/\varepsilon'$.

In terms of the loss factor, $\ln \varepsilon''$ vs. $g(T, X, \ln f)$ is the only appropriate equation and is listed as shown in Equation (5-3).

3.1.5. Macadamia Nut Kernels

The dielectric properties of macadamia nut kernels were determined at five temperatures, five moisture contents (% w.b.), and four frequencies (27, 40, 915, and 1800 MHz) [18]. The literature did not cite related empirical equations.

The results of the regression analysis are listed in Table 6. The best equations for dielectric proportion are Equations (6-1) and (6-2). In terms of the ε' and ε'' response, $\ln \varepsilon'$ or $\ln \varepsilon''$ vs. $g(T, X, \ln f)$ are the only equations that pass the normal test and the non-constant variance test.

Table 5. The relationship between the dielectric properties and the influencing factors and statistical criteria established by regression analysis for black-eyed peas.

| |
|---|
| Equation (5-1): $\ln(\varepsilon') = 2.521 - (0.0201 \times T) - (0.195 \times X) + (0.0184 \times \ln f) + (0.000242 \times T^2) - (0.000327 \times \ln f^2) + (0.00926 \times X^2) + (0.000677 \times T \times \ln f) + (0.000693 \times T \times X) - (0.00662 \times \ln f \times X) - (0.0000247 \times T \times \ln f \times X) - (0.00000124 \times (T \times X)^2)$ |
| $R^2 = 0.940$ |
| Normality Test: Passed ($p = 0.310$) |
| Constant Variance Test: Passed ($p = 0.975$) |
| Equation (5-2): $1/\varepsilon' = 0.150 + (0.000411 \times T) + (0.0268 \times X) - (0.00544 \times \ln f) - (0.0000337 \times T^2) + (0.00136 \times \ln f^2) - (0.00142 \times X^2) + (0.000264 \times T \times \ln f) + (0.0000185 \times T \times X) + (0.000664 \times \ln f \times X) - (0.0000119 \times T \times \ln f \times X) - (0.000000108 \times (T \times X)^2)$ |
| $R^2 = 0.928$ |
| Normality Test: Passed ($p = 0.082$) |
| Constant Variance Test: Passed ($p = 0.897$) |
| Equation (5-3): $\ln(\varepsilon'') = 4.531 - (0.0719 \times T) - (0.375 \times X) - (1.349 \times \ln f) + (0.000639 \times T^2) + (0.0909 \times \ln f^2) + (0.0131 \times X^2) + (0.00674 \times T \times \ln f) + (0.00315 \times T \times X) + (0.0161 \times \ln f \times X) - (0.0000621 \times T \times \ln f \times X) - (0.00000770 \times T \times \ln f^2) - (0.000000970 \times (T \times X)^2)$ |
| $R^2 = 0.952$ |
| Normality Test: Passed ($p = 0.158$) |
| Constant Variance Test: Passed ($p = 0.197$) |

Table 6. The relationship between the dielectric properties and the influencing factors and statistical criteria established by regression analysis for macadamia nut kernels.

| |
|---|
| Equation (6-1): $\ln(\varepsilon') = 1.467 - (0.000659 \times T) + (0.102 \times X) - (0.119 \times \ln f) + (0.0000327 \times T^2) + (0.0170 \times \ln f^2) + (0.00000963 \times X^2) - (0.000227 \times T \times \ln f) + (0.000304 \times T \times X) - (0.00904 \times \ln f \times X) - (0.00000325 \times T \times \ln f \times X) - (0.000000205 \times T \times \ln f^2) - (0.0000000679 \times (T \times X)^2)$ |
| $R^2 = 0.952$ |
| Normality Test: Passed ($p = 0.171$) |
| Constant Variance Test: Failed ($p = < 0.001$) |
| Equation (6-2): $\ln(\varepsilon'') = -1.719 + (0.00660 \times T) + (0.469 \times X) - (0.351 \times \ln f) + (0.0000602 \times T^2) + (0.0627 \times \ln f^2) - (0.00381 \times X^2) - (0.00102 \times T \times \ln f) + (0.000778 \times T \times X) - (0.0397 \times \ln f \times X) - (0.000118 \times T \times \ln f \times X) + (0.000000144 \times (T \times X)^2)$ |
| $R^2 = 0.959$ |
| Normality Test: Passed ($p = 0.165$) |
| Constant Variance Test: Passed ($p = 0.711$) |

3.2. Equation for Dielectric Properties with Two Variables

Some experiments consider only temperature and frequency as the influencing factors. The moisture content of fruits, vegetables, and insects was not measured because their moisture content is very high.

3.2.1. Liquid and Precooked Egg White

This literature used two types of egg whites: liquid and pre-cooked. The dielectric properties were determined at four frequencies (27, 40, 915, and 1800 MHz) and seven temperatures (20–120 °C, at intervals of 20 °C).

The results of the regression analysis are listed in Supplementary Materials Table S5. For the dielectric constants for liquid egg white, the transformation of $\ln \varepsilon'$ and $1/\varepsilon'$ passes the normal test and the constant variance test (Equations (24) and (25)). A comparison of the error mean square shows that the two s^2 values are similar, so both equations are useful models. In terms of the loss factors, the transformation of $\ln \varepsilon''$ (Equation (26)) is the only equation that expresses the relationship between the ε'' value and temperature and moisture content for liquid egg white.

The adequate equations are listed as follows (Equations (24)–(26)):

$$\ln(\varepsilon') = 5.736 + (0.000700 \times T) - (0.548 \times \ln f) + (0.0000632 \times T^2) + (0.0490 \times \ln f^2) - (0.00155 \times T \times \ln f) \quad (24)$$

$$1/\varepsilon' = -0.00480 + (0.0000107 \times T) + (0.00662 \times \ln f) - (0.000000872 \times T^2) - (0.000565 \times \ln f^2) + (0.0000193 \times T \times \ln f) \quad (25)$$

$$\ln(\varepsilon'') = 9.793 + (0.0169 \times T) - (1.403 \times \ln f) - (0.00000389 \times T^2) + (0.0553 \times \ln f^2) - (0.00113 \times T \times \ln f) \quad (26)$$

For pre-cooked egg white, the results for appropriate models are listed in Supplementary Materials Table S5. The transformation form of $\ln \varepsilon''$ and $1/\varepsilon''$ is used for the dielectric constant (Equation (27)) and the loss factor (Equation (28)).

$$\ln(\varepsilon') = 5.552 + (0.00355 \times T) - (0.443 \times \ln f) + (0.0000269 \times T^2) + (0.0372 \times \ln f^2) - (0.00140 \times T \times \ln f) \quad (27)$$

$$1/\varepsilon'' = 0.0525 + (0.000245 \times T) - (0.0292 \times \ln f) + (0.000000199 \times T^2) + (0.00438 \times \ln f^2) - (0.0000852 \times T \times \ln f) \quad (28)$$

In this literature, the relationship between dielectric properties and temperature at a fixed frequency is expressed as a 2nd-order polynomial equation ($y = b_0 + b_1T + b_2T^2$). The coefficient of determination R^2 is the only criterion. There are sixteen equations for the dielectric constant and the loss factor in this literature. For our study, the temperature and frequency are used, and the significant effect of the interaction between temperature and moisture ($X \times T$ in the equation) is determined.

3.2.2. Fruits, Nuts, and Insects

In order to develop, improve, and scale up the electromagnetic treatment devices for insect pests, basic information about dielectric properties was collected [20]. Wang et al. [20] studied the dielectric properties of five types of fruits, two types of nuts, and four insect larvae at four frequencies (27, 40, 915, and 1800 MHz) and five temperatures (20–60 °C).

The best equation was tested using regression analysis. The results are listed in Table 7. Most of the products only have an equation that passes the statistical test for normal distribution and constant variance. For the dielectric constant of Gold apple, two transformations of the response, $\ln \epsilon'$ and $1/\epsilon'$, are used. For the dielectric properties of cherry and orange, four equations are adequate: (ϵ' , $\sqrt{\epsilon'}$, $\ln \epsilon'$, $1/\epsilon'$).

Table 7. Results and criteria for the regression analysis for the dielectric properties of five fruits, two nuts, and four insect larvae.

| 1. Gold Apple | |
|---|--|
| Equation (7-1): $\ln(\epsilon') = 3.691 - (0.000619 \times T) + (0.269 \times \ln f) - (0.0000114 \times T^2) - (0.0256 \times \ln f^2) - (0.000206 \times T \times \ln f)$ | |
| $R^2 = 0.900$ | |
| Normality Test: Passed ($p = 0.637$) | |
| Constant Variance Test: Passed ($p = 0.235$) | |
| Equation (7-2): $1/\epsilon' = 0.0228 + (0.00000228 \times T) - (0.00404 \times \ln f) + (0.000000220 \times T^2) + (0.000382 \times \ln f^2) + (0.00000354 \times T \times \ln f)$ | |
| $R^2 = 0.901$ | |
| Normality Test: Passed ($p = 0.331$) | |
| Constant Variance Test: Passed ($p = 0.402$) | |
| Equation (7-3): $\ln(\epsilon'') = 10.015 + (0.0348 \times T) - (2.176 \times \ln f) + (0.0000411 \times T^2) + (0.154 \times \ln f^2) - (0.00604 \times T \times \ln f)$ | |
| $R^2 = 0.997$ | |
| Normality Test: Passed ($p = 0.131$) | |
| Constant Variance Test: Passed ($p = 0.011$) | |
| 2. Red Apple | |
| Equation (7-4): $\ln(\epsilon') = 3.788 - (0.00239 \times T) + (0.251 \times \ln f) + (0.000000945 \times T^2) - (0.0237 \times \ln f^2) - (0.000144 \times T \times \ln f)$ | |
| $R^2 = 0.926$ | |
| Normality Test: Passed ($p = 0.662$) | |
| Constant Variance Test: Passed ($p = 0.021$) | |
| Equation (7-5): $\sqrt{\epsilon''} = 25.153 + (0.175 \times T) - (7.248 \times \ln f) + (0.0000614 \times T^2) + (0.588 \times \ln f^2) - (0.0265 \times T \times \ln f)$ | |
| $R^2 = 0.996$ | |
| Normality Test: Passed ($p = 0.022$) | |
| Constant Variance Test: Passed ($p = 0.131$) | |

Table 7. Cont.

| 3. Cherry | |
|--|--|
| Equation (7-6): $\varepsilon' = 142.581 + (0.120 \times T) - (21.083 \times \ln f) - (0.00145 \times T^2) + (1.624 \times \ln f^2) - (0.0322 \times T \times \ln f)$ | |
| | $R^2 = 0.936$ |
| | Normality Test: Passed ($p = 0.153$) |
| | Constant Variance Test: Passed ($p = 0.343$) |
| Equation (7-7): $\sqrt{\varepsilon'} = 12.262 + (0.00874 \times T) - (1.118 \times \ln f) - (0.0000921 \times T^2) + (0.0858 \times \ln f^2) - (0.00211 \times T \times \ln f)$ | |
| | $R^2 = 0.941$ |
| | Normality Test: Passed ($p = 0.284$) |
| | Constant Variance Test: Passed ($p = 0.738$) |
| Equation (7-8): $\ln(\varepsilon') = 5.083 + (0.00246 \times T) - (0.236 \times \ln f) - (0.0000234 \times T^2) + (0.0181 \times \ln f^2) - (0.000546 \times T \times \ln f)$ | |
| | $R^2 = 0.946$ |
| | Normality Test: Passed ($p = 0.433$) |
| | Constant Variance Test: Passed ($p = 0.933$) |
| Equation (7-9): $1/\varepsilon' = 0.00479 - (0.0000451 \times T) + (0.00261 \times \ln f) + (0.000000376 \times T^2) - (0.000199 \times \ln f^2) + (0.00000895 \times T \times \ln f)$ | |
| | $R^2 = 0.954$ |
| | Normality Test: Passed ($p = 0.538$) |
| | Constant Variance Test: Passed ($p = 0.518$) |
| Equation (7-10): $1/\varepsilon'' = 0.0900 + (0.00195 \times T) - (0.0577 \times \ln f) - (0.0000305 \times T^2) + (0.00618 \times \ln f^2) + (0.000135 \times T \times \ln f)$ | |
| | $R^2 = 0.881$ |
| | Normality Test: Passed ($p = 0.019$) |
| | Constant Variance Test: Passed ($p = 0.251$) |
| 4. Grapefruit | |
| Equation (7-11): $\sqrt{\varepsilon'} = 13.036 + (0.0174 \times T) - (1.566 \times \ln f) + (0.0000179 \times T^2) + (0.136 \times \ln f^2) - (0.00449 \times T \times \ln f)$ | |
| | $R^2 = 0.823$ |
| | Normality Test: Passed ($p = 0.024$) |
| | Constant Variance Test: Failed ($p = < 0.001$) |
| Equation (7-12): $\ln(\varepsilon'') = 9.996 + (0.0334 \times T) - (1.926 \times \ln f) + (0.122 \times \ln f^2) - (0.00455 \times T \times \ln f)$ | |
| | $R^2 = 0.998$ |
| | Normality Test: Passed ($p = 0.495$) |
| | Constant Variance Test: Passed ($p = 0.165$) |
| Equation (7-13): $1/\varepsilon'' = -0.0353 + (0.000122 \times T) + (0.00677 \times \ln f) - (0.00000400 \times T^2) + (0.00124 \times \ln f^2) + (0.0000249 \times T \times \ln f)$ | |
| | $R^2 = 0.986$ |
| | Normality Test: Passed ($p = 0.324$) |
| | Constant Variance Test: Passed ($p = 0.030$) |

Table 7. Cont.

| 5. Orange | |
|--|--|
| Equation (7-14): $\varepsilon' = 123.333 - (0.159 \times T) - (14.544 \times \ln f) - (0.000964 \times T^2) + (1.114 \times \ln f^2) - (0.00126 \times T \times \ln f)$ | |
| $R^2 = 0.968$ | |
| Normality Test: Passed ($p = 0.592$) | |
| Constant Variance Test: Passed ($p = 0.229$) | |
| Equation (7-15): $\sqrt{\varepsilon'} = 11.381 - (0.00702 \times T) - (0.828 \times \ln f) - (0.0000692 \times T^2) + (0.0640 \times \ln f^2) - (0.000325 \times T \times \ln f)$ | |
| $R^2 = 0.969$ | |
| Normality Test: Passed ($p = 0.311$) | |
| Constant Variance Test: Passed ($p = 0.157$) | |
| Equation (7-16): $\ln(\varepsilon') = 4.930 - (0.00110 \times T) - (0.188 \times \ln f) - (0.0000193 \times T^2) + (0.0147 \times \ln f^2) - (0.000135 \times T \times \ln f)$ | |
| $R^2 = 0.969$ | |
| Normality Test: Passed ($p = 0.257$) | |
| Constant Variance Test: Passed ($p = 0.089$) | |
| Equation (7-17): $1/\varepsilon' = 0.00560 + (0.0000000811 \times T) + (0.00244 \times \ln f) + (0.000000351 \times T^2) - (0.000194 \times \ln f^2) + (0.00000351 \times T \times \ln f)$ | |
| $R^2 = 0.970$ | |
| Normality Test: Passed ($p = 0.049$) Constant Variance Test: Passed ($p = 0.033$) | |
| Equation (7-18): $\ln(\varepsilon'') = 8.981 + (0.0369 \times T) - (1.486 \times \ln f) - (0.0000568 \times T^2) + (0.0850 \times \ln f^2) - (0.00474 \times T \times \ln f)$ | |
| $R^2 = 0.998$ | |
| Normality Test: Passed ($p = 0.075$) | |
| Constant Variance Test: Passed ($p = 0.062$) | |
| 6. Almond | |
| Equation (7-19): $\sqrt{\varepsilon'} = 5.816 - (0.00407 \times T) - (1.357 \times \ln f) + (0.0000683 \times T^2) + (0.112 \times \ln f^2)$ | |
| $R^2 = 0.381$ | |
| Normality Test: Passed ($p = 0.179$) | |
| Constant Variance Test: Passed ($p = 0.133$) | |
| Equation (7-20): $\sqrt{\varepsilon''} = -6.515 - (0.0200 \times T) + (3.221 \times \ln f) + (0.000132 \times T^2) - (0.278 \times \ln f^2) + (0.00144 \times T \times \ln f)$ | |
| $R^2 = 0.879$ | |
| Normality Test: Passed ($p = 0.120$) | |
| Constant Variance Test: Passed ($p = 0.605$) | |
| Equation (7-21): $\ln(\varepsilon'') = -8.572 - (0.0505 \times T) + (3.826 \times \ln f) + (0.000401 \times T^2) - (0.328 \times \ln f^2) + (0.00268 \times T \times \ln f)$ | |
| $R^2 = 0.878$ | |
| Normality Test: Passed ($p = 0.016$) | |
| Constant Variance Test: Passed ($p = 0.030$) | |

Table 7. Cont.

| 7. Walnut | |
|--|--|
| Equation (7-22): $\varepsilon' = 11.067 - (0.0193 \times T) - (2.308 \times \ln f) + (0.132 \times \ln f^2) + (0.00855 \times T \times \ln f)$ | |
| $R^2 = 0.957$ | |
| Normality Test: Passed ($p = 0.046$) | |
| Constant Variance Test: Passed ($p = 0.313$) | |
| Equation (7-23): $\sqrt{\varepsilon'} = 3.861 - (0.00278 \times T) - (0.639 \times \ln f) - (0.0000549 \times T^2) + (0.0361 \times \ln f^2) + (0.00274 \times T \times \ln f)$ | |
| $R^2 = 0.941$ | |
| Normality Test: Passed ($p = 0.028$) | |
| Constant Variance Test: Passed ($p = 0.386$) | |
| Equation (7-24): $\sqrt{\varepsilon''} = -3.502 - (0.00606 \times T) + (1.810 \times \ln f) + (0.0000854 \times T^2) - (0.149 \times \ln f^2) - (0.00136 \times T \times \ln f)$ | |
| $R^2 = 0.936$ | |
| Normality Test: Passed ($p = 0.058$) | |
| Constant Variance Test: Passed ($p = 0.084$) | |
| Equation (7-25): $\ln(\varepsilon'') = -7.867 - (0.0248 \times T) + (3.187 \times \ln f) + (0.000201 \times T^2) - (0.264 \times \ln f^2) - (0.000704 \times T \times \ln f)$ | |
| $R^2 = 0.944$ | |
| Normality Test: Passed ($p = 0.190$) Constant Variance Test: Passed ($p = 0.559$) | |
| 8. Codling Moth | |
| Equation (7-26): $\varepsilon' = 127.988 + (0.0726 \times T) - (22.820 \times \ln f) + (0.00609 \times T^2) + (1.757 \times \ln f^2) - (0.0863 \times T \times \ln f)$ | |
| $R^2 = 0.976$ | |
| Normality Test: Passed ($p = 0.112$) | |
| Constant Variance Test: Passed ($p = 0.159$) | |
| Equation (7-27): $\ln(\varepsilon'') = 10.615 + (0.0186 \times T) - (2.044 \times \ln f) + (0.000174 \times T^2) + (0.127 \times \ln f^2) - (0.00339 \times T \times \ln f)$ | |
| $R^2 = 0.997$ | |
| Normality Test: Passed ($p = 0.390$) | |
| Constant Variance Test: Passed ($p = 0.748$) | |
| 9. Indian-Meal Moth | |
| Equation (7-28): $\sqrt{\varepsilon'} = 15.431 + (0.0545 \times T) - (2.853 \times \ln f) + (0.000248 \times T^2) + (0.226 \times \ln f^2) - (0.0110 \times T \times \ln f)$ | |
| $R^2 = 0.993$ | |
| Normality Test: Passed ($p = 0.137$) | |
| Constant Variance Test: Passed ($p = 0.015$) | |
| Equation (7-29): $\ln(\varepsilon') = 5.885 + (0.0117 \times T) - (0.640 \times \ln f) + (0.0000574 \times T^2) + (0.0478 \times \ln f^2) - (0.00249 \times T \times \ln f)$ | |
| $R^2 = 0.996$ | |
| Normality Test: Passed ($p = 0.355$) | |
| Constant Variance Test: Passed ($p = 0.939$) | |
| Equation (7-30): $\ln(\varepsilon'') = 9.086 + (0.00878 \times T) - (1.360 \times \ln f) + (0.000180 \times T^2) + (0.0626 \times \ln f^2) - (0.00229 \times T \times \ln f)$ | |
| $R^2 = 0.996$ | |
| Normality Test: Passed ($p = 0.296$) | |
| Constant Variance Test: Passed ($p = 0.779$) | |

Table 7. Cont.

| 10. Mexican Fruit Fly | |
|--|--|
| Equation (7-31): $\epsilon'^{-1.5} = -0.00167 - (0.0000389 \times T) + (0.00125 \times \ln f) - (0.0000862 \times \ln f^2) + (0.00000678 \times T \times \ln f)$ | |
| $R^2 = 0.965$ | |
| Normality Test: Passed ($p = 0.661$) | |
| Constant Variance Test: Passed ($p = 0.014$) | |
| Equation (7-32): $\epsilon'' = 1222.142 + (9.378 \times T) - (417.002 \times \ln f) + (0.0120 \times T^2) + (34.831 \times \ln f^2) - (1.417 \times T \times \ln f)$ | |
| $R^2 = 0.985$ | |
| Normality Test: Passed ($p = 0.428$) | |
| Constant Variance Test: Passed ($p = 0.159$) | |
| 11. Navel Orange Worm | |
| Equation (7-33): $1/\epsilon' = -0.00500 - (0.0000968 \times T) + (0.00703 \times \ln f) - (0.000000520 \times T^2) - (0.000456 \times \ln f^2) + (0.0000238 \times T \times \ln f)$ | |
| $R^2 = 0.997$ | |
| Normality Test: Passed ($p = 0.229$) | |
| Constant Variance Test: Passed ($p = 0.126$) | |
| Equation (7-34): $\ln(\epsilon'') = 9.662 + (0.0225 \times T) - (1.520 \times \ln f) + (0.0725 \times \ln f^2) - (0.00213 \times T \times \ln f)$ | |
| $R^2 = 0.999$ | |
| Normality Test: Passed ($p = 0.447$) | |
| Constant Variance Test: Passed ($p = 0.741$) | |

For the dielectric constant of walnut, ϵ' and $\sqrt{\epsilon'}$ are used to establish an equation. For the dielectric constant of Indian-meal moth, $\sqrt{\epsilon'}$ and $\ln \epsilon'$ are the appropriate form for the equation. Only one equation is used for other products, and the appropriate equations are listed in Table 7.

For the loss factor for grapefruit, $\ln \epsilon'$, $1/\epsilon'$ is used. For the loss factor for walnut, $\sqrt{\epsilon'}$ and $\ln \epsilon'$ are the appropriate form for the prediction equation. For other products, only one equation is appropriate. These equations are listed in Table 7.

3.3. Effect of the Storage Time on the Dielectric Properties of Eggs

This literature showed the dielectric properties of egg albumen and egg yolk at six frequencies (10, 27, 40, 100, 915, and 1800 MHz) over five weeks (0, 1, 2, 3, 4, and 5 Ws). In this literature, an analysis of variance (ANOVA) was used to determine the significance of the storage time on the dielectric properties at each frequency. However, the statistical test for this literature does not consider the effect of the frequency on the dielectric properties.

Regression analysis was applied to determine the relationship between dielectric properties and frequency. The storage time is assumed to be an influencing factor, and the regression equation involving storage time was tested. For the dielectric properties of egg yolk and albumen, the best equation has the form $\ln y = b_0 + b_1 \ln f + b_2 (\ln f)^2$. The equation for the effect of the storage time is $\ln(y) = c_0 + c_1 St + c_2 \ln f + c_{11} St^2 + c_{22} (\ln f)^2 + c_{12} St \times (\ln f)$. The results are presented in Table 8.

The results of regression equations are shown as Equations (8-2), (8-4), (8-6), and (8-8). The results of a *t*-test for each of the parameters shows that the variables, St , St^2 and $(\ln f) \times St$, are not significantly different to zero, so the term for the storage time is omitted from these equations. The results of this regression test show that the frequency has a significant effect on the dielectric properties. However, the storage time has no significant effect.

Table 8. Study of the effect of the storage time on the dielectric properties of eggs using regression analysis.

| 1. Egg Yolk | | | | |
|--|-------------|------------|---------|--------|
| Equation (8-1): $\ln(\epsilon') = 5.722 - (0.661 \times \ln f) + (0.0498 \times \ln f^2)$ | | | | |
| $R^2 = 0.967$ | | | | |
| Normality Test: Passed ($p = 0.451$) | | | | |
| Constant Variance Test: Passed ($p = 0.270$) | | | | |
| Equation (8-2): $\ln(\epsilon') = 5.717 - (0.00498 \times St) - (0.664 \times \ln f) + (0.00198 \times St^2) + (0.0498 \times \ln f^2) + (0.000975 \times St \times \ln f)$ | | | | |
| $R^2 = 0.970$ | | | | |
| | Coefficient | Std. Error | t | p |
| Constant | 5.717 | 0.106 | 53.775 | <0.001 |
| St | -0.00498 | 0.0269 | -0.185 | 0.854 |
| ln f | -0.664 | 0.0441 | -15.051 | <0.001 |
| St ² | 0.00198 | 0.00422 | 0.468 | 0.643 |
| ln f ² | 0.0498 | 0.00427 | 11.644 | <0.001 |
| St × ln f | 0.000975 | 0.00329 | 0.297 | 0.769 |
| Equation (8-3): $\ln(\epsilon'') = 9.088 - (1.315 \times \ln f) + (0.0520 \times \ln f^2)$ | | | | |
| $R^2 = 0.998$ | | | | |
| Equation (8-4): $\ln(\epsilon'') = 9.087 - (0.00768 \times St) - (1.318 \times \ln f) + (0.00210 \times St^2) + (0.0520 \times \ln f^2) + (0.00113 \times St \times \ln f)$ | | | | |
| $R^2 = 0.998$ | | | | |
| | Coefficient | Std. Error | t | p |
| Constant | 9.087 | 0.109 | 83.221 | <0.001 |
| St | -0.00768 | 0.0276 | -0.278 | 0.783 |
| ln f | -1.318 | 0.0453 | -29.089 | <0.001 |
| St ² | 0.00210 | 0.00433 | 0.484 | 0.632 |
| ln f ² | 0.0520 | 0.00439 | 11.833 | <0.001 |
| St × ln f | 0.00113 | 0.00338 | 0.336 | 0.739 |
| 2. Albumen | | | | |
| Equation (8-5): $\ln(\epsilon') = 6.269 - (0.721 \times \ln f) + (0.0604 \times \ln f^2)$ | | | | |
| $R^2 = 0.898$ | | | | |
| Equation (8-6): $\ln(\epsilon') = 6.275 - (0.0216 \times St) - (0.718 \times \ln f) + (0.00523 \times St^2) + (0.0604 \times \ln f^2) - (0.00126 \times St \times \ln f)$ | | | | |
| $R^2 = 0.901$ | | | | |
| Equation (8-7): $\ln(\epsilon'') = 10.077 - (1.300 \times \ln f) + (0.0425 \times \ln f^2)$ | | | | |
| $R^2 = 0.999$ | | | | |
| Equation (8-8): $\ln(\epsilon'') = 10.052 - (0.0107 \times St) - (1.297 \times \ln f) + (0.000141 \times St^2) + (0.0425 \times \ln f^2) - (0.00108 \times St \times \ln f)$ | | | | |
| $R^2 = 0.999$ | | | | |
| | Coefficient | Std. Error | t | p |
| Constant | 10.052 | 0.106 | 94.628 | <0.001 |
| St | 0.0107 | 0.0268 | 0.398 | 0.693 |
| ln f | -1.297 | 0.0441 | -29.432 | <0.001 |
| St ² | -0.000141 | 0.00421 | -0.0335 | 0.973 |
| ln f ² | 0.0425 | 0.00427 | 9.956 | <0.001 |
| St × ln f | -0.00108 | 0.00329 | -0.328 | 0.745 |

3.4. Categorical Test of Two Factors

3.4.1. Butter

The dielectric properties of butter were tested at two frequencies (915 and 2450 MHz) and six temperatures (30–80 °C) for two treatments: salted and unsalted in the literature [13]. The equations in the literature showed the relationships between the dielectric properties and the temperature at a fixed frequency and for different treatments. The significance of salt levels on dielectric properties was determined by visually verifying from the data distribution in the figures.

In our study, the effect of the salted treatment is an indicating factor in the regression equation. The results are listed in Table 9. The categorical factor (salted treatment) is denoted as z . Three z terms, $T^2 \times z$, and $\ln f \times z$ were validated using a t -test for each coefficient. It was found that salted treatment has a significant effect on the dielectric content and the interaction between T^2 and the $\ln f^2$ term.

Table 9. Study of the effect of two categories on the dielectric properties of butter and eggs using regression analysis.

| 1. Butter (Salted and Unsalted) | | | | |
|---|-------------|------------|---------|--------|
| Equation (9-1): $\ln(\epsilon') = 3.777 + (1.370 \times z) + (0.00355 \times T) + (0.00433 \times T \times z) - (0.000160 \times T^2) + (0.000151 \times T^2 \times z) - (0.0680 \times \ln f) - (0.349 \times \ln f \times z)$ | | | | |
| $R^2 = 0.965$ | | | | |
| | Coefficient | Std. Error | t | p |
| Constant | 3.777 | 0.206 | 18.342 | <0.001 |
| z | 1.370 | 0.291 | 4.706 | <0.001 |
| T | 0.00355 | 0.00488 | 0.728 | 0.470 |
| $T \times z$ | 0.00433 | 0.00691 | 0.627 | 0.533 |
| T^2 | -0.000160 | 0.0000440 | -3.647 | <0.001 |
| $T^2 \times z$ | 0.000151 | 0.0000622 | 2.424 | 0.018 |
| $\ln f$ | -0.0680 | 0.0223 | -3.049 | 0.003 |
| $\ln f \times z$ | -0.349 | 0.0315 | -11.065 | <0.001 |
| Equation (9-2): $\ln \epsilon'' = 3.978 + (19.066 \times z) - (0.0126 \times T) + (0.0902 \times T \times z) - (0.00000579 \times T^2) - (0.000241 \times T^2 \times z) - (0.192 \times \ln f) - (2.600 \times \ln f^2 \times z)$ | | | | |
| $R^2 = 0.989$ | | | | |
| | Coefficient | Std. Error | t | p |
| Constant | 3.978 | 0.851 | 4.674 | <0.001 |
| z | 19.066 | 1.204 | 15.839 | <0.001 |
| T | -0.0126 | 0.0202 | -0.623 | 0.536 |
| $T \times z$ | 0.0902 | 0.0285 | 3.158 | 0.002 |
| T^2 | -0.00000579 | 0.000182 | -0.0318 | 0.975 |
| $T^2 \times z$ | -0.000241 | 0.000257 | -0.935 | 0.353 |
| $\ln f$ | -0.192 | 0.0921 | -2.081 | 0.041 |
| $\ln f \times z$ | -2.600 | 0.130 | -19.950 | <0.001 |
| 2. Salmon Fish (Salted and Unsalted) | | | | |
| Equation (9-3): $\sqrt{\epsilon'} = 12.759 + (6.579 \times z) - (0.117 \times T) + (0.0296 \times T \times z) + (0.00105 \times T^2) - (0.790 \times \ln f) - (1.128 \times \ln f \times z)$ | | | | |
| $R^2 = 0.912$ | | | | |

Table 9. Cont.

| | Coefficient | Std. Error | t | p |
|----------------|-------------|------------|--------|--------|
| Constant | 12.759 | 0.837 | 15.249 | <0.001 |
| z | 6.579 | 0.800 | 8.221 | <0.001 |
| T | -0.117 | 0.0302 | -3.887 | <0.001 |
| T × z | 0.0296 | 0.0102 | 2.911 | 0.005 |
| T ² | 0.00105 | 0.000293 | 3.576 | <0.001 |
| ln f | -0.790 | 0.0816 | -9.680 | <0.001 |
| ln f × z | -1.128 | 0.115 | -9.769 | <0.001 |

Equation (9-4): $\ln \varepsilon'' = 9.649 + (1.244 \times z) - (0.0301 \times T) + (0.00760 \times T \times z) + (0.000343 \times T^2) - (0.935 \times \ln f) - (0.0831 \times \ln f \times z)$

$R^2 = 0.973$

| | Coefficient | Std. Error | t | p |
|----------------|-------------|------------|---------|--------|
| Constant | 9.649 | 0.288 | 33.473 | <0.001 |
| z | 1.244 | 0.276 | 4.513 | <0.001 |
| T | -0.0301 | 0.0104 | -2.896 | 0.005 |
| T × z | 0.00760 | 0.00350 | 2.170 | 0.033 |
| T ² | 0.000343 | 0.000101 | 3.396 | 0.001 |
| ln f | -0.935 | 0.0281 | -33.245 | <0.001 |
| ln f × z | -0.0831 | 0.0398 | -2.090 | 0.040 |

The dielectric constant equation includes the categories (Equations (29)–(31)):

$$\ln(\varepsilon') = 3.777 + (1.370 \times z) + (0.00355 \times T) + (0.00433 \times T \times z) - (0.000160 \times T^2) + (0.000151 \times T^2 \times z) - (0.0680 \times \ln f) - (0.349 \times \ln f \times z) \tag{29}$$

For unsalted, z = 0, so the dielectric constant equation is

$$\ln(\varepsilon') = 3.777 + (0.00355 \times T) - (0.000160 \times T^2) - (0.0680 \times \ln f) \tag{30}$$

For salted, z = 1, so the dielectric constant equation is (Equation (31)):

$$\ln(\varepsilon') = 5.147 + (0.00788 \times T) - (0.000009 \times T^2) - (0.417 \times \ln f) \tag{31}$$

The effect of the salted butter on the loss factor is described by Equation (13-2). The terms z, T × z, and ln f × z are valid for this equation. Salted treatment has to have a significant effect on the loss factor for butter.

The loss factor equation includes the categories (Equations (32)–(34)):

$$\ln \varepsilon'' = 3.978 + (19.066 \times z) - (0.0126 \times T) + (0.0902 \times T \times z) - (0.00000579 \times T^2) - (0.000241 \times T^2 \times z) - (0.192 \times \ln f) - (2.600 \times \ln f \times z) \tag{32}$$

For unsalted, z = 0, so the loss factor equation is

$$\ln \varepsilon'' = 3.978 - (0.0126 \times T) - (0.00000579 \times T^2) - (0.192 \times \ln f) \tag{33}$$

For salted treatment, z = 1, so the loss factor equation is

$$\ln \varepsilon'' = 23.044 - (0.0776 \times T) - (0.000208 \times T^2) - (2.792 \times \ln f) \tag{34}$$

The different equations for two treatments showed the significant effect of the salted treatment on the loss factor.

3.4.2. Salmon Fish

The dielectric properties of salmon (*Oncorhynchus keta*) at two frequencies (27 and 915 MHz) and seven temperatures (20–80 °C) and two types of treatments (unsalted and salted) were reported [16]. The effect of salting treatment on the dielectric properties of salmon were observed visually, and the data distribution for measured values is presented in the figures. At 27 MHz, the dielectric properties for salted salmon were higher than those for unsalted salmon, but at 915 MHz, the two datasets (salted and unsalted) were very difficult to observe visually.

The results for the categorical test of dielectric properties of salmon are listed in Table 9. For the dielectric constant (Equation (9-3)), the terms, z , $T \times z$, and $\ln f \times z$, are validated using a t -test. Salted treatment has a significant effect on the dielectric constant.

The result of the categorical test for loss factors (Equation (9-4)) shows that the three terms, z , $T \times z$, and $\ln f \times z$, are valid. Salted treatment has a significant effect on these loss factors.

The regression equation involves categorical factors, and the effect of the salted treatment can be quantified.

3.5. Categorical Test of Three Factors

The dielectric properties of cheese were tested for a frequency range of 300 to 3000 MHz at temperatures between 5 and 85 °C in intervals of 10 °C [15]. There are three moisture levels for the test materials: low, medium, and high. The effect of the moisture content on these properties is shown in the figures in the literature [15]. The data distribution for dielectric properties for three levels of the moisture content was observed visually, but it is difficult to ascertain significant patterns in this data.

The levels of the moisture content in samples are categorical factors, and the regression results are listed in Table 10. The form of the dielectric constant is $\sqrt{\epsilon'}$. The categorical terms z_1 , $T \times z_1$, and $T^2 \times z_1$, are valid, but the variables, z_2 , $T \times z_2$, and $T^2 \times z_2$, are invalid. The dielectric constant for low moisture content is significantly different to those for medium and high moisture content.

Table 10. Study of the effect of three categories on the dielectric properties of cheese using regression analysis.

| Moisture Content of Cheese: High, Medium and Low | | | | |
|--|-------------|------------|---------|--------|
| Equation (10-1): $\sqrt{\epsilon'} = 8.985 + (0.715 \times z_1) + (0.168 \times z_2) - (0.0322 \times T) + (0.000270 \times T^2) - (0.494 \times \ln f) + (0.0231 \times T \times z_1) - (0.000224 \times T^2 \times z_3) + (0.0183 \times T \times z_2) - (0.000142 \times T^2 \times z_2)$ | | | | |
| $R^2 = 0.932$ | | | | |
| | Coefficient | Std. Error | t | p |
| Constant | 8.985 | 0.173 | 52.025 | <0.001 |
| z_1 | 0.715 | 0.122 | 5.875 | <0.001 |
| z_2 | 0.168 | 0.123 | 1.362 | 0.176 |
| T | -0.0322 | 0.00461 | -6.978 | <0.001 |
| T^2 | 0.000270 | 0.0000495 | 5.446 | <0.001 |
| $\ln f$ | -0.494 | 0.0218 | -22.714 | <0.001 |
| $T \times z_1$ | 0.0231 | 0.00625 | 3.693 | <0.001 |
| $T^2 \times z_1$ | -0.000224 | 0.0000674 | -3.326 | 0.001 |
| $T \times z_2$ | 0.0183 | 0.00652 | 2.807 | 0.006 |
| $T^2 \times z_2$ | -0.000142 | 0.0000701 | -2.023 | 0.046 |

Table 10. Cont.

| Moisture Content of Cheese: High, Medium and Low | | | | |
|---|-------------|------------|---------|--------|
| Equation (10-2): $\sqrt{\varepsilon''} = 22.116 + (2.584 \times z_1) - (10.126 \times z_2) + (0.0445 \times T) - (0.975 \times T^2) - (2.178 \times \ln f) - (0.0293 \times T \times z_1) + (0.864 \times T^2 \times z_1) - (0.437 \times \ln f \times z_1) - (0.0335 \times T \times z_2) + (0.928 \times T^2 \times z_2) + (1.143 \times \ln f \times z_2)$ | | | | |
| $R^2 = 0.936$ | | | | |
| | Coefficient | Std. Error | t | p |
| Constant | 22.116 | 0.953 | 23.203 | <0.001 |
| z_1 | 2.584 | 1.351 | 1.913 | 0.059 |
| z_2 | -10.126 | 1.366 | -7.412 | <0.001 |
| T | 0.0445 | 0.00910 | 4.886 | <0.001 |
| T^2 | -0.975 | 0.252 | -3.863 | <0.001 |
| $\ln f$ | -2.178 | 0.113 | -19.273 | <0.001 |
| $T \times z_1$ | -0.0293 | 0.0128 | -2.282 | 0.025 |
| $T^2 \times z_1$ | 0.864 | 0.357 | 2.420 | 0.018 |
| $\ln f \times z_1$ | -0.437 | 0.160 | -2.733 | 0.008 |
| $T \times z_2$ | -0.0335 | 0.0129 | -2.591 | 0.011 |
| $T^2 \times z_2$ | 0.928 | 0.360 | 2.579 | 0.012 |
| $\ln f \times z_2$ | 1.143 | 0.163 | 7.009 | <0.001 |

The result of the regression equation for the loss factor is calculated using Equation (10-2). The categorical variables, z_1, z_2 , and other interaction terms are valid. The result indicates that three moisture levels have a significant effect on the loss factor for cheese.

3.6. Categorical Test of Four Factors

3.6.1. Salmon Fillets

Four positions of dielectric properties of Alaska pink salmon fillets (anterior, middle, tail, and belly) were tested at five frequencies (27, 40, 433, 915, and 1800 MHz) and six temperatures (from 20 to 120 °C in intervals of 20 °C). The dielectric properties of salmon fillets at four positions at different frequencies and temperatures were observed in the literature [17]. In our study, the effect of the position of salmon on the dielectric properties was tested using the categorical method, and the results of regression analysis are listed in Table 11.

3.6.2. Pecan Kernels

The dielectric properties of pecan kernels with four levels of salted contents (none, light, medium, and heavy) were determined at 15% w.b. moisture content, at four temperatures and four frequencies.

The effect of salted levels on the dielectric properties was determined using a categorical test. The results are shown in Table 12.

For the dielectric constant, the variables of three categorical factors (z_1, z_2 , and z_3) and their interaction with temperature and frequency are valid (Equation (12-1)). Therefore, salted levels have a significant effect on the dielectric constant of pecan nuts at 15% w.b. MC (moisture content).

Equation (12-2) shows the results of the categorical test on loss factors. All variables involving categorical factors and their interaction variables are valid. The results show that the salted levels have a significant effect on the loss factor of pecan kernels at 15% w.b. moisture content.

Table 11. Study of the effect of four categories on the dielectric properties of salmon fillets using regression analysis.

| Position: Anterior, Middle, Tail, Belly | | | | |
|---|-------------|------------|---------|--------|
| Equation (11-1): $\ln(\epsilon') = 5.719 - (0.0802 \times z_1) + (0.0703 \times z_2) + (0.0585 \times z_3) + (0.00917 \times T) - (0.487 \times \ln f) + (0.0352 \times \ln f^2) - (0.00160 \times T \times \ln f) + (0.000522 \times T \times z_1) + (0.000684 \times T \times z_3) + (0.0140 \times \ln f \times z_1) - (0.0160 \times \ln f \times z_3)$ | | | | |
| $R^2 = 0.973$ | | | | |
| | Coefficient | Std. Error | t | p |
| Constant | 5.719 | 0.0693 | 82.472 | <0.001 |
| z_1 | -0.0802 | 0.0352 | -2.277 | 0.023 |
| z_2 | 0.0703 | 0.0101 | 6.936 | <0.001 |
| z_3 | 0.0585 | 0.0352 | 1.660 | 0.098 |
| T | 0.00917 | 0.000372 | 24.652 | <0.001 |
| $\ln f$ | -0.487 | 0.0265 | -18.371 | <0.001 |
| $\ln f^2$ | 0.0352 | 0.00245 | 14.334 | <0.001 |
| $T \times \ln f$ | -0.00160 | 0.0000623 | -25.612 | <0.001 |
| $T \times z_1$ | 0.000522 | 0.000257 | 2.029 | 0.043 |
| $T \times z_3$ | 0.000684 | 0.000257 | 2.659 | 0.008 |
| $\ln f \times z_1$ | 0.0140 | 0.00522 | 2.685 | 0.008 |
| $\ln f \times z_3$ | -0.0160 | 0.00522 | -3.066 | 0.002 |
| Equation (11-2): $\ln(\epsilon'') = 6.368 - (0.341 \times z_1) - (0.0207 \times z_2) - (0.389 \times z_3) - (0.00129 \times T) - (0.844 \times \ln f) + (0.179 \times \ln f^2) - (0.000154 \times T \times \ln f) + (0.105 \times \ln f \times z_1) + (0.0223 \times \ln f \times z_2) + (0.0743 \times \ln f \times z_3)$ | | | | |
| $R^2 = 0.766$ | | | | |
| | Coefficient | Std. Error | t | p |
| Constant | 6.368 | 1.870 | 3.405 | <0.001 |
| z_1 | -0.341 | 0.749 | -0.455 | 0.650 |
| z_2 | -0.0207 | 0.749 | -0.0276 | 0.978 |
| z_3 | -0.389 | 0.749 | -0.520 | 0.603 |
| T | -0.00129 | 0.000399 | -3.220 | 0.001 |
| $\ln f$ | -0.844 | 0.949 | -0.890 | 0.374 |
| $\ln f^2$ | 0.179 | 0.121 | 1.485 | 0.138 |
| $T \times \ln f$ | -0.000154 | 0.0000965 | -1.593 | 0.112 |
| $\ln f \times z_1$ | 0.105 | 0.180 | 0.580 | 0.562 |
| $\ln f \times z_2$ | 0.0223 | 0.181 | 0.123 | 0.902 |
| $\ln f \times z_3$ | 0.0743 | 0.1801 | 0.411 | 0.682 |

In our study, the effect of salted levels was quantified using categorical factors. The regression equations for the dielectric properties for different salted levels at 15% w.b. moisture content are easily derived.

For the dielectric constant, the terms of categorical variables $z_1, z_2, T \times z_3, \ln f \times z_1, \ln f \times z_2,$ and $\ln f \times z_3$ were validated using a *t*-test, so the position of salmon fillets has a significant effect on the dielectric constant.

Table 12. Study of the effect of four categories on the dielectric properties of pecan nut using regression analysis.

| Treatments: No Salted, Light Salted, Medium Salted and Heavy Salted | | | | |
|---|--------------------|-------------------|----------|----------|
| Equation (12-1): $\ln(\epsilon') = 2.150 - (0.533 \times z1) - (14.653 \times z2) - (8.721 \times z3) + (0.000199 \times T) + (0.138 \times \ln f) - (0.0287 \times \ln f^2) + (0.000000720 \times T^2) - (0.000602 \times T \times \ln f) + (0.0257 \times T \times z1) - (0.000158 \times T \times z3) + (6.999 \times \ln f \times z2) + (4.786 \times \ln f \times z3) - (0.661 \times \ln f^2 \times z2) - (0.468 \times \ln f^2 \times z3)$ | | | | |
| $R^2 = 0.625$ | | | | |
| | Coefficient | Std. Error | t | p |
| Constant | 2.150 | 2.034 | 1.057 | 0.291 |
| z1 | -0.533 | 0.321 | -1.661 | 0.098 |
| z2 | -14.653 | 2.708 | -5.411 | <0.001 |
| z3 | -8.721 | 2.495 | -3.495 | <0.001 |
| T | 0.000199 | 0.000857 | 0.232 | 0.817 |
| ln f | 0.138 | 0.840 | 0.164 | 0.870 |
| ln f ² | -0.0287 | 0.0765 | -0.375 | 0.708 |
| T ² | 0.00000072 | 0.000000235 | 3.060 | 0.002 |
| T × ln f | -0.000602 | 0.000181 | -3.327 | <0.001 |
| T × z1 | 0.0257 | 0.00681 | 3.781 | <0.001 |
| T × z3 | -0.000158 | 0.000220 | -0.718 | 0.473 |
| ln f × z2 | 6.999 | 1.094 | 6.397 | <0.001 |
| ln f × z3 | 4.786 | 1.022 | 4.684 | <0.001 |
| ln f ² × z2 | -0.661 | 0.0991 | -6.667 | <0.001 |
| ln f ² × z3 | -0.468 | 0.0932 | -5.022 | <0.001 |
| Equation (12-2): $\ln(\epsilon'') = -7.341 + (6.370 \times z1) - (4.537 \times z2) + (2.928 \times z3) - (0.00236 \times T) + (4.163 \times \ln f) - (0.448 \times \ln f^2) + (0.000000707 \times T^2) + (0.0000175 \times T \times \ln f) + (0.0321 \times T \times z1) - (3.082 \times \ln f \times z1) + (2.987 \times \ln f \times z2) + (0.302 \times \ln f^2 \times z1) - (0.281 \times \ln f^2 \times z2)$ | | | | |
| $R^2 = 0.694$ | | | | |
| | Coefficient | Std. Error | t | p |
| Constant | -7.341 | 1.276 | -5.755 | <0.001 |
| z1 | 6.370 | 3.322 | 1.918 | 0.056 |
| z2 | -4.537 | 2.110 | -2.150 | 0.032 |
| z3 | 2.928 | 0.204 | 14.335 | <0.001 |
| T | -0.00236 | 0.000453 | -5.215 | <0.001 |
| ln f | 4.163 | 0.532 | 7.827 | <0.001 |
| ln f ² | -0.448 | 0.0503 | -8.903 | <0.001 |
| T ² | 0.000000707 | 0.000000251 | 2.81 | 0.005 |
| T × ln f | 0.0000175 | 0.00000289 | 6.059 | <0.001 |
| T × z1 | 0.0321 | 0.00767 | 4.182 | <0.001 |
| ln f × z1 | -3.082 | 1.371 | -2.249 | 0.025 |
| ln f × z2 | 2.987 | 0.836 | 3.575 | <0.001 |
| ln f ² × z1 | 0.302 | 0.125 | 2.413 | 0.016 |
| ln f ² × z2 | -0.281 | 0.0756 | -3.723 | <0.001 |

The effect of the position of salmon fillets on the loss factor was determined, and the regression result is presented using Equation (11-2). All terms for categorical variables (z_1 , z_2 , $T \times z_3$, $\ln f \times z_1$, $\ln f \times z_2$ and $\ln f \times z_3$, etc.) are invalid. There is no significant difference between these datasets for loss factors for different positions of salmon.

3.7. The Best Regression Equations for Each Food Ingredient

From the results of this study, the best regression equations (Equations (35)–(52)) for each food ingredient are listed as follows:

3.7.1. Egg White Powder

$$\ln(\varepsilon') = 0.400 - (0.00242 \times T) + (0.0434 \times \ln f + (0.0140 \times X) - (0.0000462 \times T^2) - (0.00271 \times \ln f^2) + (0.00180 \times X^2) + (0.00181 \times T \times \ln f + (0.00159 \times T \times X) - (0.00422 \times \ln f \times X) - (0.000197 \times T \times \ln f \times X) \quad (35)$$

$$\varepsilon'' = 1.975 - (0.0471 \times T) - (0.347 \times X) - (0.178 \times \ln f) + (0.00932 \times X^2) + (0.00723 \times T \times \ln f) + (0.00729 \times T \times X) + (0.0236 \times \ln f \times X) - (0.000924 \times T \times \ln f \times X) \quad (36)$$

3.7.2. Chicken Flour

$$1/\varepsilon' = 0.560 - (0.00263 \times T) + (0.0000684 \times f) - (0.0161 \times X) - (0.0000110 \times T^2) - (0.0000000260 \times f^2) + (0.000117 \times X^2) + (0.000000459 \times T \times f) + (0.00000309 \times T \times X) + (0.00000239 \times f \times X) - (0.0000000544 \times T \times f \times X) \quad (37)$$

$$\ln(\varepsilon'') = 3.935 - (0.268 \times T) - (0.339 \times X) - (0.595 \times \ln f) + (0.00300 \times T^2) + (0.0584 \times \ln f^2) + (0.00903 \times X^2) + (0.00888 \times T \times \ln f) + (0.0122 \times T \times X) - (0.000623 \times T \times \ln f \times X) - (0.0000115 \times T^3) - (0.00000589 \times (T \times f)^2) - (0.00000191 \times (T \times X)^2) \quad (38)$$

3.7.3. Bread

$$1/\varepsilon' = 1.236 - (0.0136 \times T) - (0.0289 \times X) + (0.0959 \times \ln f) - (0.00626 \times \ln f^2) + (0.000194 \times T \times \ln f) + (0.000307 \times T \times X) \quad (39)$$

$$\ln(\varepsilon'') = -8.366 + (0.136 \times T) + (0.336 \times X) - (0.716 \times \ln f) + (0.0000507 \times T^2) + (0.0793 \times \ln f^2) - (0.00369 \times T \times \ln f) - (0.00291 \times T \times X) - (0.0137 \times \ln f \times X) \quad (40)$$

3.7.4. Black-Eyed Peas

$$\ln(\varepsilon') = 2.521 - (0.0201 \times T) - (0.195 \times X) + (0.0184 \times \ln f) + (0.000242 \times T^2) - (0.000327 \times \ln f^2) + (0.00926 \times X^2) + (0.000677 \times T \times \ln f) + (0.000693 \times T \times X) - (0.00662 \times \ln f \times X) - (0.0000247 \times T \times \ln f \times X) - (0.00000124 \times (T \times X)^2) \quad (41)$$

$$\ln(\varepsilon'') = 4.531 - (0.0719 \times T) - (0.375 \times X) - (1.349 \times \ln f) + (0.000639 \times T^2) + (0.0909 \times \ln f^2) + (0.0131 \times X^2) + (0.00674 \times T \times \ln f) + (0.00315 \times T \times X) + (0.0161 \times \ln f \times X) - (0.0000621 \times T \times \ln f \times X) - (0.00000770 \times T \times \ln f^2) - (0.000000970 \times (T \times X)^2) \quad (42)$$

3.7.5. Macadamia Nut Kernels

$$\begin{aligned} \ln(\varepsilon') &= 1.467 - (0.000659 \times T) + (0.102 \times X) - (0.119 \times \ln f) + (0.0000327 \times T^2) + (0.0170 \times \ln f^2) \\ &+ (0.00000963 \times X^2) - (0.000227 \times T \times \ln f) + (0.000304 \times T \times X) - (0.00904 \times \ln f \times X) - \\ &(0.00000325 \times T \times \ln f \times X) - (0.000000205 \times T \times \ln f^2) - (0.0000000679 \times (T \times X)^2) \end{aligned} \quad (43)$$

$$\begin{aligned} \ln(\varepsilon'') &= -1.719 + (0.00660 \times T) + (0.469 \times X) - (0.351 \times \ln f) + (0.0000602 \times T^2) + (0.0627 \times \ln f^2) \\ &- (0.00381 \times X^2) - (0.00102 \times T \times \ln f) + (0.000778 \times T \times X) - (0.0397 \times \ln f \times X) - (0.000118 \times T \\ &\times \ln f \times X) + (0.000000144 \times (T \times X)^2) \end{aligned} \quad (44)$$

3.7.6. Liquid Egg White

$$\ln(\varepsilon') = 5.736 + (0.000700 \times T) - (0.548 \times \ln f) + (0.0000632 \times T^2) + (0.0490 \times \ln f^2) - (0.00155 \times T \times \ln f) \quad (45)$$

$$\ln(\varepsilon'') = 9.793 + (0.0169 \times T) - (1.403 \times \ln f) - (0.00000389 \times T^2) + (0.0553 \times \ln f^2) - (0.00113 \times T \times \ln f) \quad (46)$$

3.7.7. Precooked Egg White

$$\ln(\varepsilon') = 5.552 + (0.00355 \times T) - (0.443 \times \ln f) + (0.0000269 \times T^2) + (0.0372 \times \ln f^2) - (0.00140 \times T \times \ln f) \quad (47)$$

$$\begin{aligned} 1/\varepsilon'' &= 0.0525 + (0.000245 \times T) - (0.0292 \times \ln f) + (0.000000199 \times T^2) + (0.00438 \times \ln f^2) - \\ &(0.0000852 \times T \times \ln f) \end{aligned} \quad (48)$$

3.7.8. Almond

$$\sqrt{\varepsilon'} = 5.816 - (0.00407 \times T) - (1.357 \times \ln f) + (0.0000683 \times T^2) + (0.112 \times \ln f^2) \quad (49)$$

$$\sqrt{\varepsilon''} = -6.515 - (0.0200 \times T) + (3.221 \times \ln f) + (0.000132 \times T^2) - (0.278 \times \ln f^2) + (0.00144 \times T \times \ln f) \quad (50)$$

3.7.9. Walnut

$$\varepsilon' = 11.067 - (0.0193 \times T) - (2.308 \times \ln f) + (0.132 \times \ln f^2) + (0.00855 \times T \times \ln f) \quad (51)$$

$$\ln(\varepsilon'') = -7.867 - (0.0248 \times T) + (3.187 \times \ln f) + (0.000201 \times T^2) - (0.264 \times \ln f^2) - (0.000704 \times T \times \ln f) \quad (52)$$

By inspecting these best equations, no universal equation could be used to express the relationship between dielectric properties and influencing factors. Each food ingredient has its special appropriate prediction equation.

4. Discussion

The dielectric properties of foods are necessary elements of food technology and engineering. The factors that affect dielectric properties include quantitative and qualitative variables. The applied frequency, ambient temperature, bulk density, and moisture content of samples are quantitative variables. The treatment method, position of samples, and constituents of foods are qualitative variables.

A modern regression analysis allows the prediction equations of dielectric properties to be established, and the quantitative factors are the dependent variables. The interaction term and square term for variables is integrated into these equations. The basic assumption is that there is a normal

distribution and a constant variance in data. The qualitative factors, such as salted or unsalted and position of samples, are determined using categorical testing.

This study uses the quantitative factors, such as moisture content, frequency, and temperature, to establish the modern regression analysis. To obtain the appropriate equations for the dielectric properties, the dielectric constant and loss factor for dependent variables and the frequency of independent variables is sometimes transformed as a logarithmic value ($\ln y$), an inverse power ($1/y$), or a square root (\sqrt{y}). Then, adequate equations of the dielectric constant and loss factor are established using modern regression analysis.

In this study, two bases of the moisture content, percent dry basis, M_{db} [8], and percent wet basis, M_{wb} [11,12,14,18,19], were used to express the moisture content of products. After checking the fitting agreement of the regression analysis models, dry or wet bases all could be used to establish the prediction equations. Both moisture bases easily convert with the equation $M_{wb} = M_{db}/(100 + M_{db})$.

For other studies, the four quantitative factors are frequency, moisture content, temperature, and density [26]. To develop a moisture meter, three quantitative factors are involved: moisture content, frequency, and the bulk density of grains and seeds [40]. A modern regression analysis can be used to establish the equations for the dielectric properties using these datasets.

A regression equation defines which dependent variables (influencing factors) are important. These equations can be used for prediction in the development of heating equipment that uses electromagnetic wave energy. Most of the appropriate equations are the form of $\ln(y)$ or $1/y$ for dependent variables and temperature, moisture, logarithmic form of the frequency, and their power and interaction terms for independent variables. The best form of the best equation is $c_0 + c_1T + c_2X + c_3 \ln f + c_{11}T^2 + c_{22}X^2 + c_{33} \ln f^2 + c_{12}T \times X + c_{13}T \times \ln f + c_{23}X \times \ln f$.

All the published data for the dielectric properties in the literature that are listed in Table 2 are measured with an impedance analyzer with the open-end coaxial-line probe. This method was introduced and detailed [3,4,6]. This method is particularly suitable for food materials of liquid and semi-solids. The advantages of this method are simple to use and there is no damage for the sample [3–6]. The reports of the accuracy for this method is $\pm 5\%$ and it could be improved to $\pm 2\%$ after careful calibration [41]. All the literature related to the published data in Table 2 mention the calibration procedure. However, the accuracy of the dielectric properties of foods was not reported. The effect of the measurement errors on the regression analysis equations needs to be studied further. The method to calculate the measurement uncertainty on the prediction equation could be adopted [42].

In this study, six categories of foods were studied: eggs, vegetables, dairy products, fishes, nuts, and insects. The application of dielectric properties on the food processing includes measuring, heating, and classification. The moisture content and water activity of foods can be determined by the design and calibration of electrical instruments. The moisture content and water activity of foods can be measured by detecting the dielectric constant of foods and then be calculated with previous established calibration equations. The dielectric properties provide the basic information to the construction of heating devices with microwave frequencies. The disinfection of insect pests in foods could be performed by heating. The dielectric properties of fruits, nuts, and insect pests support the requirement information to arrange with appropriate frequency and time [20]. The effect of the treatment such as salted and unsalted has a significant effect on the dielectric properties of foods. The measurement of dielectric properties proposes a possible way to quantify the treatment of foods [15–17,19].

The power density of the thermal energy of foods can be expressed as shown in Equation (2). The relationship between loss factor ϵ'' can be predicted with the established equation of this study. That is, the power density could be computed in the specific conditions of the moisture content, temperature, and frequency. When the prediction equations of loss factors of insects and nuts or fruits are established, the disinfection system of insect pests can be design to control insects without damaging food products. With the measurement of dielectric properties in the preset frequency and temperature, the moisture content of food materials can be calculated by prediction equations.

The significant effect of the dielectric properties of foods with different treatments could be evaluated by the adequate predicted equations of products and categorical testing of the regression analysis.

5. Conclusions

The measurement of dielectric properties of food materials is used to quantify the interaction of foods with outer electromagnetic energy during processing. The dielectric properties are affected by the applied frequency, temperature, bulk density, concentration, and the constituents of foods.

Previous studies established the relationship between dielectric properties and their influencing factors using classical regression analysis. The criteria to determine the adequacy of these equations are the coefficient of determination, R^2 , and the p -value. Modern regression techniques have been developed. The statistical test include tests for data normality, a constant variance, and residual plots.

This study uses sixteen datasets from the literature to establish prediction equations for dielectric properties. The dependent variables are the dielectric constant and the loss factor. The independent variables are the frequency, temperature, and moisture content. The dependent variables and the frequency term are often transformed to establish an appropriate equation for dielectric properties.

This study uses categorical testing to determine the significance of the effect of different conditions on the dielectric properties. These conditions include salted treatment, the position of samples, moisture conditions, and ion concentrations. The results show that this method of categorical testing quantitatively determines the effect. The method can be used for other datasets of dielectric properties to classify the influencing quantitative and qualitative factors. The application of predicted equations of dielectric properties is discussed.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2304-8158/9/10/1472/s1>, Table S1: title, Video S1: The relationship between the dielectric constant and the influencing factors and statistical criteria established by regression analysis for chickpea flour; Table S2: The relationship between the loss factor and the influencing factors and statistical criteria established by regression analysis for chickpea flour; Table S3: The relationship between the dielectric constant and the influencing factors and statistical criteria established by regression analysis for white bread; Table S4: The relationship between the loss factor and the influencing factors and statistical criteria established by regression analysis for white bread; Table S5: The relationship between the dielectric properties and the influencing factors and statistical criteria established by regression analysis for two types of egg white.

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References

1. Icier, F.; Baysal, T. Dielectrical properties of food materials—1: Factors affecting and industrial uses. *Crit. Rev. Food Sci. Nutr.* **2004**, *44*, 465–471. [[CrossRef](#)] [[PubMed](#)]
2. Icier, F.; Baysal, T. Dielectrical properties of food materials—2: Measurement techniques. *Crit. Rev. Food Sci. Nutr.* **2004**, *44*, 473–478. [[CrossRef](#)] [[PubMed](#)]
3. Venkatesh, M.S.; Raghavan, G.S.V. An overview of dielectric properties measuring techniques. *Can. Biosyst. Eng.* **2005**, *47*, 15–30.
4. Jha, S.N.; Narsaiah, K.; Basediya, A.L.; Sharma, R.; Jaiswal, P.; Kumar, R.; Bhardwaj, R. Measurement techniques and application of electrical properties for nondestructive quality evaluation of foods—A review. *J. Food Sci. Technol.* **2011**, *48*, 387–411. [[CrossRef](#)] [[PubMed](#)]
5. Sosa-Morales, M.E.; Valerio-Junco, L.; López-Malo, A.; García, H.S. Dielectric properties of foods: Reported data in the 21st century and their potential applications. *LWT Food Sci. Technol.* **2010**, *43*, 1169–1179. [[CrossRef](#)]

6. Khaled, D.E.; Novas, N.; Gazquez, J.A.; Garcia, R.M.; Manzano-Agugliaro, F. Fruit and vegetable quality assessment via dielectric sensing. *Sensors* **2015**, *15*, 15363–15397. [[CrossRef](#)]
7. Venkatesh, M.S.; Raghavan, G.S.V. An overview of microwave processing and dielectric properties of agri-food materials. *Biosyst. Eng.* **2004**, *88*, 1–18. [[CrossRef](#)]
8. Boreddy, S.R.; Subbiah, J. Temperature and moisture dependent dielectric properties of egg white powder. *J. Food Eng.* **2016**, *168*, 60–67. [[CrossRef](#)]
9. Wang, J.; Tang, J.; Wang, Y.; Swanson, B. Dielectric properties of egg whites and whole eggs as influenced by thermal treatments. *LWT Food Sci. Technol.* **2009**, *42*, 1204–1212. [[CrossRef](#)]
10. Guo, W.; Trabelsi, S.; Nelson, S.O.; Jones, D.R. Storage effects on dielectric properties of eggs from 10 to 1800 MHz. *J. Food Sci.* **2007**, *72*, 335–340. [[CrossRef](#)]
11. Guo, W.; Tiwari, G.; Tang, J.; Wang, S. Frequency, moisture and temperature-dependent dielectric properties of chickpea flour. *Biosyst. Eng.* **2008**, *101*, 217–224. [[CrossRef](#)]
12. Jiao, S.; Johnson, J.A.; Tang, J.; Tiwari, G.; Wang, S. Dielectric properties of cowpea weevil, black-eyed peas and mung beans with respect to the development of radio frequency heat treatments. *Biosyst. Eng.* **2011**, *108*, 280–291. [[CrossRef](#)]
13. Ahmed, J.; Ramaswamy, H.S.; Raghavan, V.G.S. Dielectric properties of butter in the MW frequency range as affected by salt and temperature. *J. Food Eng.* **2007**, *81*, 351–358. [[CrossRef](#)]
14. Liu, Y.; Tang, J.; Mao, Z. Analysis of bread dielectric properties using mixture equations. *J. Food Eng.* **2009**, *93*, 72–79. [[CrossRef](#)]
15. Everard, C.D.; Fagan, C.C.; O'Donnell, C.P.; O'Callaghan, D.J.; Lyng, J.G. Dielectric properties of process cheese from 0.3 to 3 GHz. *J. Food Eng.* **2006**, *75*, 415–422. [[CrossRef](#)]
16. Al-Holy, M.; Wang, Y.; Tang, J.; Rasco, B. Dielectric properties of salmon (*Oncorhynchus keta*) and sturgeon (*Acipenser transmontanus*) caviar at radio frequency (RF) and microwave (MW) pasteurization frequencies. *J. Food Eng.* **2005**, *70*, 564–570. [[CrossRef](#)]
17. Wang, Y.; Tang, J.; Rasco, B.; Kong, F.; Wang, S. Dielectric properties of salmon fillets as a function of temperature and composition. *J. Food Eng.* **2008**, *87*, 236–246. [[CrossRef](#)]
18. Wang, Y.; Zhang, L.; Gao, M.; Tang, T.; Wang, S. Temperature- and moisture-dependent dielectric properties of macadamia nut kernels. *Food Bioprocess Technol.* **2013**, *6*, 2165–2176. [[CrossRef](#)]
19. Zhang, J.; Li, M.; Cheng, J.; Wang, J.; Ding, Z.; Yuan, X.; Zhou, S.; Liu, X. Effects of moisture, temperature, and salt content on the dielectric properties of Pecan kernels during microwave and radio frequency drying processes. *Foods* **2019**, *8*, 385. [[CrossRef](#)]
20. Wang, S.; Tang, J.; Johnson, J.A.; Mitcham, E.; Hansen, J.D.; Hallman, G.; Drake, S.R.; Wang, Y. Dielectric properties of fruits and insect pests as related to radio frequency and microwave treatments. *Biosyst. Eng.* **2003**, *85*, 201–212. [[CrossRef](#)]
21. Routray, W.; Orsat, V. Recent advances in dielectric properties—measurements and importance. *Curr. Opin. Food Sci.* **2018**, *23*, 120–126. [[CrossRef](#)]
22. Calay, R.K.; Newborough, M.; Probert, D.; Calay, P.S. Predictive equations for the dielectric properties of foods. *Int. J. Food Sci. Technol.* **1995**, *29*, 699–713. [[CrossRef](#)]
23. Dev, S.R.S.; Raghavan, G.S.V.; Garipey, Y. Dielectric properties of egg components and microwave heating for in-shell pasteurization of eggs. *J. Food Eng.* **2008**, *86*, 207–214. [[CrossRef](#)]
24. Kannan, S.; Dev Satyanarayan, S.R.S.; Garipey, Y.; Raghavan, G.S.V. Effect of radiofrequency heating on the dielectric and physical properties of eggs. *Prog. Electromagn. Res. B* **2013**, *51*, 201–220. [[CrossRef](#)]
25. Zhu, X.; Guo, W.; Wang, S. Sensing moisture content of buckwheat seed from dielectric properties. *Trans. ASABE* **2013**, *56*, 1855–1862.
26. Boldor, D.; Sanders, T.H.; Simunovic, J. Dielectric properties of in-shell and shelled peanuts at microwave frequencies. *Trans. ASAE* **2004**, *47*, 1159–1169. [[CrossRef](#)]
27. Yu, D.U.; Shrestha, B.L.; Baik, O.D. Radio frequency dielectric properties of bulk Canola seeds under different temperatures, moisture contents, and frequencies for feasibility of radio frequency disinfestation. *Int. J. Food Prop.* **2015**, *18*, 2746–2763. [[CrossRef](#)]
28. Zhang, S.; Zhou, L.; Ling, B.; Wang, S. Dielectric properties of peanut kernels associated with microwave and radio frequency drying. *Biosyst. Eng.* **2016**, *145*, 108–117. [[CrossRef](#)]
29. Zhu, Z.; Guo, W. Frequency, moisture content, and temperature dependent dielectric properties of potato starch related to drying with radio-frequency/microwave energy. *Sci. Rep.* **2017**, *7*, 9311. [[CrossRef](#)]

30. Ling, B.; Liu, X.; Zhang, L.; Wang, S. Effects of temperature, moisture, and metal salt content on dielectric properties of rice bran associated with radio frequency heating. *Sci. Rep.* **2018**, *8*, 4427. [[CrossRef](#)]
31. Montgomery, D.C.; Peck, E.A.; Vining, C.G. *Introduction to Linear Regression Analysis*, 5th ed.; John Wiley & Sons, Inc.: New York, NY, USA, 2012; p. 836.
32. Myers, R.H. *Classical and Modern Regression with Applications*, 2nd ed.; Duxbury Press: Monterey, CA, USA, 2000.
33. Weisberg, S. *Applied Linear Regression*, 4th ed.; Wiley: New York, NY, USA, 2013; p. 384.
34. Chen, H.; Chen, C. On the use of modern regression analysis in liver volume prediction equation. *J. Med. Imaging Health Inform.* **2017**, *7*, 338–349. [[CrossRef](#)]
35. Wang, C.; Chen, C. Use of modern regression analysis in plant tissue culture. *Propag. Ornam. Plants* **2017**, *17*, 83–94.
36. Chen, C. Relationship between water activity and moisture content in floral honey. *Foods* **2019**, *8*, 30. [[CrossRef](#)]
37. Fox, J. *Regression Diagnostics*; Sage: Newbury Park, CA, USA, 1991. [[CrossRef](#)]
38. Zeileis, A.; Hothorn, T. Diagnostic checking in regression relationships. *R. News* **2002**, *2*, 7–10. Available online: <http://CRAN.R-project.org/doc/Rnews/> (accessed on 31 July 2020).
39. Liu, D.; Zhang, H. Residuals and diagnostics for ordinal regression models: A surrogate approach. *J. Am. Stat. Assoc.* **2018**, *113*, 845–854. [[CrossRef](#)]
40. ASABE. *ASAE D293.4 JAN2012 (R2016)—Dielectric Properties of Grain and Seed*; ASABE: St. Joseph, MI, USA, 2016.
41. La Gioia, A.; Porter, E.; Merunka, I.; Shahzad, A.; Salahuddin, S.; Jones, M.; O'Halloran, M. Open-ended coaxial probe technique for dielectric measurement of biological tissues: Challenges and common practices. *Diagnostics* **2018**, *8*, 40. [[CrossRef](#)]
42. Chen, L.-H.; Chen, J.; Chen, C. Effect of Environmental Measurement Uncertainty on Prediction of Evapotranspiration. *Atmosphere* **2018**, *9*, 400. [[CrossRef](#)]

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