Effect of drying temperature on the electrical impedance characteristics of ginger slices**

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A b s t r a c t. Moisture removal during drying may induce structural changes in ginger, which may be correlated with its electrical impedance characteristics. In this study, ginger slices were dried using hot-air drying at temperatures of 50, 60 and 70°C. The drying kinetics and moisture diffusivity were determined. Also, the impedance changes during drying were evaluated using electrical impedance spectroscopy in the frequency range of 5 Hz to 1 MHz. The results showed that effective moisture diffusivity increased with increasing temperature, this lies in the range of 6.51×10^{-9} m² s^{-1} to 2.15×10^{-8} m² s^{-1}. The impedance plot was found to be influenced by the drying temperature, moisture content and frequency. Impedance at 50°C decreased as the drying process proceeded, and started to increase during the final stage of drying. As for frequency, impedance decreased as the frequency increased. However, it was found that the impedance values at temperatures of 60 and 70°C were not recommended for further analysis due to scattered results. Therefore, this study suggested that the best temperature at which to study the impedance characteristics of ginger slices between the frequencies of 50 Hz and 1 MHz was found to be at the drying temperature of 50°C.

K e y w o r d s: ginger, hot air drying, moisture diffusivity, impedance analysis, drying kinetics

INTRODUCTION

Ginger (*Zingiber officinale*) is a common ingredient used in cooking as a spice or flavouring agent (Srinivasan, 2017; Jelled *et al.*, 2015). It is composed of many active compound such as gingerol and shagaol that can be used for medical treatment and home remedies – to reduce the pain of tooth-aches, asthma, inflammation and gastrointestinal disorders (Ho *et al.*, 2013; Gümüşay *et al.*, 2015; Srinivasan, 2017). However, the ginger is also a living tissue, which has a limited durability, it may be classified as a highly perishable product similar to other types of fruits or vegetables (Sousa Gallagher and Mahajan, 2011; Hlaváčová *et al.*, 2015). For these reasons, there is a need for a simple postharvest process to maintain product quality with high-level nutrient retention.

Drying is a common processing technique in the food industry and it has been used for centuries (Taheri-Garavand *et al.*, 2011). Drying is a process conducted with the purpose of reducing moisture content in the food matrix to a safe level for storage, it may slow down microbial activity and extend the shelf-life of food (Ando *et al.*, 2014; Betoret *et al.*, 2016). However, during the drying process, the food will be exposed to heat stress for a longer time and this will affect its physical properties. According to Ando *et al.* (2014), a qualitative study of the cellular structure and cell damage during drying may provide insight into the physical properties of plants and vegetables.

In recent times, many studies have described the status of the cellular structure with electrical impedance properties. Islam *et al.* (2019) conducted an electrical impedance analysis on onion and found that the physiological status of the cell was sensitive to changes in the moisture content inside the onion. Ando *et al.* (2014) reported that changes in the impedance properties of potato tissue were due to membrane injury during the early stage of drying and loss of moisture content during the late drying stage. Other relevant studies reported in literature concerning the use of electrical impedance properties to characterize physiological properties were performed on pumpkin (Ando *et al.*, 2019), banana (Chowdhury *et al.*, 2017) and apple (Vozáry and D-né, 1998).

Electrical impedance spectroscopy (EIS) is recognized as the most highly favoured non-destructive technique used to study the electrical properties of materials. EIS is frequently applied in multiple applications including the characterization of corrosion systems (Zulkifli *et al.*, 2017), membrane/electrolyte (Hafiza and Isa, 2017; Mejenom *et al.*, 2018) and concrete (Layssi *et al.*, 2015) with the purpose of determining the ionic conductor behaviour. For food products, the impedance data acquired from EIS can be used to detect the changes in cell structural tissue (Chowdhury *et al.*, 2017). Basically, EIS is measured by inducing an alternating current signal as a function of frequency in order to generate electrical impedance (Zhao *et al.*, 2017). In mathematical terms, the impedance, $Z\angle(\theta)$ is given as the voltage drop over applied current and it can also be described in a complex form as shown in Eqs (1) and (2), respectively (Islam *et al.*, 2019; Thoresen *et al.*, 2016):

$$Z\angle(\theta) = \frac{V\angle(\theta)}{I\angle(\theta)}, \qquad (1)$$

$$Z = Z_r + jZ_i. \qquad (2)$$

From the equation above, $V\angle(\theta)$ is the voltage drop, $I\angle(\theta)$ is the applied current, θ is the phase angle, Z_r is the real part of complex impedance, Z_i is the imaginary part of complex impedance and j is $\sqrt{-1}$.

Generally, EIS can be conducted in various frequency ranges depending on the type of sample. Most of the literature reported on electrical properties in the high frequency range, while a limited volume of work can be found using the frequency range below 1 MHz. Therefore, the aim of this study was to investigate the effect of drying temperature on the electrical impedance properties of ginger using a parallel-plate holder in the frequency range of 5 Hz to 1 MHz. The impedance data acquired from the EIS was then correlated with moisture content and effective diffusivity in order to elucidate the status of the structural tissue of ginger. All of the results obtained in this study were also compared in order to determine the optimal drying temperature for impedance measurement within the specified frequency range.

MATERIAL AND METHODS

Fresh ginger (*Zingiber officinale*) was purchased from the local market in Kuala Nerus, Terengganu, Malaysia. The initial moisture content (%) of the ginger was approximately 89.13 ± 0.89 on a wet basis (AOAC, 2000). Prior to characterization, the ginger samples were cleaned manually with water and wiped with absorbent paper to remove residual water on the surface. Then, the ginger samples were cut into slices using a stainless steel mechanical slicer and shaped using a cutter kit to form circular slices with a diameter of 0.02 m and a thickness of 0.006 ± 0.001 m. All of the samples obtained were used directly without any further treatment.

Fresh ginger slices were dried in a hot air drier (Memmert UNB 100, Germany) at three different drying temperatures (50, 60 and 70°C) until their mass reached a constant fixed value. A Mettler Toledo GR-200 analytical balance with 0.001 g accuracy was used to determine the mass loss before conversion to moisture content. The change in moisture content can be expressed by moisture ratio, M_R as in Eq. (3) below:

$$M_R = \frac{M - M_e}{M_o - M_e}, \qquad (3)$$

where: M_R refers to the moisture ratio; M, M_o, and M_e denote the local moisture content, initial moisture content and equilibrium moisture content, respectively.

Further, the modified Page model (Eq. (4)) was used to simulate the experimental data. This empirical drying model has been widely used to describe the drying kinetics of various agricultural and biological products (Akoy, 2014; Md Salim *et al.*, 2019; Deshmukh *et al.*, 2014; Mewa *et al.*, 2018):

$$M_R = \exp[-(kt)^n]. \qquad (4)$$

From Eq. (4), k is the drying rate constant, n is the unit coefficient and t is the drying time (min).

The goodness of fit was determined using the coefficient of determination (R^2), chi-square (χ^2) and root mean square error ($RMSE$) which can be described by the following:

$$R^2 = 1 - \frac{\sum_{i-1}^{i=n}\left(MR_i^{exp} - MR_i^{pred}\right)^2}{\sum_{i=n}^{i=n}\left(MR_i^{exp} - \overline{MR}^{exp}\right)^2}, \qquad (5)$$

$$\chi^2 = \sum_{i-1}^{i=n} \frac{(MR_i^{pred} - MR_i^{exp})^2}{n - m}, \qquad (6)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(MR_i^{pred} - MR_i^{exp})^2}, \qquad (7)$$

where: n is the number of observations, MR_i^{pred} is the ith predicted dimensionless MR, MR_i^{exp} is the ith experimental dimensionless MR, m is the number of variables and $\overline{MR}^{exp}$ is the mean of the experimental dimensionless MR (Md Salim *et al.*, 2019).

The phenomenon of moisture diffusivity during drying can be estimated by using Fick's equation. In this study, the analytical solution for drying a thin layer sample (negligible shrinkage, constant diffusion coefficient and temperature) is given by Eq. (8) (Kertész *et al.*, 2015):

$$M_R = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}t}{4l^2}\right). \quad (8)$$

Here, t is the drying time (s), D_{eff} is the effective diffusivity of the ginger slices (m^2 s^{-1}), l denotes the half thickness of the ginger slices (m) and n is the positive integer. Equation (8) can also be written in a simplified form as expressed by Eq. (9).

$$M_R = \frac{8}{\pi^2} exp\left(-\frac{\pi^2 D_{eff}t}{4l^2}\right). \quad (9)$$

The value of effective moisture diffusivity, D_{eff} can be determined from the linear slope of $\ln M_R$ against $\ln t$ graph as written in Eq. (10):

$$slope = \frac{\pi^2 D_{eff}}{4l^2}. \quad (10)$$

The electrical properties of ginger were obtained using the electrical impedance spectroscopy (EIS) model HIOKI 3532-50 LCR Hi-Tester connected to a computer and sample holder. The sample was sandwiched between the two stainless steel blocking electrodes of the sample holder. The measurement was performed in a frequency range between 5 Hz and 1 MHz at a selected time and 1 V voltage. All of the measured data were presented in the form of a Cole-Cole plot (imaginary part of the complex impedance, -Z_i against the real part of the complex impedance, Z_r).

RESULTS AND DISCUSSION

The changes in the moisture content of fresh ginger were related to the drying temperatures (Fig. 1). It can also be observed that the drying time decreased as the temperature increased. The total drying time required to lower the moisture content to a specified level (~ 7% w.b.) at drying temperatures of 50, 60 and 70°C were 1 470, 1 110 and 570 min, respectively.

During the early stage of the drying period, a higher water concentration gradient accelerates the water removal process, which is then diminished as the drying process continues. This trend is consistent with previous reports on carrot (Kertész *et al.*, 2015), potato (Ando *et al.*, 2014) and pumpkin (Seremet *et al.*, 2015). The fitted modified Page model with the experimental data is shown in Fig. 1 and the statistical analysis for this curve fitting is listed in Table 1. The model produced an excellent fit for all the
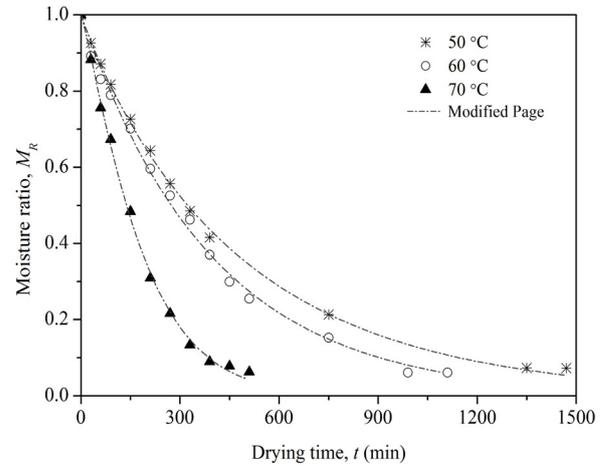

Fig. 1. Changes in the moisture ratio of fresh ginger slices at different drying temperatures. Dash-dotted line represents the approximation of the exponential function given by Eq. (4).

experimental data with an R^2 value of 0.99, χ^2 in the range between 1.21×10^{-4} and 4.12×10^{-4} and with *RMSE* lower than 1.47×10^{-2}. It can also be observed that the value of the drying constant k parameter increased with the increase in drying temperature.

A further study concerning effective moisture diffusivity, D_{eff} is important to describe the rate of moisture transfer of ginger throughout the drying process (Touil *et al.*, 2014). The value of D_{eff} was obtained from Eq. (10) and the results are given in Table 2. As can be observed from the table, the value of D_{eff} increases greatly with increasing temperature. The higher value of D_{eff} at 70°C may be explained by the increase in thermal energy received by the ginger which facilitates more moisture transfer inside the ginger tissue as the bonding of the water molecules becomes loosely bound to its matrix (Touil *et al.*, 2014; Onu Chijioke *et al.*, 2017; Mewa *et al.*, 2018). However, all of the D_{eff} values obtained from this study are acceptable and found within the range of drying biological materials ($10^{-8} - 10^{-12}$ m^2 s^{-1}) (Md Salim *et al.*, 2017).

The study of electrical impedance is a useful way of understanding the electrical properties of ginger at various frequency and temperature ranges (Islam *et al.*, 2019). Besides, it can also provide insight into the physical state and inner structure of biological tissue when subjected to any testing (Bai *et al.*, 2018; Kertész *et al.*, 2015). The Cole-Cole plot of ginger during drying at 50 and 60°C is shown in Fig. 2. The plot at a temperature of 70°C could not be presented here as the graph only provides scattered data and was not suitable for further analysis. This may be due to the abrupt changes in ginger structure at higher temperatures which may interfere the flow of the electrical current passing through the sample. Previous studies also reported that the physical properties and freshness of the
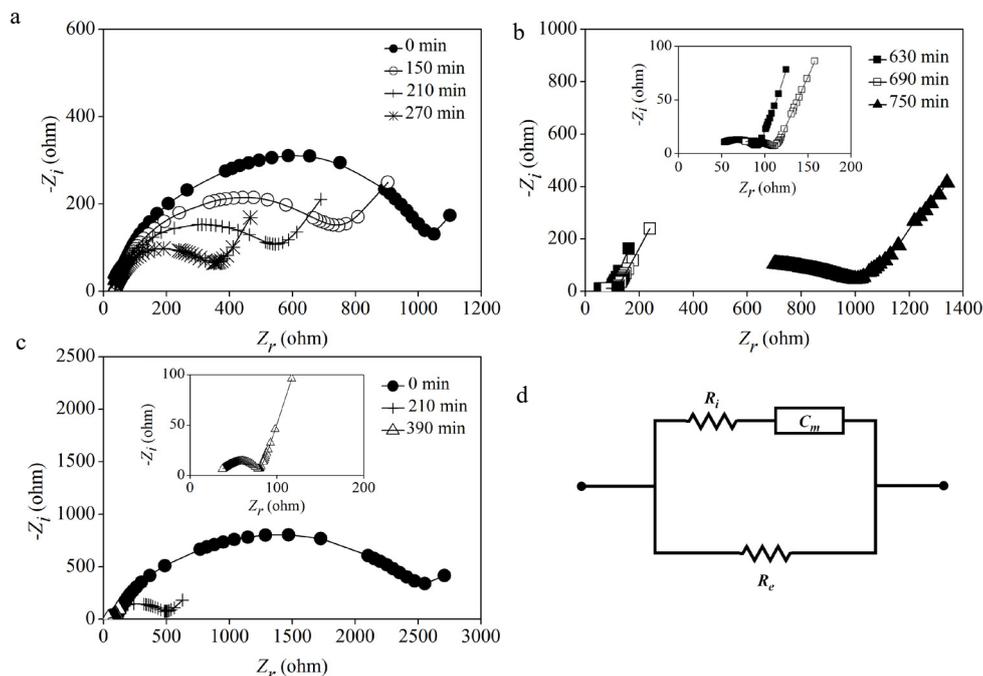
Fig. 2. Cole-Cole plot of the sample dried at 50°C for: a) 0 – 270 min, b) 630 – 750 min, c) Cole-Cole plot of the sample dried at 60°C for 0 – 390 min with d) their equivalent circuit (Inset of Fig. 2b and Fig. 2c represents the enlarged Cole-Cole plot for 630 – 690 min and 390 min, respectively).

Table 1. Effect of drying temperature on modified Page model regression parameters

Drying temperature (°C)	Parameters				
	k	n	χ^2	*RMSE*	R^2
50	2.10×10^{-3}	0.95	1.21×10^{-4}	1.10×10^{-2}	0.99
60	2.54×10^{-3}	1.00	4.12×10^{-4}	1.20×10^{-2}	0.99
70	5.28×10^{-3}	1.16	2.16×10^{-4}	1.47×10^{-2}	0.99

Table 2. Effective moisture diffusivity of ginger at different drying temperatures

Drying temperature (°C)	Effective moisture diffusivity D_{eff} (m^2 s^{-1})
50	6.51×10^{-9}
60	9.84×10^{-9}
70	2.15×10^{-8}

dried biological product were also decreased by heating at a temperature of 70°C and above (Kertész *et al.*, 2015; Ando *et al.*, 2014).

From Fig. 2, all plots exhibit a combination of incomplete semicircle in the higher frequency region and an inclined spike in the lower frequency region. The incomplete semicircle refers to the impedance effect inside the ginger tissue, which can also be described through an equivalent

circuit model. Following the simplified Hayden model as proposed by Ando *et al.* (2014), the Cole-Cole plot in Fig. 2 can be represented by a parallel combination of extracellular resistance (R_e) and a series connection of intracellular resistance (R_i) with cell membrane (C_m) (Fig. 2d). The inclined spike refers to the polarization phenomenon at the electrode surfaces, however, this effect can be ignored as it does not relate to the ginger cell structure (Ando *et al.*, 2014, 2019).

It can be observed from Fig. 2a, c that the diameter of the incomplete semicircle decreased with increasing drying time. The decreasing semicircle resulted in a decreasing impedance value, which is presumably due to the injury of the cell membrane during drying or when exposed to heat stress. Similar results were also reported by previous studies in heating pumpkin (Ando *et al.*, 2019) and potato slices (Ando *et al.*, 2014). However, during the final drying stage (Fig. 2b), the diameter of the semicircle is drastically increased. At this stage, the moisture level is
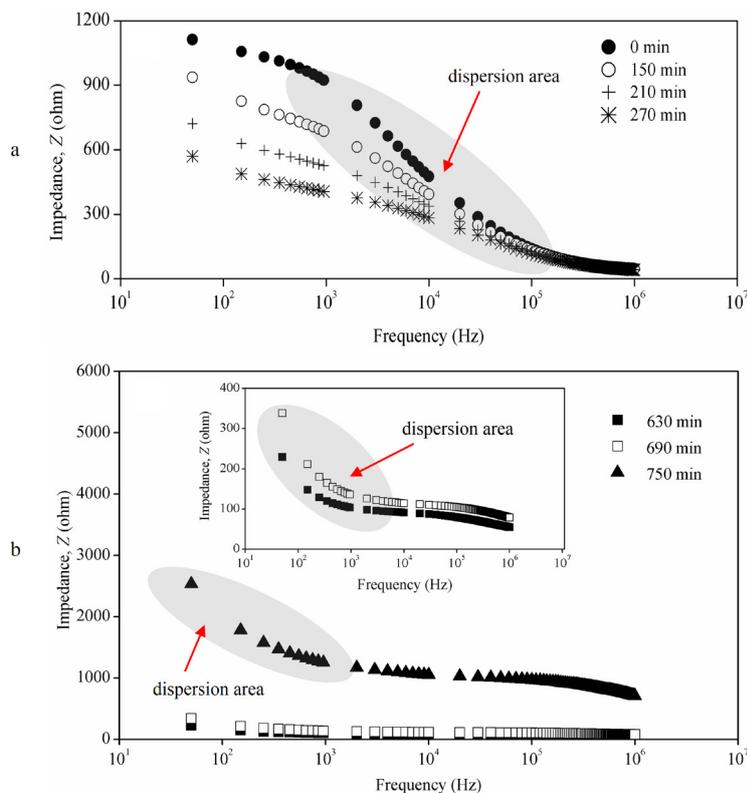
Fig. 3. Plot of impedance against frequency for fresh ginger slices during drying at 50°C. Impedance characteristic of the sample dried for: a) 0 – 270 min and b) 630 – 750 min. Inset of Fig. 3b represents the enlarged impedance plot for 630 – 690 min.

relatively low which implies that the water content gives a dominant effect on the impedance behaviour of the ginger slices. A further loss of moisture leads to a hardening of the cellular membrane and an increase in cell membrane capacitance, which will limit the activity of the free ion and also reduce the current path inside the ginger tissue. As a consequence, the impedance value becomes very high as the drying process continues (Liu, 2006; Islam *et al.*, 2019). Based on this analysis, it is suggested that the best impedance characteristic of ginger was occurred with a hot-air drying temperature at 50°C within the frequency range of 50 Hz and 1 MHz.

In order to further quantify the impedance characteristics of the dried ginger, the impedance value against frequency was plotted as depicted in Fig. 3. The plot in Fig. 3a shows a decrease in the impedance value as the frequency increased and it also exhibits a drastic drop between 10^3 and 10^5 Hz. A significant drop in impedance measurement reflects the ion flow or relaxation at a particular frequency range in biological tissue, and this phenomenon is known as dispersion (Bai *et al.*, 2018; Kuang and Nelson, 1998). Many types of dispersions have been proposed in the literature, the one that is observed in this study is the β-dispersion – which occurred due to cell interface polarization. The result is in accordance with the work reported by Ando *et al.*, (2014) who proposed a similar dispersion type when heating their potato sample in the early drying stage.

For the ginger dried from 630 – 750 min (Fig. 3b), the impedance value increased as the time increased and the dispersion area shifted to a lower frequency region ($< 10^3$ Hz). The shifting of the dispersion area indicates the changes in the electrical capacity of the drying ginger. The observed type of dispersion is termed the α-dispersion, it arises from the relaxation of the non-permanent dipole during ionic flows across the cell surface (Ando *et al.*, 2014; Bai *et al.*, 2018). The change in impedance value depends on the frequency of the applied electric field and this can be further described using the schematic diagram shown in Fig. 4 (Grossi and Riccò, 2017; Islam *et al.*, 2019). At low frequencies (Fig. 4a), the electrical current can only flow within the extracellular fluid due to high cellular membrane capacitance, this explains the rise in the impedance value.
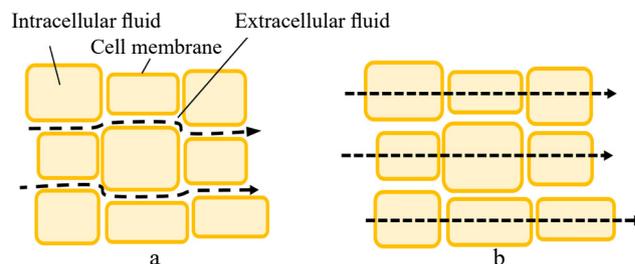

Fig. 4. Schematic diagram of the direction of electric current flow through ginger tissue in: a) lower frequency region and b) higher frequency region.

However, as the frequency increases, the current is able to penetrate more deeply into the cellular membrane and this allows the current to flow through the intracellular fluid (Fig. 4b). This results in a decreased impedance value. In this region, the total impedance is due to both intracellular and extracellular resistance. Due to these observations, it can be concluded that the changes in the impedance properties of ginger are affected by moisture content, temperature and frequency.

CONCLUSIONS

The drying kinetics and electrical impedance characteristics of ginger were studied at different drying temperatures (50, 60 and 70°C). The results can be summarized as follows:

1. The drying time decreased as the temperature increased. The modified Page model was successfully fit to the experimental data to describe the drying kinetics of ginger.

2. The ginger had the lowest effective diffusivity at a drying temperature of 50°C in comparison with 60 and 70°C, and this temperature was more appropriate for impedance analysis as it produced a slower water removal rate and induced fewer structural changes in the ginger.

3. The impedance plot at 50°C showed a decreasing trend during the early stage of drying, and started to increase as the drying rate decreased. In addition to that, the value of impedance is inversely proportional to the frequency.

4. The drying temperature, frequency and moisture content influenced the impedance characteristics of ginger.

5. The optimal drying temperature with which to study the impedance characteristics of ginger (specifically for a parallel-plate method) with the frequency ranging between 5 Hz and 1 MHz was at 50°C.

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