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Contact Impedance Measurements Using Compound Electrodes from Electrical Impedance Spectroscopy (EIS) Study During Banana Ripening

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Abstract: In this study, electrode contact impedances and their effects on the measurement have been studied in a fruit impedance measurement system using Electrical Impedance Spectroscopy (EIS). The EIS study has been conducted on the banana samples during their ripening and the variation of contact impedance with frequency at different ripening state has been observed. The contact impedance under each electrode has been calculated by using compound electrodes developed from stainless steel sheets and the effect of the contact impedance on the measurement accuracy has been studied. The total contact impedance has been computed by comparing electrical impedance of banana obtained with two terminal and four terminal method using the compound electrodes consisting of current and voltage electrodes concentrically placed on banana surface. It is found that banana impedance obtained with two terminal method is higher in magnitude than the four terminal method with compound electrodes. It is also found that the contact impedance under each electrode is maximum at low frequency and minimum at high frequency.

Key words: Electrical Impedance Spectroscopy (EIS), skin contact impedance, compound electrodes, fruit ripening, frequency, measurement

INTRODUCTION

The electrical impedance of biological tissue called electrical bioimpedance or bioelectrical impedance, (Ackman and Seitz, 1984; Lukaski *et al*., 1985; Orjan and Grimnes, 2011; Kanti, 2014; Bera and Nagaraju, 2013) varies with the tissue composition and the frequency (ω) of the electrical signal applied for impedance measurement (Kanti, 2014). The Electrical Impedance Spectroscopy (EIS) (Macdonald, 1992; Macdonald and Johnson, 2005; Orazem and Tribollet, 2008; Zhang *et al*., 2014; Barsoukov and Macdonald, 2005) measures and analyzes the variation of electrical impedance of an object by injecting an electrical signal at different frequencies to characterize the material composition of the object under test. Therefore, EIS has been applied in material engineering (Tai *et al*., 2017; Bera *et al*., 2014; Morrison *et al*., 2001; Moisala *et al*., 2006), electrical and electronic engineering (Bera and Nagaraju, 2011a; Glatthaar *et al*., 2007; West *et al*., 1997; Lanfredi *et al*., 2002), mechanical engineering (Bonora *et al*., 1996; Song and Xiao, 2003), chemical engineering (Kendig and Scully, 1990; Murray and Moran, 1989), civil engineering (Christensen *et al*., 1994; Park *et al*., 2000), aerospace engineering (Pohl *et al*., 2001; Almuhammadi *et al*., 2017) and other fields of engineering, technologies and applied science (Wang *et al*., 2001; He *et al*., 2007). Due to its several advantages, EIS has widely been used in the field of biomedical engineering (Bera *et al*., 2013; Bera and Nagaraju, 2011; Bera *et al*., 2016a-c; Chakraborty *et al*., 2015; Sammer *et al*., 2014; Ruiz *et al*., 2014; Birgersson *et al*., 2012; Rothlingshofer *et al*., 2011; Dean *et al*., 2008) for non-invasive tissue characterization, health monitoring and disease diagnosis. Also, the EIS has been regarded as a useful diagnostic tools to study electrical impedance of the fruits (Varlan and Sansen, 1996; Ross *et al*., 1960; Bauchot *et al*., 2000; Harker and Forbes, 1997; Harker and Dunlop, 1994; Harker and Maindonald, 1994; Jackson and Harker, 2000; Juansah *et al*., 2012; Vozary *et al*., 1999; Chowdhury *et al*., 2015; Chowdhury *et al*., 2017a, b; Caravia *et al*., 2015; Brady, 1987; Fang *et al*., 2007; Euring *et al*., 2011; Amoros *et al*., 2003; Inaba *et al*., 1995) and vegetables (Repo *et al*., 2002; Wu *et al*., 2008; Zhang and Willison, 1990; Bera *et al*., 2016a-c; Hayden *et al*., 1969; Ando *et al*., 2014; Zhang and Willison, 1991; Azzarello *et al*., 2006; Zhang and Willison, 1992). Apart from the fruits and vegetables, plant

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physiology and the different plant parts are studied (Azzarello *et al*., 2006; Zhang and Willison, 1992; Laarabi, 2014; Lafontaine and Bajazet, 2005) such as root (Azzarello *et al*., 2006; Zhang and Willison, 1992; Laarabi, 2014; Lafontaine and Bajazet, 2005; Vozary *et al*., 2011; Cao *et al*., 2011), steam (Mizukami *et al*., 2006; Repo *et al*., 2004) and leaves (Vainola and Repo, 2000; Zhang *et al*., 2002). Bio-impedance measurement such as EIS has widely been applied in fruits and vegetables to assess the maturity, freshness or food quality. The fruit impedance is studied with EIS to asses its electrical properties (Varlan and Sansen, 1996; Ross *et al*., 1960; Bauchot *et al*., 2000; Harker and Forbes, 1997; Harker and Dunlop, 1994; Harker and Maindonald, 1994; Jackson and Harker, 2000; Juansah *et al*., 2012; Vozary *et al*., 1999; Chowdhury *et al*., 2015; Chowdhury *et al*., 2017a, b; Caravia *et al*., 2015; Brady, 1987; Fang *et al*., 2007; Euring *et al*., 2011; Amoros *et al*., 2003; Inaba *et al*., 1995) to characterize the tissue physiology to evaluate the ripening status, nutrients value and freshness. The plant tissues are alo been studied and assessed to detect and characterize tissue age, disease and various injuries caused by heat, cold and frost (Varlan and Sansen, 1996; Xing, 2006; Repo *et al*., 2002 Borges *et al*., 2013).

Being a non-invasive technique, the EIS needs surface electrodes (Kanti, 2014; Bera *et al*., 2016a-c; Bera and Nagaraju, 2014a, b, 2015; John, 2009) to interface the impedance measuring instrumentation and the sample under test. Therefore, the surface electrodes used to create electrical contacts develops an electrode-skin interface which produces contact impedance (Hua *et al*., 1993; Hwang *et al*., 1997; Alistair and Adler, 2011; Cardu *et al*., 2012). The contact impedance, produces measurement errors which may significantly reduce the measurement accuracy. Sometimes highly conducting medium such as electrolyte or conducting gel is applied between the electrode surface and the object surface to reduce the contact impedance. Poor or uneven contact develops large contact impedance producing more measurement errors. The contact impedance also depends on the frequency of the applied signal and hence, the measurement errors varies with the frequency. The contact area, contact quality and the contact impedance also depend on the sample under test and measuring electrode geometry and other electrode properties. Therefore, a detail study on the electrode sample interface and the contact impedance is essential to understand the contact impedance behavior and the assess the measurement accuracy variations with frequency. EIS has been found an effective tool for studying the fruit ripening analysis (Ross *et al*., 1960; Harker and Forbes, 1997; Harker and Dunlop, 1994; Harker and Maindonald, 1994; Chowdhury *et al*., 2015; Chowdhury *et al*., 2017a, b; Caravia *et al*., 2015; Brady, 1987; Amoros *et al*., 2003). The surface electrodes are placed on the fruit surface with the help of some sticky tape or foam facilitating the suitable contact between the electrodes and the fruit sample. The electrodes with or without gel produces contact impedance which varies from the sample to sample and also with the applied signal frequency.

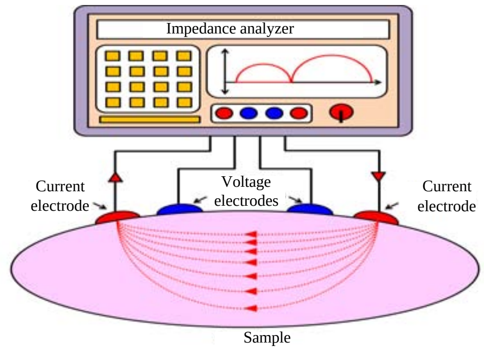

Fig. 1: Electrical Impedance Spectroscopy (EIS) studies on a sample using an impedance analyzer

The contact impedance also influence the internal current density distribution is effected by the contact impedance. The effect of the contact impedance is minimized using four electrode method (Kanti, 2014; Bera *et al*., 2016a-c; Chowdhury *et al*., 2015; Sone *et al*., 1996; Plonsey and Barr, 1982) in which two separate sets of electrodes are used for current injection and voltage measurement. Compound electrodes (Woo *et al*., 1992; Hua *et al*., 1993; Wang *et al*., 2001) are sometimes used for impedance measurement with four electrode method to eliminate the contact impedance problem. Using a compound electrode system contact impedance could be easily studied by measuring the electrical impedance with two and four electrode method simply changing the wire connections for current electrode and voltage electrodes. In this study, the EIS studies have been conducted with the compound electrode used for measuring and analyzing the contact impedance of banana during its different ripening states. The amplitude, phase angle, real part and imaginary parts of the banana impedance are measured and studied. The contact impedance is calculated and the frequency response of the contact impedance has been analysed (Fig. 1).

MATERIALS AND METHODS

Introduction to bio-impedance and fruit impedance: The opposition of the biological tissues to the flow of an alternating current under an alternating electric field is termed as the electrical bioimpedance or bioelectrical impedance (Ackman and Seitz, 1984; Lukaski *et al*., 1985;

Orjan and Grimnes, 2011; Kanti, 2014; Bera and Nagaraju, 2013). The impedance of biological tissue originates from the current flowing through extracellular fluids, cell membrane and Intracellular Fluids (ICF) (Kanti, 2014; Bera *et al*., 2016a-c; Loan *et al*., 1993) at various frequencies. The intracellular fluid and Extra Cellular Fluid (ECF) (Kanti, 2014; Bera *et al*., 2016a-c; Loan *et al*., 1993) are separated by cell membranes. The cell membrane produces cell membrane capacitance ($C_{membrane}$) which provides some capacitive reactance (Kanti, 2014; Bera *et al*., 2016a-c) under an alternating electrical excitation. Thus, the Cell membranes of biological tissue produce a frequency dependent capacitive reactances ($1/j\omega C_{membrane}$) as a result of an alternating current or voltage application where as intracellular and extracellular fluids provide resistive properties. At low frequency, the magnitude of the capacitive reactance becomes large and hence the current signal flows through the extracellular fluids but as the frequency increases, the capacitive reactance reduces and the current flows through the cell membrane also (Kanti, 2014; Bera *et al*., 2016a-c; Loan *et al*., 1993). Thus, at high frequency, alternating current can penetrate the cell membrane and hence it flows through the intracellular and extracellular fluids. Thus, information about the properties of various parts of biological tissue during current movement at different frequencies is obtained by EIS studies (Loan *et al*., 1993; Fraczek *et al*., 2016).

In EIS technique applied for bioimpedance measurement, the complex electrical impedance of the biological tissue sample is generally, measured by injecting a constant amplitude electrical current signal (I_{sample}) to the sample at different frequencies ($\omega = 2\pi f$) and measuring the developed potential data (V_{sample}) on the sample surface at every frequency points. The frequency dependent complex impedance (Z_{sample}) of a biological sample can be expressed as:

$$Z_{sample}(\omega) = \frac{V_{sample}(\omega)}{I_{sample}(\omega)} \quad (1)$$

Fruit-impedance measurement instrumentation: Electrical impedance of an object could be measured either by injecting a constant amplitude current signal and measuring the developed potential. The current injection and the voltage measurement could be performed either a two electrode method or the four electrode method. The two electrode method (Kanti, 2014; Bera *et al*., 2016a-c; Fraczek *et al*., 2016; Boulier *et al*., 1990) employs two electrodes through which current injection and voltage measurement both are performed. But in four electrode method (Kanti, 2014; Bera *et al*., 2016a-c; Chowdhury *et al*., 2015; Sone *et al*., 1996; Plonsey and Barr, 1982) the current injection and voltage measurement are conducted with two separate pair of electrodes. The electrodes through which the current signal injected are called the current electrodes (Kanti, 2014; Bera *et al*., 2016a-c) and the voltage electrodes (Kanti, 2014; Bera *et al*., 2016a-c) are the electrodes across which the developed potential is measured. In EIS, the current injection is performed with a constant current source and the voltage data are measured with a voltmeter or a data acquisition system. Modern impedance analyzers are equipped with the constant current signal generator and the voltage measuring systems within it and hence directly provide the impedance data at different frequencies.

Measurement of bio-electrical impedance of fruits can be conducted with a two probe method or two electrode method as well as four probe method or four electrode method. In two electrode method only two electrodes are used for impedance measurement and current injection and voltage measurement are performed using the same pair of electrodes and hence it is called the two probe method. In four probe method, four electrodes (two pairs of electrodes) are used: one pair for current injection and the other pair for voltage measurement, thus, the method is called the four electrode method.

As shown in Fig. 2a, in four electrode method four electrodes are used for voltage-current data collection: two electrodes are used for current injection and other two are used for voltage measurement. As the voltage electrodes carry a very little amount of current, the voltage drop across the contact impedances of the voltage electrodes are found negligible and the estimated impedance data are almost equal to the sample impedance. On the other hand, in the two electrode method (Fig. 2b) uses only one pair of electrodes which is used both for current injection and voltage measurement and hence the contact impedance of the electrodes comes across the voltage measurement circuit and the voltmeter reading

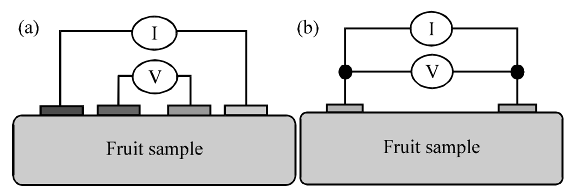

Fig. 2: Electrical Impedance Spectroscopy (EIS) with four and two electrode methods: a) Four electrode method and b) Two electrode method

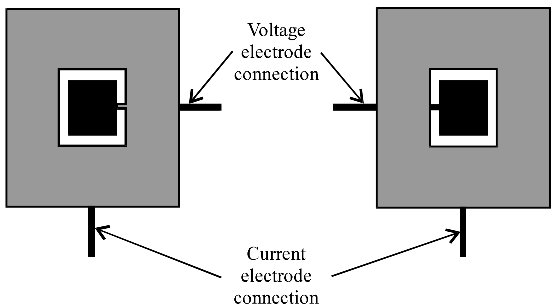

Fig. 3: Compound electrodes for EIS studies

includes the voltage drops across the electrode contact impedances which misleads us in estimating the actual sample impedance.

Impedance measurement with compound electrodes: About 4 terminal electrical impedance measurement can be performed with non-compound and compound electrodes (Woo *et al*., 1992; Hua *et al*., 1993; Wang *et al*., 2006). In noncompound electrode geometry four electrodes are required for four electrode based measurement whereas in compound electrode geometry only two compound electrodes are required for four electrode method because a single compound electrode consists of a current electrode and a voltage electrode within it (Fig. 3). Thus four electrode method needs only two compound electrodes as shown in Fig. 3. It is to be noted that, using compound electrode the four electrode configuration can be implemented within a small or specified sample dimension. In compound electrodes arrangement, voltage electrodes are made very small and current electrodes are made larger.

As shown in Fig. 3, compound electrodes are developed with two concentric electrodes which are electrically insulated from each other and performs the function of current and voltage electrodes. The outer electrode or the electrode with larger area is used for current injection whereas the inner or smaller electrode is used for voltage measurement.

The compound electrodes are made from square shaped stainless steel sheets (type 304) of 50 μ thickness (Fig. 4). The larger current electrodes are made up of a 35×35 mm^2 shaped stainless steel sheet whereas the voltage electrodes are made up of 10×10 mm^2 shaped stainless steel sheet. The 10×10 mm^2 shaped area of the voltage electrode center is removed to make a squared shaped hole. Thus, the current electrode and the voltage electrodes are electrically separated or isolated by an air gap of thickness 2.5 mm (Fig. 4). As a result, each of these compound electrodes consists of larger squared shaped

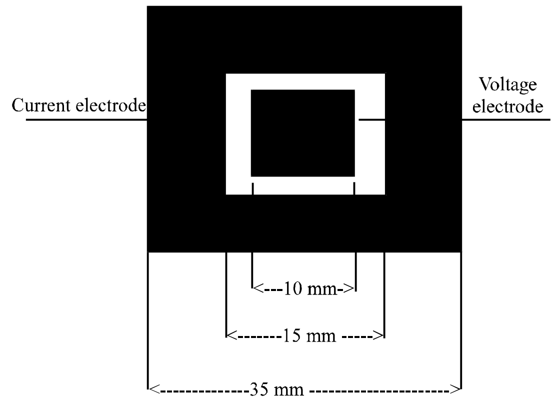

Fig. 4: Geometry of the compound electrode developed from stainless steel sheet

current electrodes with a squared hole inside which the voltage electrode (10×10 mm) is placed. Thus, the effective current electrode area is found as 1000 m^2 (1225-225 m^2).

The skin property of fruits and vegetables changes with ripening and storage period which in turn changes the contact impedance. As the contact impedance is frequency dependent, contact impedance can be calculated over a wide range of frequencies and can be studied to calculate the accurate fruit impedance over the entire frequency band chosen for the EIS. Any change in contact impedance either due to the sample skin physiology or the frequency dependent variation, will influence the impedance response of the fruits and vegetables during EIS study.

Contact impedance calculation for fruits: The effect of contact impedance can be minimized using four electrode method. Comparing the impedance measured with two electrode and four electrode method the contact impedance can also be calculated. In the present study, compound electrodes are developed with stainless steel sheets and used for measuring the electrical impedance of the fruit. Using two electrode and four electrode method the impedances with two electrode method (Z_{2E}) and impedance with four electrode method (Z_{4E}) have been calculated. Subtracting Z_{4E} from Z_{2E} the contact impedance ($Z_{contact}$) is calculated. The difference between the Z_{2E} and Z_{4E} (Z_{2E}-Z_{4E}) gives the total contact impedance (Z_T), i.e., the sum of the contact impedances of two electrodes. Therefore, the half of the total contact impedance ($Z_T/2$) will be found as the contact impedance of a single electrode.

Using the developed compound electrodes, the four electrode based impedance is measured by injecting current through the outer electrodes (larger electrodes) and measuring the voltage across the inner electrodes (smaller electrodes). On the other hand with the same compound electrode array, the two electrode based impedance measurement is conducted by injecting current through the inner electrodes (smaller electrodes) and measuring the voltage across the same electrodes (inner or smaller electrodes). For the present studies, the electrical impedance of banana [Z_{banana} (ω)] during its ripening has been measured with two terminal and four terminal method using the compound electrodes and the variation of impedance with different ripening stage have been observed. The total contact impedance ($Z_T = Z_{contact}$) has been calculated by comparing electrical impedance values obtained with four terminal (Z_{4E}) and two terminal (Z_{2E}) and then dividing the total contact impedance ($Z_{contact}$) by 2, contact impedance of single electrode ($Z_{contact}/2$) is obtained.

Two compound electrodes are placed on a sample under test and the current is injected through the outer electrodes and the voltage is measured between the smaller electrodes to calculate the electrical impedance. Thus using these compound electrodes the fruit bioimpedance is measured with four electrodes electrode configuration and the results are saved as Z_{4E}. Using the inner electrodes both for current injection and voltage measurement the impedance data are saved as Z_{2E}. The impedance amplitude and phase angle for both Z_{2E} and Z_{2E} are collected and the real and imaginary parts are estimated for both the two electrode and four electrode based measurement strategies.

The research conducted on compound electrodes is limited (Woo *et al*., 1992; Hua *et al*., 1993; Wang *et al*., 2006). The fruit contact impedance analysis is required to be explored more for better fruit characterization the method for estimation of contact impedance during EIS studies of fruits and vegetables. In this direction, contact impedance measurement has been performed during banana ripening by developing compound electrodes from stainless steel sheet material as discussed above. The compound electrodes are used for banana impedance measurement and its contact impedance estimation. The compound electrodes developed with the stainless steel sheets are found suitable for banana impedance analysis, contact impedance analysis and the bio-impedance measurement for other fruits and vegetables.

Skin electrolyte electrode model: Surface electrodes play an important role in complex bio-impedance measurement techniques such as EIS or else. They act as an interfacing medium between biological tissue and measurement set up and hence, sometimes they are called the sensors. Electrodes are used to create electrical contact with the skin of biological tissue through electrolyte medium (such as conducting gel used for physiological measurements in clinics and hospitals). Electrode gel containing ions acts as a chemical interface between skin and the electrode and ensures good electrical contacts between electrode and skin and reduces the skin-electrode contact impedance (Hua *et al*., 1993; Hwang *et al*., 1997; Alistair and Adler, 2011; Cardu *et al*., 2012; Scott, 2002). The conversion from ionic current to electric current is taken place at the electrode-electrolyte junction. There is low electrode polarization impedance (Mirtaheri *et al*., 2005) for the electrode with large metal-electrolyte interface area.

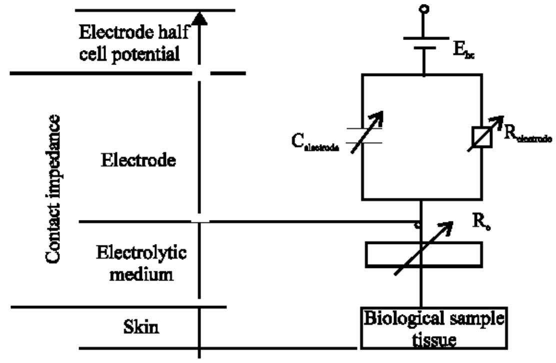

Fig. 5: Equivalent model of skin-electrolyte-electrode junction

The simplified equivalent circuit model of skin-electrolyte-electrode junction (John, 2009; Alper *et al*., 2013; Meziane *et al*., 2013) can be found as the following circuit as shown in Fig. 5. In the equivalent circuit shown in Fig. 5, the contact impedance is found to be developed with the electrode impedance and the impedance of the electrolytic medium (electrode skin interface impedance) which is denoted by the resistor (R_{el}). The R_{el} is connected in series with the equivalent electrode impedance which is a parallel combination of a resistance ($R_{electrode}$) and capacitance ($C_{electrode}$). The entire equivalent circuit model is found with a voltage source representing the half-cell potential (John, 2009; Alper *et al*., 2013; Meziane *et al*., 2013) as shown in Fig. 5. In the above circuit, electrode half-cell potential is denoted by E_{hc} and the electrode impedance ($Z_{electrode}$) is found as:

$$Z_{electrode} = R_{electrode} || \frac{1}{j\omega C_{electrode}} \quad (2)$$

In the electrode-electrolytic medium, the metallic part of the electrode is in contact with electrolytic medium represented by a series resistance R_{el}.

R_{el} is defined as the resistance of electrolytic medium, i.e., resitance between electrode-electrolyte interface. As a result, electron ion-electrolyte ion orientation occurs which in turn produce half cell potential at the electrode-electrolyte junction. The total impedance is:

$$Z_{Total} = Z_{skin} + Z_{contact} \tag{3}$$

The contact impedance ($Z_{contact}$) at electrode-electrolyte junction can be expressed as:

$$Z_{contact} = R_{el} + \left(R_{electrode} \| \frac{1}{j\omega C_{electrode}} \right) \tag{4}$$

$$Z_{contact} = R_{el} + \frac{R_{electrode}}{1+j\omega R_{electrode} C_{electrode}} = R_{el} + \frac{R_{electrode} - j\omega (R_{electrode})^2 C_{electrode}}{1+\omega^2 (R_{electrode} C_{electrode})^2}$$

$$= \frac{R_{el}\left[1+\omega^2 (R_{electrode} C_{electrode})^2\right] + R_{electrode}}{1+\omega^2 (R_{electrode} C_{electrode})^2} - \frac{j\omega (R_{electrode})^2 C_{electrode}}{1+\omega^2 (R_{electrode} C_{electrode})^2} = \left(R_{el} + \frac{R_{electrode}}{1+\omega^2 (R_{electrode} C_{electrode})^2} \right) - j\frac{\omega (R_{electrode})^2 C_{electrode}}{1+\omega^2 (R_{electrode} C_{electrode})^2}$$

$$Z_{contact} = \text{Real}\{Z_{contact}(\omega)\} - j\text{Imaginary}\{Z_{contact}(\omega)\} \tag{5}$$

Where:

$$\text{Real}\{Z_{contact}(\omega)\} = \left(R_{el} + \frac{R_{electrode}}{1+\omega^2 (R_{electrode} C_{electrode})^2} \right) \tag{6}$$

And:

$$\text{Imaginary}\{Z_{contact}(\omega)\} = \frac{\omega (R_{electrode})^2 C_{electrode}}{1+\omega^2 (R_{electrode} C_{electrode})^2} \tag{7}$$

Contact impedance measurement of banana samples: The EIS experiments for banana impedance measurement were performed on a matured banana samples for continuous 5 days. Banana was collected from the market and stored at room temperature. Banana samples were cleaned thoroughly with normal water and then with distilled water for removing the dusts and other materials. Compound electrodes developed from stainless steel sheets are attached to banana surface through electrolytic gel to ensure good electrical contact between skin of the banana and electrodes. Compound electrodes are firmly placed with sticky tape to ensure the fixed attachement with the banana smaples. Impedance measurement of banana samples were conducted during ripening with two terminal method (Fig. 6) and four terminal method (Fig. 7) using KeySight impedance analyser (4294 A). Banana impedances were measured at 100 frequency point from 50 Hz to 2 MHz by injecting 1 mA sinusoidal through the compound electrodes attached to the banana samples. The impedance data are collected from the sample both for the two electrodes and four electrode method and two sets of data are collected: banana impedance measured with four electrode method ($Z_{4Ebanana}$) and the banana impedance measured with two electrode method ($Z_{2Ebanana}$). The result obtained with four terminal method ($Z_{4Ebanana}$) is then subtracted from two terminal method ($Z_{2Ebanana}$) to calculate the total contact impedance ($Z_{Tbanana} = Z_{2Ebanana} - Z_{4Ebanana}$). The total contact impedance ($Z_{tbanana}$) is then divided by 2 to get the contact impedance for single electrode. Thus, the contact impedance of each electrode is found as $(Z_{2Ebanana} - Z_{4Ebanana})/2$.

Fig. 6: Schematic of the impedance measurement with two electrode method using compound electrodes developed

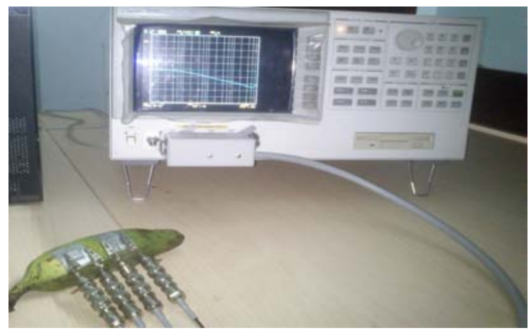

Fig. 7: Schematic of the impedance measurement with four electrode method using compound electrodes developed

RESULTS AND DISCUSSION

The banana impedance is estimated from EIS studies conducted with two terminal and four terminal method using compound electrodes. The banana impedance measured with two electrode method ($Z_{2Ebanana}$) and four electrode method ($Z_{4Ebanana}$) are presented in Fig. 8 and 9, respectively. The contact impedance of each electrode obtained after comparing banana impedances measured with two terminal and four terminal method is also presented in Fig 10.

It is seen from Fig. 8 and 9, that the banana impedance increases with time during ripening both for the two electrode and four electrode method. Results also demonstrate that the banana impedance decreases with the increase in frequency. The impedance obtained with two terminal method is higher in magnitude than the four terminal method as the impedance data collected by two terminal method contains the contact impedance terms. The variations in impedance in both the method are found to be large at lower frequencies and very small at higher frequencies. The impedance becomes extremely low at the higher frequencies of the applied alternating current signal. Hence, current can penetrate all the cell membrane due to extremely low value of the cell membrane reactance ($1/\omega C_{membrane}$) (Kanti, 2014; Bera *et al*., 2016a-c). Results demonstrated that the electrode contact impedance is maximum at lower frequency and minimum at higher frequency. It is observed that the electrodes in the impedance measurement process in the present study produces contact impedance in the range of 200-450 Ω at lower frequencies below 500 kHz which then reduces as the frequency further increases and becomes around 50 Ω at 500 kHz.

It is also seen from Fig. 10, that the contact impedance for a single electrode is maximum at low frequency. It decreases with increasing frequency. This is due to the presence of capacitance in the contact impedance model. As the frequency increases, the capacitive reactance ($1/\omega C_{electrode}$) decreases. At high frequencies, the contact impedance is minimum as the $1/\omega C_{electrode}$ term becomes of very low amplitude and hence, the impedance offered by the interface layer of banana skin is small. As the impedance is highly dependent on electrode materials, configuration and electrode geometry, different types of compound electrodes could be developed and applied for contact impedance studies which will be communicated in future (Table 1).

Practical implementation of the technology: Contact impedance generally degrades the impedance data quality and data accuracy for the errors occurred in the measurement process in two probe method. Though standard four probe techniques eliminates the contact impedance but for improved impedance measurement larger current electrode and smaller voltage electrodes are required. In this direction compound electrodes array is

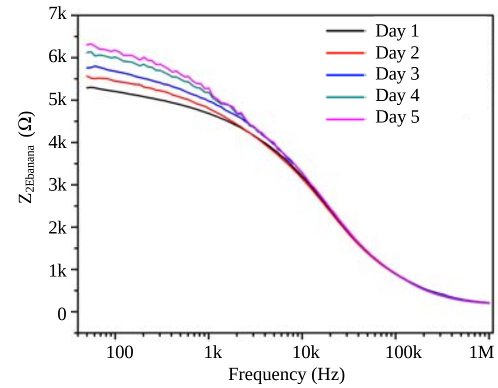

Fig. 8: Banana impedance vs. frequency over different days obtained with two terminal method

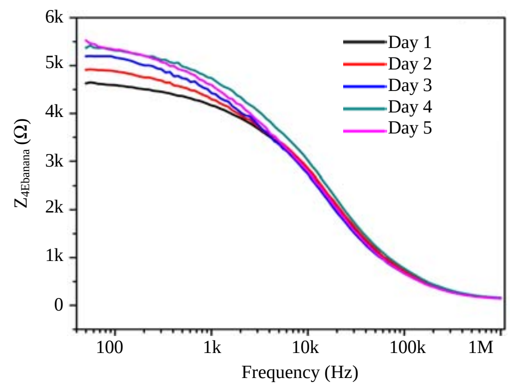

Fig. 9: Banana impedance vs. frequency over different days obtained with four terminal method using compound electrodes

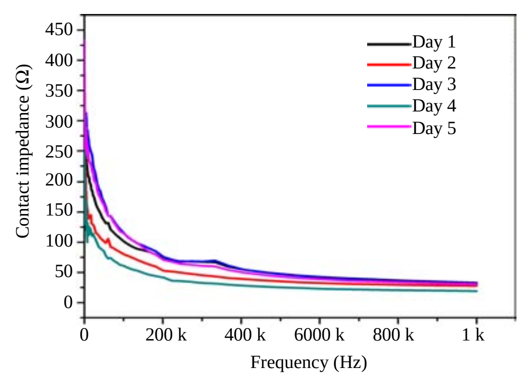

Fig. 10: Contact impedance of single electrode against frequency

Table 1: Contact impedance variations with time and frequency for banana ripening experimentation studied by EIS

	Contact impedance variations (Ω)				
Frequency (Hz)	Day 1	Day 2	Day 3	Day 4	Day 5
50	331.78850	329.35330	282.22790	375.81750	388.68050
100.712	304.28800	281.54960	254.81100	350.16000	426.18180
247.791	284.03050	270.35960	236.36980	291.94530	394.34210
499.113	263.11400	259.17040	262.56520	255.26660	353.39880
1005.339	257.51400	254.77330	276.76970	221.18040	345.06320
2473.518	241.45200	209.31730	273.33820	172.32220	267.91490
4982.283	235.39750	183.42950	292.16060	167.85850	287.75590
10035.56	208.88450	144.92390	271.42370	127.45690	248.53480
24691.32	174.62800	126.38770	219.93890	109.91930	202.54170
49734.48	136.10950	101.60570	166.29950	85.02043	161.87350
74205.58	116.30840	90.05362	135.83000	69.50952	133.51120
100177.6	101.67060	80.12292	115.61020	60.89041	114.58460
246475.4	68.38403	49.72280	67.69791	35.61267	63.95826
496462.9	47.72985	35.39422	47.09264	25.19423	43.13316
740739.9	38.41635	30.19054	37.38478	21.12783	34.78300
1000000	32.82100	27.71482	32.14574	19.13478	30.38700

developed with stainless steel sheet and the electrode contact impedance is assessed for banana ripening studies with EIS.

This procedure provides us accurate banana impedance without any contact impedance error. For the fruits with larger surface area such as banana, impedance measurement with standard four probe electrode array is possible but for the fruits with smaller volume or smaller surface area such as grapes, litchi, etc., placement of four electrodes as a linear array is difficult. In this situations, the compound electrodes are very suitable for EIS studies. Also, the compound electrode based contact impedance correction will improve the measurement accuracy.

CONCLUSION

Contact impedance studies on fruits are found essential for impedance based fruit characterization to obtain the actual fruit impedance profiles. As the contact impedance varies with frequency, the frequency response of the electrode contact impedance has been found with a significant research interest. In this direction, the frequency variations of electrical impedance during banana ripening have been studied with compound electrodes using Electrical Impedance Spectroscopy (EIS). The banana impedance has been measured with two electrode and four electrode method using the compound electrodes developed from stainless steel sheets to evaluate the electrode contact impedance. The contact impedance of each electrode is then calculated by comparing banana impedances obtained with two terminal and four terminal methods. It is observed from the results that the contact impedance reduces from lower frequency to higher frequency. It is found that contact impedance is maximum at lower frequency and minimum at higher frequency. Results also demonstrate that the banana impedance increases with time during ripening both for the two electrode and four electrode method. Results show that the contact impedance of an electrode used in the present study produces contact impedance in the range of 200-450 Ω at lower frequencies which then reduces to around 50 Ω at higher frequency range. It is revealed from the research studies conducted that the two terminal impedance measurement process includes contact impedance which is almost zero in case of four terminal method with compound electrodes.

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