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Assessment of quality of fruits using impedance spectroscopy

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Summary This study deals with the development of a nondestructive impedance spectroscopic technique that may assess the conditions of the fruits to pluck them with the help of robotic arms. Preliminary investigations are made with the help of two-terminal probe and an accurate LCR meter. The bulk impedance of mango has been measured to characterise raw and ripe fruits. Effective resistance and effective capacitance vs. frequency characteristics have been determined. The bulk effective resistances, of the ripe fruits, are found to be more than those of the raw fruits, in the frequency range of 1–6 kHz. In the same frequency range, effective capacitances of the raw fruits are found more than those of the ripe fruits. In the light of the data obtained, it can be said that the effective resistance may be used to differentiate between raw and ripe fruits in the frequency range of 1–6 kHz.

Keywords Automatic sorting of fruits, electrical impedance spectroscopy, nondestructive testing of fruits, post harvest assessment, quality assessment of fruits.

Introduction

The characterisation of fruits has been an important issue in the automatic sorting of fruits from the harvest site as well as from the cool storage. The quality of the fruits, at the time of consumption, also depends on the maturity stage reached at the time of harvest. Characterisation techniques may be divided into two groups, i.e., nondestructive and destructive techniques. For automatic sorting of fruits, with the help of robotic arms, generally, nondestructive techniques are preferred. Impedance spectrometry has been successfully used in the characterisation of fruits in a very high frequency range (Harker & Dunlop, 1994; Harker & Maindonald, 1994; Inaba *et al*., 1995; Bauchot *et al*., 2000). However, their aim was to analyse the fruits with the help of impedance spectroscopy, and they used both destructive and nondestructive techniques for this purpose. They did not plan to develop any technique for the characterisation of fruits for commercial purposes. Nondestructive techniques based on ultrasonic, optical, microwave, image categorization and semiconductor sensors have been used successfully for the testing of fruits, for commercial purposes (Mizrach, 2000; Alonso *et al*., 2003; Krairiksh *et al*., 2004; Rocha *et al*., 2010 and Xiao-bo *et al*., 2010). Nondestructive ultrasonic tests have been used to elucidate the influences of storage temperature and time on the softening process of avocado fruit. This method is based on the measurement of acoustic wave attenuation in the fruit tissue, by means of ultrasonic probes in contact with the fruit peel (Mizrach, 2000). An automated firmness monitoring system, for apples, was developed based on nondestructive acoustic impulse response technique to estimate the firmness during storage and determine the time when cool stores should be opened (Belie *et al*., 2000). An application of high-frequency electromagnetic waves was developed to test the mango by measuring its dielectric property at 12.4 GHz (Krairiksh *et al*., 2004). A tomato maturity predictive sensor was developed to be used at packing houses for detecting unripe tomatoes that will never turn red by making spectral and colour measurements of green-mature tomatoes just after harvest. Colour was measured daily and used as an index for classifying harvest day spectral data into ripe or unripe tomato (Hahn, 2002). Applications of ion selective field effective transistors (ISFET) as sensors have been increasing because of their fast response, integrated signal conditioning, possibility of multiple sensors on single chip and requirement of very small sample volume for testing purposes. These are used to analyse calcium, potassium and nitrates in several apple varieties, both in juice and in situ fruits. Results show that the analysis of potassium, calcium and nitrate permits to distinguish among apple varieties and can also be used to determine correctly the concentrations of these ions (Alonso *et al*., 2003).

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Impedance spectrometry is a low cost and simple technique and has a lot of potential to be used to characterise fruits nondestructively *in vivo* and at the site of harvest and storage. It has been recently used for the analysis of eggplant pulp (Wu *et al.*, 2008). Effects of drying, freezing and thawing treatments on its impedance characteristics have been determined. An integrated approach to electrochemical impedance spectroscopy has been presented by Orazem & Tribollet, 2008. Impedance microbiology has been successfully used for the quantification of bacterial content in milk by means of capacitance growth curves (Felice *et al.*, 1998). In another research work, impedance spectroscopy has been used in the study of apple juices and apple pasteurised pulp (Zywica *et al.*, 2005). Main aim of this study is to categorise unripe, ripe and over ripe fruits that are available at a place or on a tree, with the help of measurement of impedance of the fruit. In this connection, an attempt has been made to develop a low-cost technique for the characterisation of raw and ripe fruits, through nondestructive impedance spectroscopy, for commercial applications. In practice, impedance is measured as either bulk impedance or surface impedance. Both techniques have their advantages and limitations. In this study, bulk impedance (assuming parallel combination of resistance and capacitance) is used for the assessment of the ripeness of the mango fruit. For this purpose, effective capacitance vs. frequency and effective resistance vs. frequency characteristics have been determined for the cases of mangoes.

Materials and methods

Fruit characterisation by electrical properties

The equivalent circuit of a fruit may be represented by the electrical equivalent circuit shown in Fig. 1. If effective impedance (Z_{ef}) is measured, with the help of a bridge, either series or parallel mode may be used.

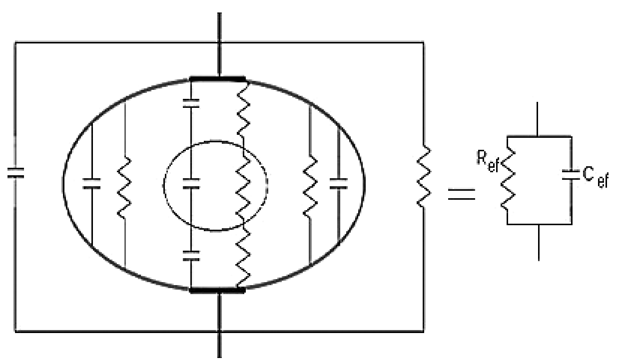

Figure 1 Electrical equivalent circuit of the mango.

However, in the present investigations, parallel combination of effective capacitance (C_{ef}) and effective resistance (R_{ef}) is selected. It may be given by the following expression:

$$\frac{1}{Z_{ef}} = \frac{1}{R_{ef}} + \mathrm{jwC_{ef}} \qquad (1)$$

The values of the effective capacitance and effective resistance will depend upon the structure of the fruit. Effective values are taken because it will not be pure resistance or pure capacitance but combination of resistances and capacitances because of the complex nature of the equivalent circuit (Hague & Foord, 1971]. These will be different when measured for raw, ripe and over ripe fruits of nearly same size because impedances offered by skin, pulp and seed of the fruit will be different in the above conditions. Hence, raw and ripe fruits may be characterised in terms of their effective resistances and effective capacitances. Optimum frequency, at which maximum difference among impedances of raw, ripe and over ripe fruits may be achieved, may be assessed by determining their effective resistance vs. frequency and effective capacitance vs. frequency characteristics in the frequency range of 1–200 kHz.

The effective impedance of a fruit, as measured by a probe and LCR meter, may depend upon a number of factors. The effect of some factors may be assessed systematically, while others that affect randomly may be determined statistically. Hence, impedance of a fruit may be represented by following expression:

$$Z_{ef} = f(x_1, x_2, x_3 \ldots x_n)$$

where x_1, x_2, x_3……….x_n are the variables that affect the value of Z_{ef} in two ways: either it will be a systematic effect or a random effect. The corresponding changes because of systematic effect in Z_{ef} may be obtained by careful experimentation. Similarly, the effect of the factors that affect randomly may be assessed by taking large number of readings and determine the effect statistically. Some of the factors are discussed below:

x_1 is attributed to the condition of the fruit which is the function of time, i.e., it may be unripe, ripe or over ripe. This should represent the major systematic change in Z_{ef} with time. Our aim is to use this change to characterise the fruit. It may be obtained by measuring the effective impedance at suitable time intervals.

x_2 factor may be related to the shape of the fruit. If fruit is symmetrical, impedance may remain approximately constant when measured across a certain periphery having nearly same diameter, like apple, tomato, etc. In the case of unsymmetrical shape, bulk impedance will have different values, i.e., mango. However, in the case of mango, two nearly parallel surfaces may be used to define the bulk impedance for analysis purposes.

x_3 factor may depend upon the size/weight of the fruit. Size will decide the distance between the electrodes as well as the parallel paths in the fruit. It may be assessed by measuring impedances of the fruits of different weights to develop a relationship between capacitance/resistance verses mass.

x_4 factor will decide the value of impedance depending upon the contact area of the electrodes of the probe. It will decide the value of the impedance that will be measured by the LCR Bridge. For small area, value of impedance will be large, while large areas will offer small impedance only. However, for constant area probe, there will be no variation in impedance.

x_5 factor may be the temperature of the fruit. It will affect the impedance directly and can be assessed by measuring the impedance at different temperatures.

x_6 is a factor that will change the impedance of the fruit at constant controlled temperature because of random variation of temperature around the controlled temperature as well as because of the random variation of contact resistance. Effect may be assessed by measuring the impedance several times with in a very short interval of time. Its effect may be assessed in terms of standard deviation.

x_7 is a factor that affects the impedance of the fruit by changing the position of the probe slightly around one point only. The change may be because of the variation in the impedance offered by the fruit at different positions in a symmetrical surface.

x_1 to x_7 factors will affect the measured value of the impedance of the fruit. However, at a particular instant, fruit will have one condition, i.e., it will be ripe, unripe or overripe. With the help of impedance measurement, it is to be proved that the variations in the value of Z_{ef}, because of variables other than time, are negligible or very small in comparison with variations because of time. This variation is our requirement and will be measured with good order of accuracy. However, the variations in the value of Z_{ef}, because of random effects will be ascertained in terms of standard deviations using Excel software. The effects of other variables which affect the measurement systematically will be minimised by making the measurements under controlled conditions. Condition of the fruit is assessed on sensory basis only because of the nonavailability of facilities for chemical analysis, etc. The variety of mango which is available on the trees of University area is used for testing purposes. It changes colour from dark green to bright yellow colour on ripening. The change in impedance and change in colour follow one another, and yellow fruit is appreciably sweet when tested by a number of staff members and students. If raw and ripe fruits have distinctly different impedances at a particular frequency, a signal proportional to the impedance of the ripe fruit may be generated to actuate a robot to pluck a ripe fruit (Edan, 1995).

The bulk impedance measuring system

The bulk impedance measuring system is shown in Fig. 2(a), and its full cross-sectional view is shown in Fig. 2(b). Lower potential electrode is spring loaded and can be moved in vertical direction only. It can be fixed in its position at the time of experimentation. Higher potential electrode can be moved in vertical direction as well as in the horizontal direction (towards or opposite to the position of lower potential electrode). The order of impedance offered by the fruit will be governed by the cross-sectional area of the electrodes. Bigger cross-section will provide low resistance and higher capacitance and will not be able to make good contact with the fruits that mostly have curved surfaces. Smaller cross-section of the electrode will provide higher resistance as well as low capacitance and will be able to make good contact with the surface of the fruit. Different cross-sections were tried and finally electrodes of 5 mm diameter were selected. Fruits of maximum width 7.2 cm and maximum height 8.5 cm may be tested for their bulk impedances by the designed setup. The pressure applied on the fruits will be governed by the high-potential electrode because lower potential electrode is stationary as well as spring loaded. The mass of the fruit is measured with the help of a digital mass measuring system installed in the bottom of the device, while temperature is measured with the help of a temperature sensor based on AD590. To provide uniform temperature inside the container, exhaust fan and holes are provided.

Post harvest experiments

Determination of effective resistance vs. frequency and effective capacitance vs. frequency characteristics of mango

For the preliminary investigations, the bulk effective impedances (Hague & Foord, 1971) of the fruits have been measured, with the help of an LCR meter (LCR-800, Gw Instek; Good Will Instrument Co., Ltd., Taiwan) and two-terminal probe, developed for this project, as shown in Fig. 2(a,b), to characterise the conditions of the fruits. The bulk effective impedance is measured in terms of the parallel combination of effective capacitance and effective resistance in the frequency range of 1–200 kHz. LCR meter has digitally controlled frequency and voltage variations. It can measure impedance in series or parallel mode, which can be easily selected from the front panel. To decrease the errors because of stray fields, short circuit and open circuit adjustments are made. Samples are selected of uniform size and mass and are properly cleaned, and their dimensions, mass and temperature are correctly

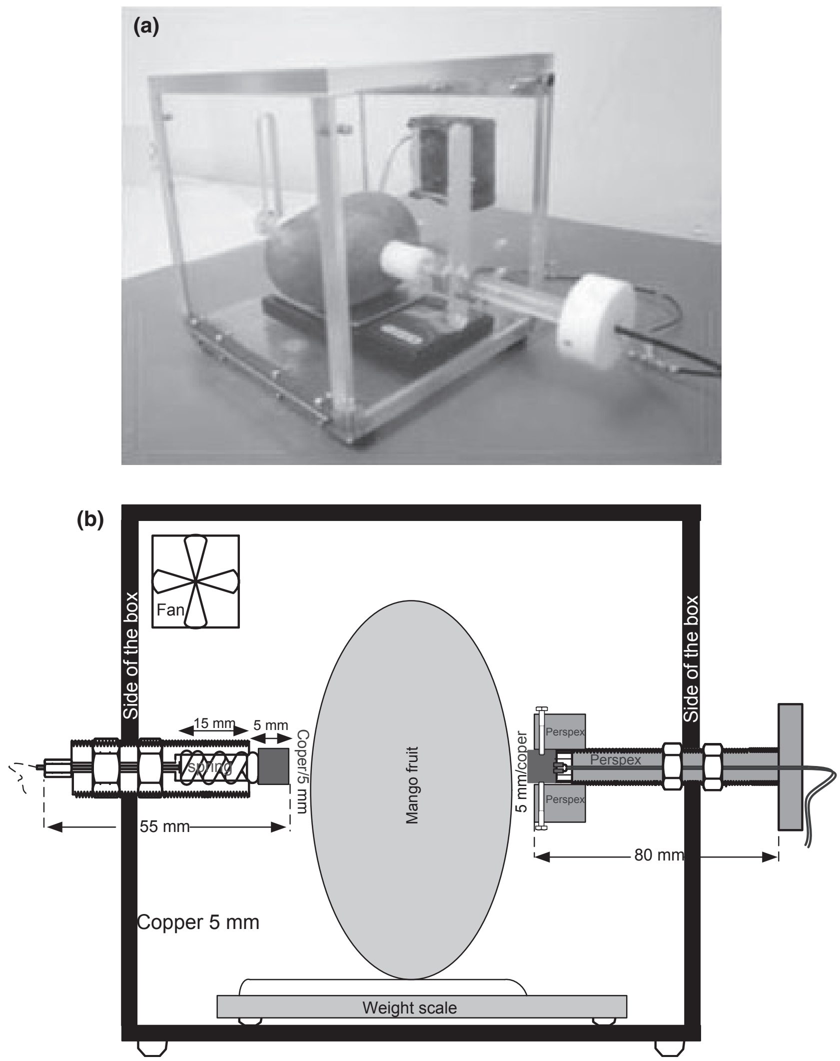

Figure 2 (a) Photograph of the experimental set-up. (b) Cross-sectional view of the probe.

recorded. Proper contacts are made between the electrodes of the probe and the fruit skin. Arrangements are available to measure the mass and width of the fruit in the system. Effective resistances and effective capacitances of the samples are measured at one volt, in the frequency range of 1–200 kHz, and the results are shown in Figs 3 and 4. Higher voltage and very high frequencies are not used to avoid self-heating.

Results and discussion

Effective resistance vs. frequency characteristic of mango

Figure 3 shows the variations of the effective resistance of a mango fruit when subjected to frequencies from 1 to 200 kHz for 7 days. In this duration, unripe mango becomes ripe/overripe depending upon the condition of the fruit in the beginning. It is concluded, after the analysis of the characteristics shown in Figs 3 and 4, that fruits have highest effective resistance and capacitance at 1 kHz (in the frequency range of 1–200 kHz).

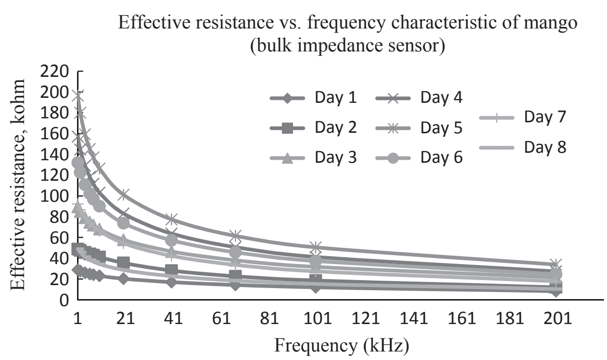

Figure 3 Effective resistance vs. frequency characteristics of mango.

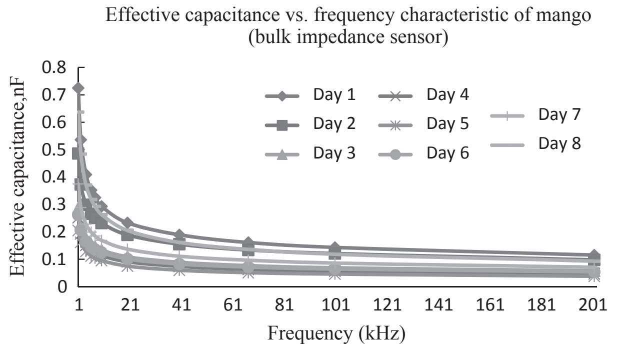

Figure 4 Effective capacitance vs. frequency characteristics of mango.

It is also observed that the variations because of random effects decrease with increase in frequency. However, because of higher variations, it is decided to measure impedance of the fruit, at 1 kHz. In the case of raw mango of the available size, the effective bulk resistance varies from (28.8 ± 0.8) kΩ at 1 kHz to (8.3 ± 0.1) kΩ at 200 kHz when measured with the help of the designed probe system, including the random effects. However, the same mango on the fifth day, when it is nearly ripe (when colour changed from dark green to yellow), offers an effective resistance, which varies from (196.5 ± 0.8) kΩ at 1 kHz to (33.88 ± 0.12) kΩ at 200 kHz. The results show that appreciable ratio (6.8) exists between the effective resistances of ripe and raw fruits at 1 kHz. On the other hand, the ratio reduces to 4.1 at 200 kHz. The variation in the effective resistance of the fruit (Mango) at 1 kHz, which is shown in Fig. 5, is enough to characterise raw and ripe fruits in terms of their effective resistances only. The variation because of random effect is nearly negligible under controlled conditions. However, changes in effective resistance from raw to ripe mango are so large that small variations because of changes in size, temperature and contact resistances will not affect the final assessment of the fruit. Hence, an electronic circuit that may develop signals proportional to effective resistance and effective capacitance separately may be used in the development of a low-cost fruit characterisation instrument (Rehman & Hasan, 1998). The referenced circuit could be effectively used to characterise fruits in terms of the ranges of resistances. The bars to represent random errors in effective resistance vs. frequency are not used, as errors are nearly negligible in comparison with resistances shown by the LCR meter.

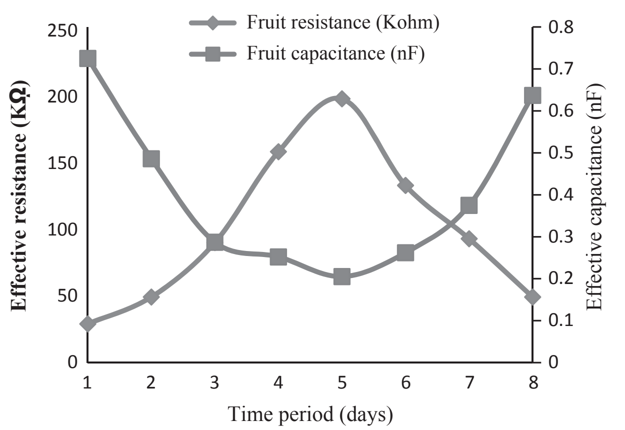

Figure 5 Effective resistance and capacitance variations for a mango, at 1 kHz, with time.

Effective capacitance vs. frequency characteristic of mango

Effective capacitance vs. frequency characteristic is shown in Fig. 4. The effective capacitance varies from (0.725 ± 0.021) nF at 1 kHz to (0.115 ± 0.003) nF at 200 kHz in the case of raw mango (first day, dark green). The same mango, on the fifth day, has effective capacitance, which varies from (0.205 ± 0.021) nF at 1 kHz to (0.038 ± 0.003) nF at 200 kHz. It can be easily concluded that the ratio between the effective capacitances of raw and ripe fruit at 1 kHz is 3.3, which is quite low in comparison with the ratio of effective resistances of ripe and raw fruits (6.8).

Effective resistance and effective Capacitance vs. time characteristic at 1 kHz

To study the variations in the values of impedances offered by the fruit, under test, at 1 kHz, data are extracted from the characteristics shown in Figs 3 and 4. It is redrawn in Fig. 5. It clearly shows that effective resistance of the fruit under test increases with time and reaches a peak and starts decreasing with the passage of time. Initially when fruit was clearly raw and had green colour, effective resistance was lowest and effective capacitance was highest. When fruit started changing colour, effective resistance started increasing and effective capacitance started decreasing and reached a highest value and lowest value, respectively, on the same day as shown in Fig. 5. With further delay, effective resistance started decreasing and reached a new lowest value on eighth day. It is the most important characteristic that may be utilised to establish relationship between conditions of fruit and effective resistance and effective capacitance as measured by the bridge. The duration is so selected that it covers all the conditions of fruit from raw to over ripe. The frequency selected is 1 kHz, which is suitable with respect to its effect on the fruit because of self-heating caused by different type of losses. It shows that the ratio of effective resistance of ripe to raw fruit is 6.8, while ratio of effective capacitance of ripe to raw fruit is 1/3.3.

Study of variation in the values of effective resistance and capacitance because of random variations of contact resistance and temperature

The effect of the random variations of contact resistance (because of random changes in contact pressure) and random variation of temperature, on the measured values of the effective impedances of the fruit, is ascertained by measuring the impedances of the fruits, at 1 kHz, in a batch of ten readings where each reading is the average of three readings. These measurements were made at a controlled temperature of 25 °C. The standard deviations for effective resistance and effective capacitance are ±0.799 kΩ and ±0.021 nF, respectively, calculated from experimental data. Results are given in Table 1.

Study of the effect of the mass of the mango on the impedance when measured at 1 kHz

To study the variation of impedances with mass, four samples of fruits with different masses are selected from the same branch of the tree. The impedance is measured at 1 kHz ten times under controlled conditions, and averaged value of the effective resistances and capacitances of the samples is measured with the help of designed probes and precision grade LCR meter. The resistance increases by 8.4% per gram, while capacitance also increases by 3.7% per gram, approximately. The result is given in Table 2.

Table 2 Variation of the resistance and capacitance of the mango samples with mass

	Mass, g	Resistance, K Ω	Capacitance, nF
SAM 4	247.7	32.54	0.547
SAM 3	255	30.24	0.694
SAM 1	263	28.83	0.725
SAM 2	282	26.66	0.877

Conclusion

The impedance spectrometric technique has been developed and applied successfully in the characterisation of raw and ripe mangos in the frequency range (1–200 kHz). By measuring the effective resistances and effective capacitances of the fruits, at a particular frequency, raw and ripe conditions may be established. The characterisation, through impedance spectrometry, will be simpler and low cost at lower frequencies. The effect of random variation of temperature and pressure is also determined and found negligible in comparison with change in effective capacitance and resistance because of ripening process. The ratio between the effective resistances of ripe and raw mango, measured at 1 kHz, is 6.8, while ratio between effective capacitances of ripe and raw mangos is 1/3.3. Hence, the effective resistances and effective capacitances of mango fruits may be used to differentiate between raw and ripe mangos. These are the preliminary results; further experimentation may be done to improve the construction of probe, and optimum frequency may be selected with respect to reliability and repeatability. Further work may be extended to the cases of other fruits also. Microcontroller-based system may be developed to pluck the fruits at an impedance at which fruit is most suitable for commercial purposes.

Table 1 Study of the random variation of the effective resistance and capacitance of a mango sample with respect to contact area of the electrodes and temperature. (Readings are taken at the same point). Applied frequency 1 kHz

Repetition no	Fruit resistance, K Ω	Fruit capacitance, nf
1	23.86	0.591
2	25.25	0.583
3	26.31	0.615
4	24.91	0.602
5	25.37	0.622
6	25.83	0.645
7	26.53	0.583
8	25.37	0.591
9	24.91	0.596
10	26.18	0.628
Average value	25.45	0.605
Standard deviation σ	0.799	0.021

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