Rapid on-line non-destructive detection of the moisture content of corn ear by bioelectrical impedance spectroscopy

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Abstract: Moisture content of corn directly affects its quality and storage time, and the rapid on-line detection of the moisture content of corn ears not threshed or *in vivo* in the fields is required. Because of the special shape of corn ear, the rapid, low cost and non-destructive bioelectrical impedance measurement is more suitable for its moisture content detection. Using the four-electrode method with the Agilent E4980A precision LCR meter, the electrical impedance spectroscopies of the sweet corn ears and waxy corn ears at different moisture contents were acquired. The frequency range of the detection was from 20 Hz to 2 MHz and to enhance the contact, the attached-type electrodes were wrapped in cotton soaked with 0.1% NaCl solution. The impedance data over the frequency range from 300 Hz to 5 kHz were used to obtain the parameters of the bio-impedance Cole-Cole model. The results showed a good linear correlation (coefficient of determination R^2=0.960) between the equivalent parallel resistance R_∞ of sweet corn ear and the moisture content value determined by standard chemical method. The research proved that the bioelectrical impedance spectroscopy can be used for detecting the moisture content of corn ear.

Keywords: moisture content, non-destructive detection, bioelectrical impedance spectroscopy, corn ear
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1 Introduction

Moisture content is an important quality index of corn, which must be detected in the processes of its acquisition, storage, processing and transportation. With the continuous improvement of the automatic production level, there exists an increasingly higher demand for the rapidity and accuracy of the corn kernels moisture detection, especially the rapid on-line moisture detection of the corn ears which are not threshed or *in vivo* in the fields is required.

The researches on the rapid on-line moisture detection of corn kernels were focused on capacitance measurement[1-3] and microwave measurement[4-7]. Because of the special shape of corn ear, uneven surface, gaps between kernels and two-layered structure (the kernels and the cob), it is more difficult for its rapid on-line moisture detection using capacitance measurement or microwave measurement. With certain commercial handheld wood moisture meters, several researchers detected the moisture content of the corn ears *in vivo* in the fields using electrical impedance method[8,9]. Besides, the rapid, low cost and non-destructive bioelectrical impedance measurements had been widely developed in

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many research fields, e.g. determination of the composition content of plant tissues (leaves, roots, fruits, etc.)[10-12].

The aim of this work was to investigate the electrical properties of corn ear by bioelectrical impedance spectroscopy, and explore its relationship with the moisture content of total ear. Based on the study, we propose a rapid on-line non-destructive method to measure the moisture content of the corn ear not threshed or *in vivo* in the fields.

2 Bioelectrical impedance spectroscopy

Considering biological tissues with the amount of tissue fluid and the activity of cell membrane, the bioelectrical impedance acts as a complex circuit. In this resistance-capacitance circuit, the membranes, the extracellular fluid (ECF) and the intracellular fluid (ICF), which change obviously with the activity of tissue reduced, determine the electrical properties. Fricke took the biological tissue as the equivalent circuit as shown in Figure 1, in which R_e represents the resistance of the ECF, and R_i is the resistance of the ICF, and C_m shows the capacitance of the cell membranes[13].

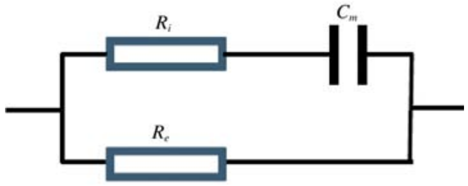
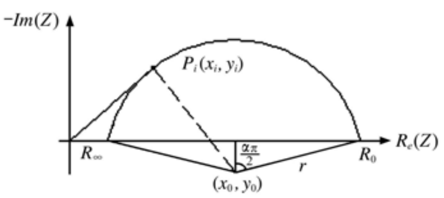


Figure 1 Equivalent circuit of biological tissue

Based on the previous research, Cole put forward that the bio-electrical impedance could be represented by a segment of circular arc in the complex plane, which is shown in Figure 2, and then Cole developed it as the Cole-Cole theory[13], in which the complex function used to describe the equivalent circuit model of biological tissue was derived for the first time.



Notes: Im(Z) is imaginary part of impedance, $R_e(Z)$ is real part of impedance. (x_0, y_0) represents the coordinates of midpoint. R_0 is the resistance at a frequency of zero and R_∞ is the resistance at infinite frequency. r is the radius of the circle. $P(x_i, y_i)$ is impedance at the frequency f_i. $\frac{\alpha\pi}{2}$ is an angle.

Figure 2 Cole plot for tissue

The bio-impedance can be described by Equation (1) and its parameters are given by Equation (2):

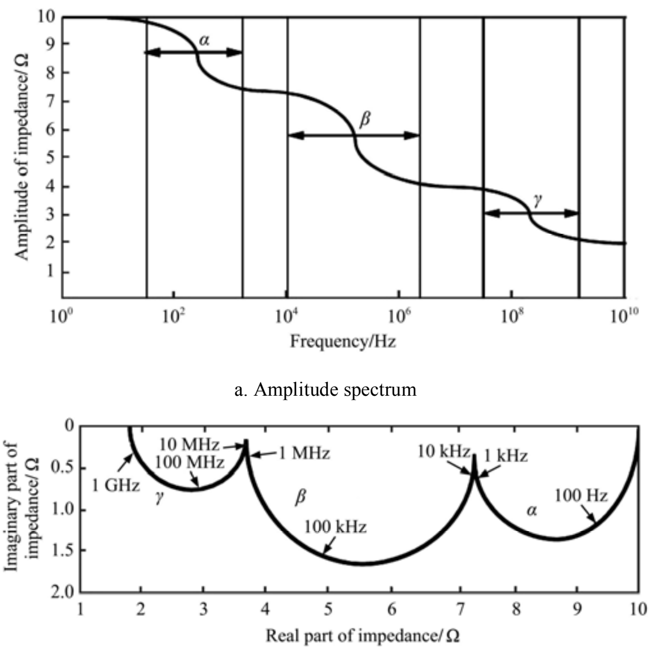
$$Z(\omega) = R_\infty + \frac{R_0 - R_\infty}{1 + (j\omega\tau)^\alpha} \tag{1}$$

$$\tau = (R_i + R_e)C_m;\quad R_0 = R_e;\quad R_\infty = \frac{R_i R_e}{R_i + R_e} \tag{2}$$

According to Zhang et al (2009)[14], using an iterative method, the midpoint (x_0, y_0) and radius r can be firstly derived, and then R_0, R_∞ and α can be obtained, and finally R_e, R_i and C_m can be calculated from the equations below:

$$R_i = \frac{R_0 R_\infty}{R_0 - R_\infty};\ R_e = R_0;\quad C_m = \frac{1}{2\pi f_0 (R_e + R_i)} \tag{3}$$

Schwan[13] proposed the dispersion theory, as is shown in Figure 3. The electrical properties of biological tissue obviously changes in the three different frequency bands, the α band, the β band and the γ band.



a. Amplitude spectrum

b. Nyquist diagram

Figure 3 Schematic diagram of dispersion theory

When a current flows through biological tissue, the current pathway depends on the source frequency. As is depicted in Figure 4, at low frequencies, the current is hardly able to pass through the cell membranes, so it crosses the ECF and the measured impedance value stands for the impedance of the ECF; And due to the various differences in the composition, construction and arrangement of the cells in tissue, the anisotropy of the current pathway is great; At high frequencies, the current is able to penetrate the cell, so it crosses not only the ECF but also the ICF and the measured impedance value stands for the impedance of both of them, and the anisotropy of the current pathway is little[15-17].

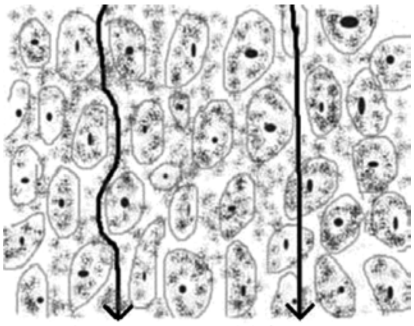


Figure 4 Schematic diagram of current pathway at low and high frequencies

3 Materials and methods

3.1 Experimental materials

The experimental materials were 20 sweet corn ears and 20 waxy corn ears, which were all bought from the same supermarket in Beijing. For the sweet corn ears, the average length, diameter, weight and moisture contents were (17.5±1.5) cm, (5.0±0.5) cm, (280.08±10) g and 71.07%-75.21%, respectively. And they were (14.5±1) cm, (5.0±0.5) cm, (240.91±10) g, and 61.55%-66.45% respectively for the waxy corn ears. All the corn ears were bought before the experiment, and they were detected after their husks were stripped. Moisture contents were measured by oven-drying method at 105°C for 24 h.

3.2 Instruments and equipment

E4980A Precision LCR Meter and 16048A Test Lead (Agilent Technologies Inc.-United States); DHG-9011A Heating and Drying Oven (Shanghai Jing Hong Laboratory Instrument Co., Ltd.); YP402N Electronic Balance (Shanghai Precision Instruments Co., Ltd.).

3.3 Impedance measurement

The impedance measurement of corn ear using four electrodes AC impedance method is shown in Figure 5. There are two pairs of probes used in the four-electrode measuring method[18]. The outside pair of probes provided the drive current and the inside pair of probes was used to measure the voltage. With the exciting probes and detecting probes separated, the detecting probes located in the area where the distribution of current was relatively uniform and a voltage amplifier with high input impedance was used. The contact resistance between the probes and the tissue and the polarization between the probes and the tissue fluid can be ignored.

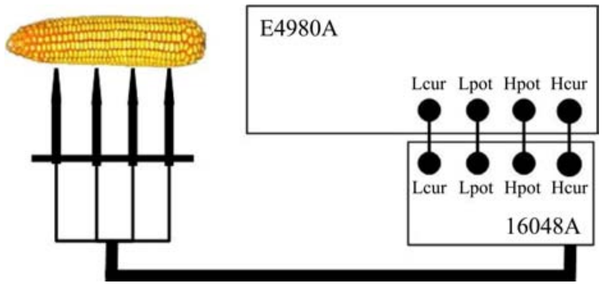
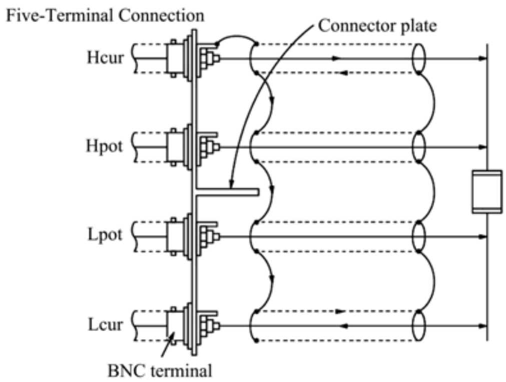


Figure 5 Schematic diagram of impedance detection of corn ear using four-electrode method

The 16048A test leads can extend the measurement port with a 4 terminal-pair configuration. It is provided with a BNC (Bayonet Nut Connector) female connector board to allow the attachment of user-fabricated test fixtures. According to the shielded five-terminal connection in the user's guide of Agilent E4980A precision LCR meter shown in Figure 6a, the user-fabricated test fixture shown in Figure 6b was made.

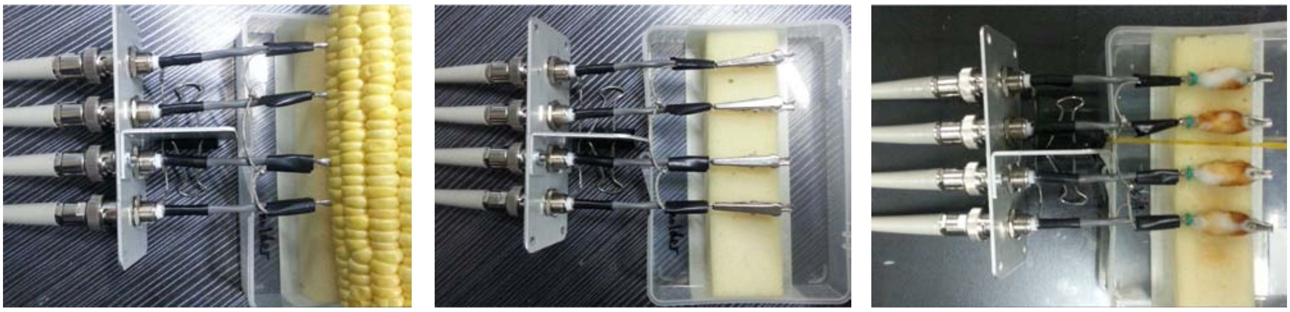


a. Schematic diagram

b. Real picture

Figure 6 User-fabricated test fixture based on the shielded five-terminal connection

Based on whether it is destructive or not, the contact types can be mainly classified into the inserted-type and the attached-type. In the inserted-type measurement shown in Figure 7a, the probes were inserted into the kernels of the corn ear and well contacted with the tissue fluid, so the contact impedance was very small; In the attached-type measurement shown in Figure 7b, the probes were attached to the testa of the corn kernels, whose major components are cellulose, hemicellulose and lignin, and badly contacted with the surface of the corn ear, so the contact impedance was large. As is shown in Figure 7c, with the probes wrapped in cotton soaked with 0.1% NaCl solution, the attached-type was modified and the contact was enhanced. In the study, the main contact type was the modified attached-type.



a. Inserted-type b. Attached-type c. Modified attached-type

Figure 7 Real pictures of different contact types

3.4 Data analysis

Data analysis was performed using Excel software (Version 2010). Firstly, the impedance data of corn ears in CSV format, measured with the E4980A precision LCR meter, were input into the Excel and then analyzed in the forms of spectrum of the real part, spectrum of the imaginary part and Cole plot; Secondly, using the LINEST function in Excel (using line regressions), the impedance data within a certain frequency range were applied to calculate the parameters of the bio-impedance Cole-Cole model; finally, using the least squares method, the relationship between the equivalent parallel resistance R_∞ of corn ear and the moisture content was investigated.

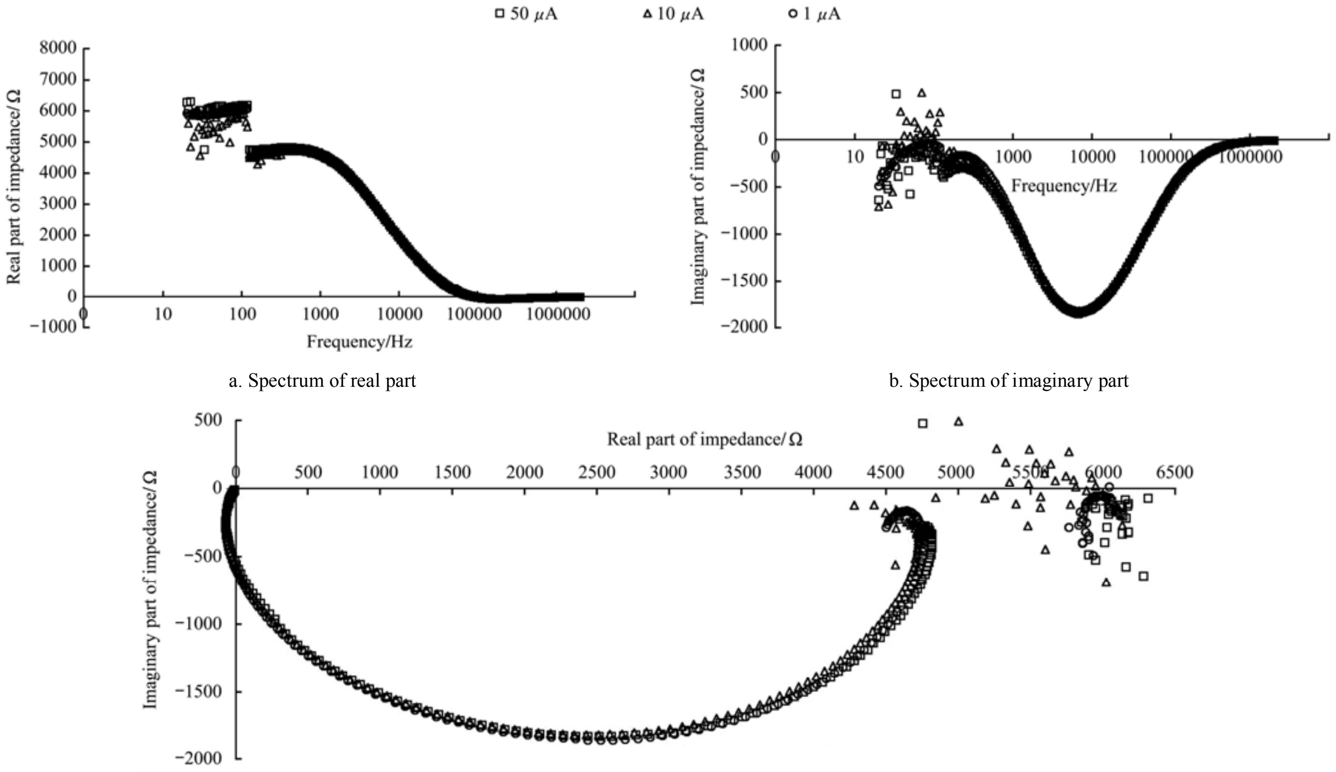
4 Results and discussion

4.1 Effects of different injected current levels on the impedance detection of corn ear

To investigate the effects of different injected current levels on the impedance detection of corn ear, at three different levels, 50 μA, 10 μA and 1 μA, the electrical impedance spectroscopies of 5 sweet corn ears and 5 waxy corn ears in the frequency range from 20 Hz to 2 MHz were acquired with the modified attached-type contact. The electrical impedance spectroscopies of the same waxy corn ear at the three injected current levels are shown in Figure 8. As the real part, imaginary part and Cole plot shown in Figure 8a-8c respectively, there were differences among the measurements at three different injected current levels in the range from 20 Hz to 300 Hz, and the differences were significant when the frequency was less than 100 Hz. At the same time, there were similar characteristics in the measurements of the same sweet corn ear under the same conditions above. The experimental result showed that at low frequencies below 300 Hz the result at lower injected current level is more stable, so lower injected current should be adopted in the impedance detection of corn ear.

4.2 Comparison of electrical impedance spectroscopies of sweet corn ear and waxy corn ear

To compare the electrical impedance spectroscopies of sweet corn ear and waxy corn ear, 5 sweet corn ears and 5 waxy corn ears were detected under the same conditions (the injected current level of 1 μA, the frequency range from 20 Hz to 2 MHz and the modified attached-type contact). The typical electrical impedance spectroscopies of sweet corn ear and waxy corn ear under the same conditions above are shown in Figure 9. In the spectrum of real part shown in Figure 9a, both of them had the same trend, but over the range from 100 Hz to 1 kHz and from 40 kHz to 100 kHz the real part values of the sweet corn ear were larger and in the latter range decreased more slowly with the increase of frequency; in the spectrum of imaginary part shown in Figure 9b, both of them also had the same trend, but the spectrum of the sweet corn ear had the less useful data point at frequencies less than lowest point and in the range above the frequency of the lowest point the imaginary parts of the sweet corn ear increased more slowly with the increase of frequency; In the Cole plot shown in Figure 9c, in the range below 300 Hz both of them were not in accordance with the Cole plot, but only the spectrum of sweet corn ear in the range above the frequency of its lowest point was not accordance with the Cole plot which it firstly tended to be a straight line, and then both of them had the same trend with the increase of frequency.

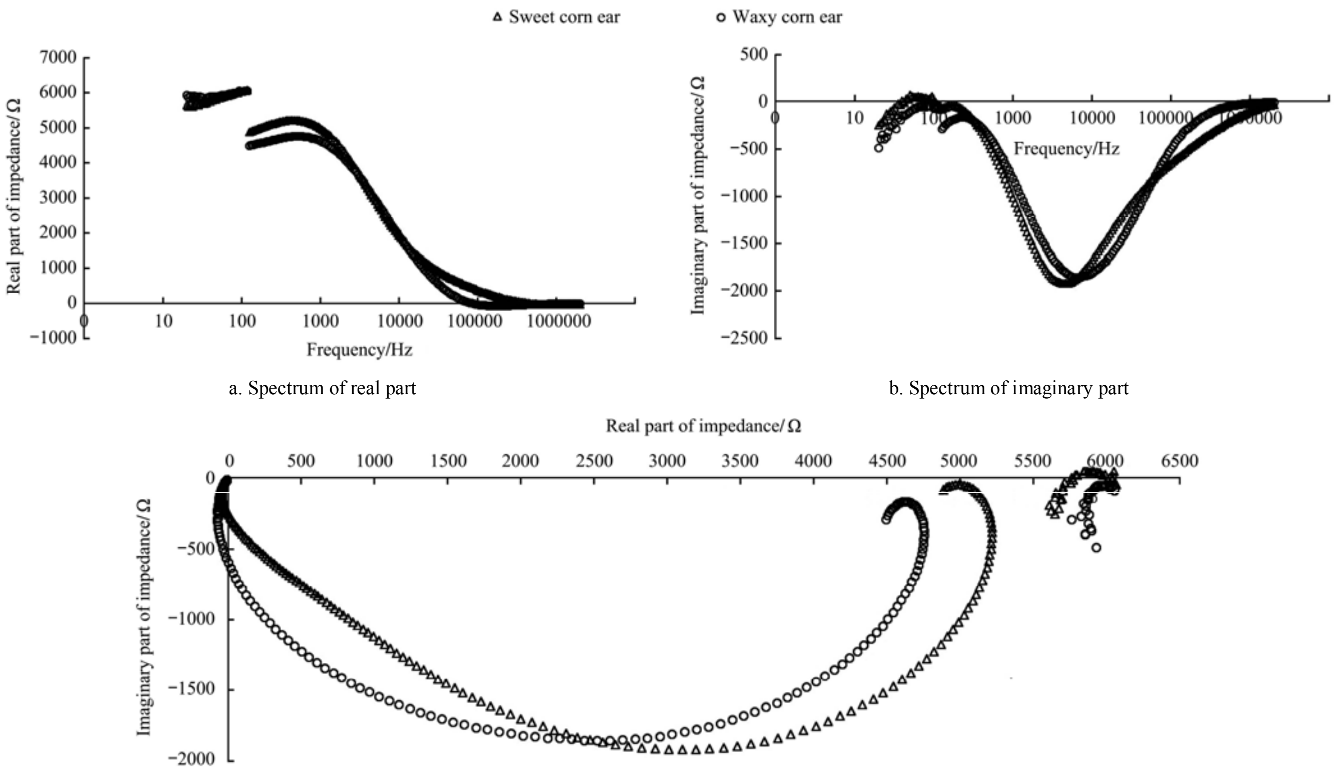


a. Spectrum of real part

b. Spectrum of imaginary part

c. Cole plot

Figure 8 Electrical impedance spectroscopies of the same waxy corn ear at three different injected current levels



a. Spectrum of real part

b. Spectrum of imaginary part

c. Cole plot

Figure 9 Electrical impedance spectroscopies of sweet corn ear and waxy corn ear. Triangle indicates sweet corn ear. Circle indicates waxy corn ear

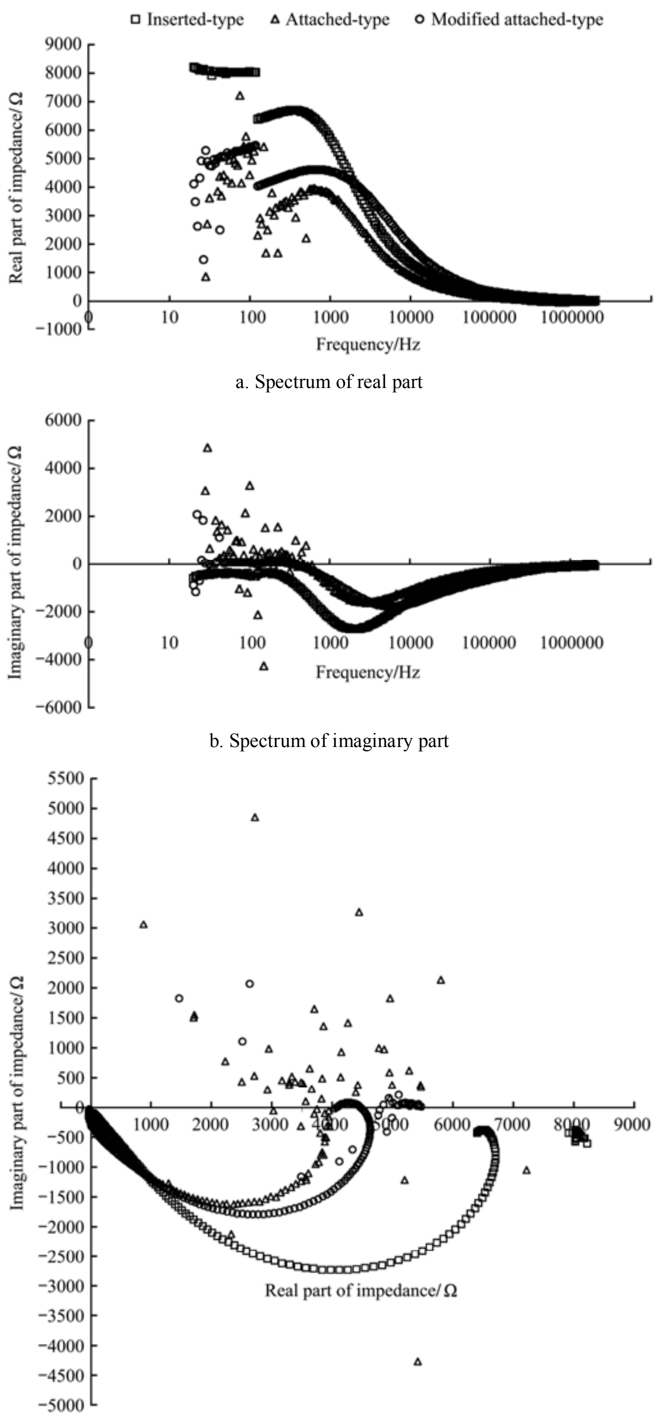
The experimental results showed that at low frequencies below 300 Hz the impedance data of both sweet corn ear and waxy corn ear should not be used to calculate the parameters of the bio-impedance Cole-Cole model and the impedance data of sweet corn ear in the range above the frequency of its lowest point are also not available, so only the impedance data of corn ear in the appropriate frequency range could be applied to calculating the parameters of bio-impedance.

4.3 Effects of different contact types on impedance detection of corn ear

To investigate the effects of different contact types on the impedance detection of corn ear, 5 sweet corn ears and 5 waxy corn ears were detected using the inserted-type contact, the attached-type contact and the modified attached-type contact. The injected current level was 1 μA and the frequency ranged from 20 Hz to 2 MHz. The electrical impedance spectroscopies of the same sweet corn ear using the three different contacts above are shown in Figure 10. As the real part, imaginary part and Cole plot shown in Figure 10a, Figure 10b and Figure 10c respectively, all of the three spectra had the same trend, but there were significant differences among them, and while the largest data using the plug-type contact were the most stable, the secondary data using the modified attached-type contact were less fluctuant than the least data using the attached-type contact. At the same time, there were similar characteristics in the measurements of the same waxy corn ear using the three different contacts above. The experimental result shows that there are differences among the data using the three different contacts, but all of them have the same trend, and while the largest data using the inserted-type contact are the most stable, the secondary data using the modified attached-type contact are less fluctuant than the least date using the attached-type contact, so the modified attached-type contact is available and better than the attached-type contact.

4.4 Relationship between the bioelectrical impedance spectroscopy of sweet corn ear and the moisture content

To investigate the relationship between the bioelectrical impedance spectroscopy of sweet corn ear and the moisture content, one sweet corn ear was dried in natural wind at temperature 22°C and relative humidity 35%, and its impedance spectroscopy was detected at 0 h, 24 h, 48 h and 72 h under the same conditions (the injected current level of 1 μA, the frequency range from 20 Hz to 2 MHz and the modified attached-type contact). The electrical impedance spectroscopies of the same sweet corn ear detected at the four times above are shown in Figure 11.

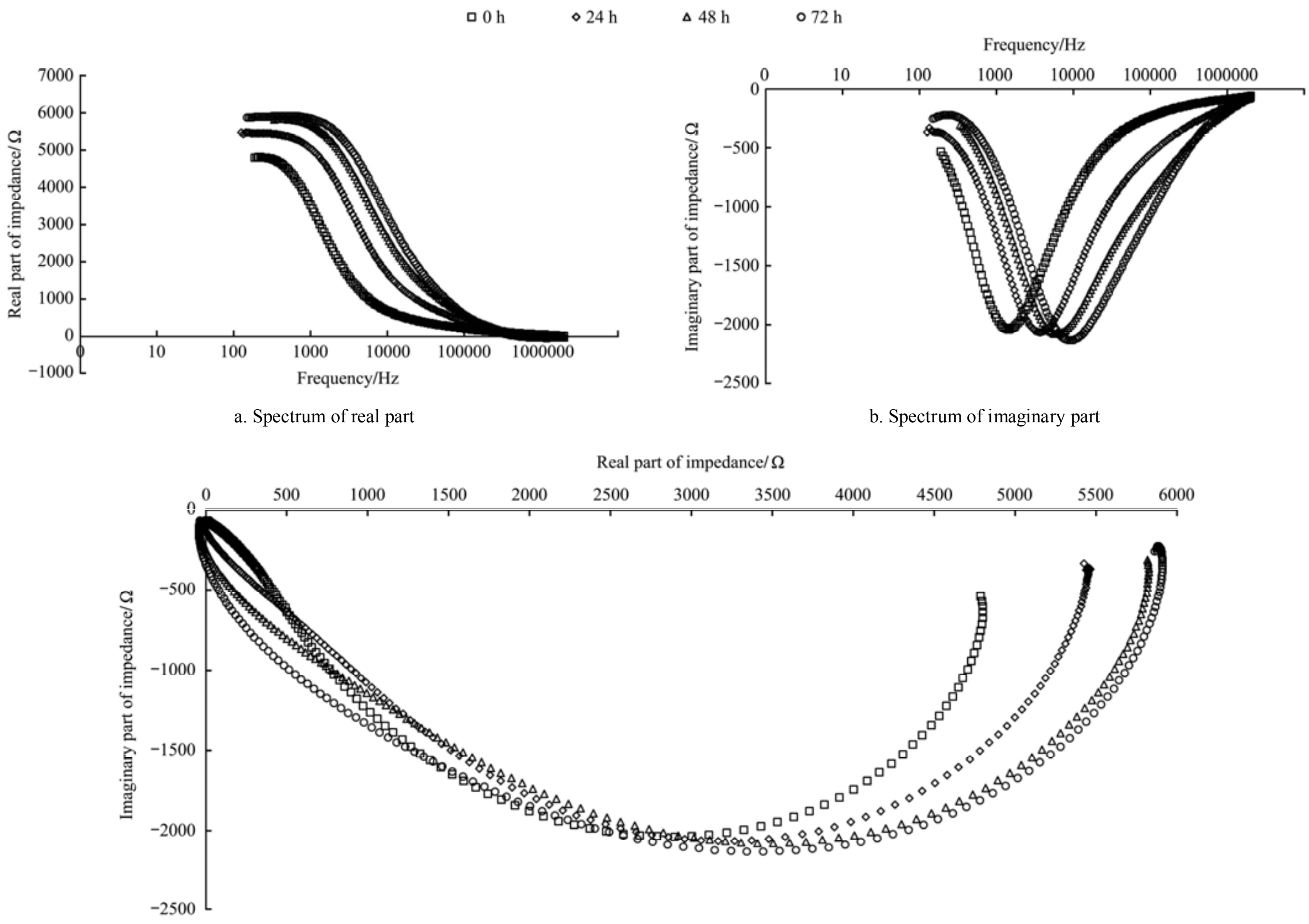


a. Spectrum of real part

b. Spectrum of imaginary part

c. Cole plot

Figure 10 Electrical impedance spectroscopies of sweet corn ear using three different contacts



a. Spectrum of real part

b. Spectrum of imaginary part

c. Cole plot

Figure 11 Electrical impedance spectroscopies of the same sweet corn ear detected at 0 h, 24 h, 48 h and 72 h during its natural withering

As shown in Figure 11a, in the range from 300 Hz to 100 kHz, the real parts were the least at 0 h and increased obviously with the decrease of the moisture content (the increase of the drying time); as shown in Figure 11b, the frequency of the lowest point was the least at 0 h and increased obviously with the decrease of the moisture content; as shown in Figure 11c, while the spectrums at high frequencies above the frequency of their respective lowest points were not in accordance with the Cole plot and as for their trend there were significant differences, the spectrums at low frequencies below the frequency of their respective lowest points (from 300 Hz to 5 kHz) were well in accordance with the Cole plot and the spectrum continued to shift to the right with the decrease of the moisture content. The experimental result shows that the bioelectrical impedance spectroscopy of the same sweet corn ear changes obviously and regularly with the decrease of its moisture content and the impedance data in the range from 300 Hz to 5 kHz are more suitable for calculating the parameters of bio-impedance.

In addition, another sweet corn ear was dried using the DHG-9011A heating and drying oven at temperature 50°C and both its impedance spectroscopy and weight were measured for 5 times during the drying process. The measurement at each time was conducted after the temperature of the corn ear dropped to the room temperature and the conditions of the impedance detection were the injected current level of 1 μA, the frequency range from 20 Hz to 2 MHz and the modified attached-type contact. The moisture content at each time was calculated using the weight and the dry weight of the corn ear measured by oven-drying it at 105°C for 24 hours, and the parameter R_∞ at each time was calculated using the impedance data in the range from 300 Hz to 5 kHz. As shown in Figure 12, the experimental result shows that there is a good linear correlation (coefficient of determination R^2=0.960) between the equivalent parallel resistance R_∞ of sweet corn ear and the moisture content value.

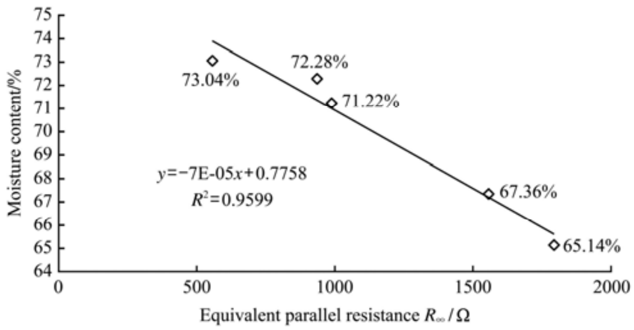


Figure 12 Relationship between the equivalent parallel resistance R_∞ of sweet corn ear and the moisture content value

5 Conclusions

The electrical impedance spectroscopies of the sweet corn ears and waxy corn ears at different moisture contents were acquired using the four-electrode method with the Agilent E4980A precision LCR meter. The frequency range of the detection was from 20 Hz to 2 MHz and to enhance the contact, the attached-type electrodes were wrapped in cotton soaked with 0.1% NaCl solution. The impedance data over the frequency range from 300 Hz to 5 kHz were used to obtain the parameters of the bio-impedance Cole-Cole model, and the results show that there is a good linear correlation (coefficient of determination R^2=0.960) between the equivalent parallel resistance R_∞ of sweet corn ear and the moisture content value determined by standard chemical method. The results show that the bioelectrical impedance spectroscopy could be used for detecting the moisture content of corn ear.

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