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Evaluating banana ripening status from measuring dielectric properties ☆

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ABSTRACT

Electrical properties of banana fruit were studied in order to develop a rapid and non-destructive assessment method and to control its ripening treatment. A 5 V sine wave AC power supply and a rectangular parallel plate capacitor sample were used to span the difference in capacitance caused by the introduction of a banana fruit between the plates. To remove the effect of air gap between the plates, an equivalent capacitor was derived. The correlation between dielectric constant and quality parameters of banana fruit was investigated. The dielectric constant of banana fruit decreased as a result of the ripening treatment. Experiments indicated that the best frequency of sine wave that can predict the level of ripeness was 100 kHz. The coefficient of determination (R^2) of ripeness level prediction was obtained 0.94 at this frequency. This method can confidently predict the ripeness level of banana fruit.

1. Introduction

Non-destructive quality evaluation has recently been the subject of studies and researches. Most of the techniques invented by researchers are often expensive and impracticable in agricultural industry. A low-cost and reliable technique that has authority of usage in on-line quality evaluation is the ideal method, because it reduces the price cost of agricultural products. Many researchers have studied on quality and maturity indices of fruits including apple, avocado, mango, tomato, etc. (Kim et al., 2009; Lee, 1981; Halm, 2004; Lien et al., 2009). Most of these studies require expensive laboratory equipment. Banana is one of the fruits that require on-line quality inspection during ripening treatment. For preserving a firm pulp texture, good color and flavor and also to avoid contusion, bananas are cut at a mature-green stage and exported to consumer countries. The imported banana fruits are kept in airtight warehouses with ethylene gas control system. The bananas are typical fruits having a climacteric rise. The ripening treatment of banana fruits with climacteric rise could be artificially made by using controlled ethylene gas. The quality of ripening banana fruits could be controlled by ethylene treatment in commercial practice (Terai et al., 1973). The banana fruits are then taken to market when they are full-yellow. The ripening treatment of banana fruits has been improved through a tentative method by the empirical of trained laborers into a programmatic ethylene gas control method. However, this method has not always attained in bringing the uniformed ripening of banana fruits, because of its lacking of any monitoring system to detect the ripening quality of banana fruits (Morita et al., 1992). To estimate the ripening level of banana fruits during the ripening treatment, it is needed to institute non-destructive detecting method of ripening quality in easy operative application.

Many workers have studied banana quality evaluation during ripening treatment. Primary researches focused on the change of banana firmness as a function of ripening stage (Finney et al., 1967). Next researchers studied the relationship between ripeness indices and some banana properties such as delayed light emission (Chuma et al., 1980), and light reflectance (Morita et al., 1992). These attempts were far from reaching a practical application. Therefore, it is very important to devise an evaluation technique to assess the ripening quality of banana fruits. The electrical measurement technique seems to be an appropriate method of banana quality evaluation. This method has been utilized for quality evaluating of some agricultural products such as common bean and eggplant (Berbert et al., 2002; Wu et al., 2008). When calculating the electrical properties of fruits and vegetables, the physical properties of agricultural product such as volume, surface area, dimensions and porosity influence the experiments. To eliminate the effects of these properties, a developmental modeling is necessary. For example, to measure the relative permittivity of soybean, the porosity of granular material was taken into account in calculations by Sirikulrat and Sirikulat (2008). Different mathematical and numerical methods have been applied to estimate the surface area and volume of fruits and vegetables. Soltani et al. (2010) developed a mathematical modeling of banana fruit that estimated the volume, surface area and projected area of banana fruit.

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This paper aims to study electrical impedance technique by developing a model in order to eliminate the effects of banana fruit dimension and air gap, when estimating the ripening level of banana fruit during ripening treatment, and also aims to apply the capacitive technique to an automatic control system for the ripening process of banana fruits.

2. Materials and methods

2.1. Fruit materials

The Cavendish variety of banana fruits transported from the Ecuador was used in this experiment. The banana fruits have been stored at 14 °C temperature when transferred. Fifty-eight fingers of banana were randomly selected from banana bags in a ripening room of Damirchiloo warehouse located in Karaj city in Iran. The experiment was carried out at airtight ground-warehouses with fruits kept at humidity level of 85–88% for 5 days, the time needed for completing the ripening treatment of fruits. At this site, ripeness is currently assessed visually by comparing the peel color of banana with standardized color charts that describe various stages of ripeness. In trade market, seven ripening stages of bananas are usually discerned (Fig. 1). Color stage is judged visually using a chart scale provided by SH Pratt & Co. Ltd (Luton, United Kingdom) to categorize banana based on its level of ripeness. Stage 7 is not performed in the warehouse and at the end of stage six the fruits are transported to the market. On the first day, banana fruits were at stage 1 and on the fifth day, they were at stage 6. Ethylene gas with 1000 ppm concentration was treated about 24 h on first day. It is very important to control temperature, humidity and ethylene gas concentration in the ripening room.

In order to give a good artificial climacteric rise of banana fruits during the ripening, electrical impedance measurements were performed in the ripening room. The experiments were conducted in controlled temperature room at 15.5 °C. To measure capacitive properties of banana, a rectangular parallel plate capacitor with 25 cm in length and 10 cm in width was constructed as a standard hardware instrument. The conductive plates were selected from aluminum materials because of its consistency which would not be easily ionized as a factor that will ruin the results of experiments. The impedance of capacitive sensor was measured by a voltage divider circuit (Fig. 2) as:

$$\frac{V_o}{V_i} = \frac{Z_2}{Z_1 + Z_2} \tag{1}$$

where V_i and V_o are the input (5 V_{P-P}) and output voltages shown in Fig. 2 and Z_1 and Z_2 are the impedances of C_1 and C_2, respectively. After replacing Z_1 and Z_2 by $\frac{1}{j\omega C_1}$ and $\frac{1}{j\omega C_2}$, and simplifying we get:

$$\frac{V_o}{V_i} = \frac{C_1}{C_1 + C_2} \tag{2}$$

To remove the effects of lateral forces due to the weight of fruit, banana fruit was set through the sensor by means of suspension method. To measure the mean relative permittivity of banana fruits (including air gap), the following procedure was adopted:

1. A 5 V peak to peak sine wave, 10 kHz–10 MHz frequency sweep signal is applied to the circuit in Fig. 2 and V_o is measured when the sensor is vacant.
2. The vacant capacitance of sensor is calculated from the Eq. (2).
3. Test specimen is hung between the sensor plates, while the whole specimen is placed inside the sensing plates.
4. Capacitance of sensor is calculated from the Eq. (2).
5. Mean relative permittivity is obtained from dividing the capacitance including banana fruit to the vacant capacitance.
6. Measurements are taken each day.

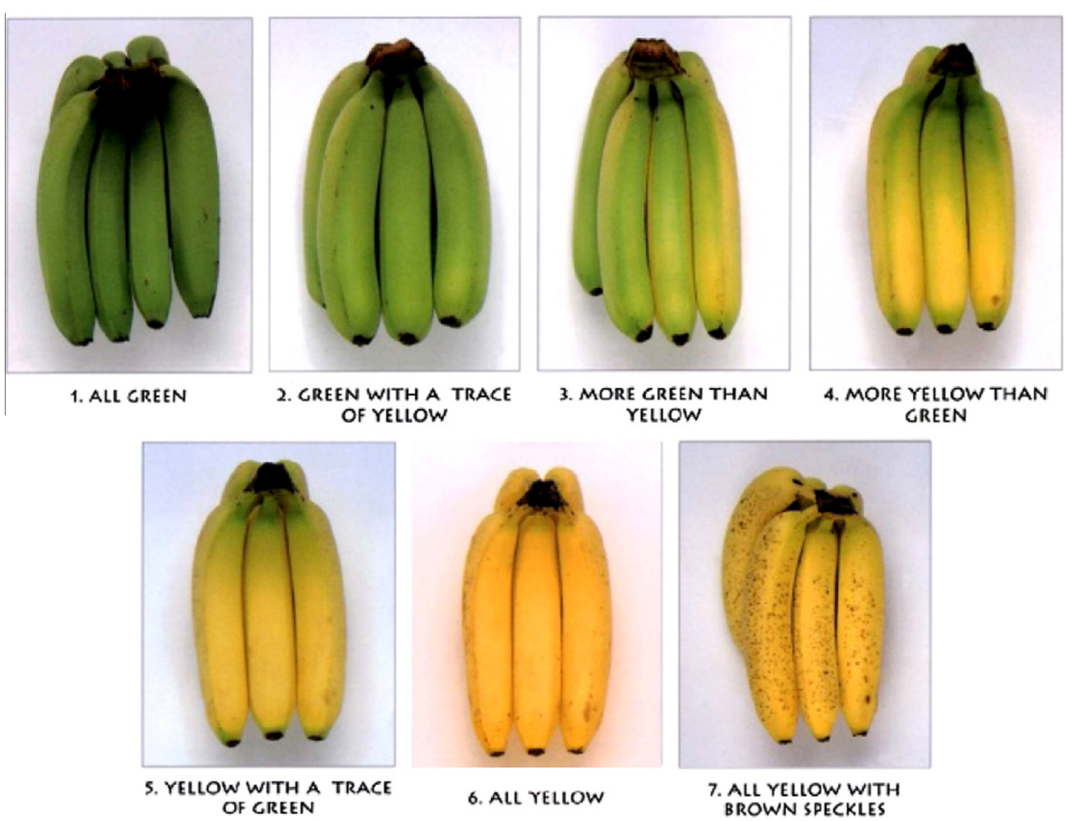

Fig. 1. Color chart of banana fruits in various stages.

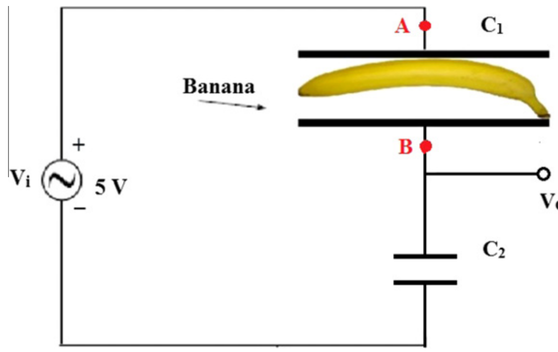

Fig. 2. Side view of sensor in a voltage divider setup. A banana is hung between the driving and sensing system.

2.2. Modeling of banana fruit

When a banana specimen has been set in the middle of sensor, a series – parallel capacitors is formed as a result of air presence. Fig. 3 shows the proposed model to calculate dielectric constant of fruit.

When V_o is measured and is inserted in Eq. (2), C_{eq} is computed, not the capacitance of banana (C_b). Dielectric constant of banana is computed from following equations:

$$C_{eq} = 2C'_{air} + C'_{eq} \tag{3}$$

where:

$$\frac{1}{C'_{eq}} = \frac{1}{2C_{air}} + \frac{1}{C_b} \tag{4}$$

and

$$C'_{air} = \varepsilon_\circ \frac{(A - A')}{2d} \tag{5}$$

$$C_{air} = \frac{\varepsilon_\circ A'}{\frac{d-t}{2}} \tag{6}$$

$$C_b = \frac{\varepsilon_r \varepsilon_\circ A'}{t} \tag{7}$$

where ε_r is the dielectric constant of banana, ε_0 is permittivity of free space ($8.854 \times 10^{-12}\ \mathrm{Fm^{-1}}$), A is the area of capacitor plate ($\mathrm{m^2}$), A' is the projected area of banana ($\mathrm{m^2}$), t is the effective thickness of banana (m), and d is the distance between the plates (m).

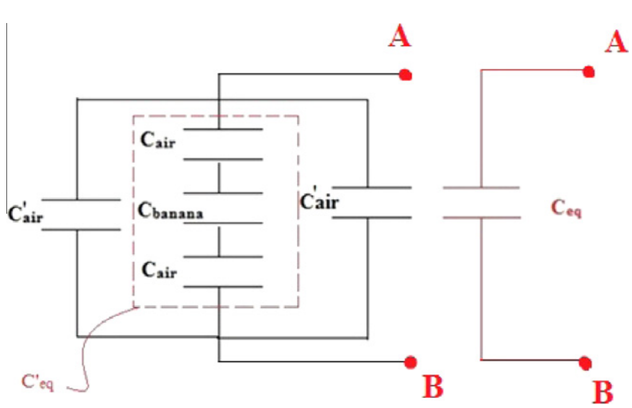

Fig. 3. A proposed model to measure the dielectric constant of banana fruit.

Substituting (6) and (7) into (4), and simplifying, we obtain:

$$C'_{eq} = \frac{A'}{\frac{d-t}{\varepsilon_\circ} + \frac{t}{\varepsilon_r \varepsilon_\circ}} \tag{8}$$

Finally, by simplifying the Eq. (8), we obtain:

$$\varepsilon_r = \frac{C'_{eq} t}{A' \varepsilon_\circ - C'_{eq}(d - t)} \tag{9}$$

In this expression C'_{eq} is found from (3) and (5) as:

$$C'_{eq} = C_{eq} - \varepsilon_\circ \frac{(A - A')}{d} \tag{10}$$

where C_{eq} is the measured capacitance of the whole arrangement (F).

To calculate the projected area (A') and the effective thickness (t), the mathematical modeling of banana is necessary. Soltani et al. (2010) developed a new method of banana modeling. Accordingly, the effective thickness of banana can be estimated from Eq. (11):

$$t = \frac{1.5 \times V_b}{A'} \tag{11}$$

where V_b ($\mathrm{m^3}$) and A' ($\mathrm{m^2}$) are the estimated volume and projected area of banana, respectively.

Therefore, dimensions of banana were measured and the volume and projected area of samples were estimated by the method developed by Soltani et al. (2010). To evaluate the reliability of this mathematical modeling, the mass of each sample was measured by a digital balance with an accuracy of ±0.1 g. Kachru et al. (1995) reported that the specific gravity of Cavendish variety of banana fruit is 0.933. Therefore, the volume of each sample was found by Eq. (12):

$$V_M = \frac{M}{0.933} \tag{12}$$

where V_M is the volume of banana ($\mathrm{cm^3}$), obtained from measured mass (M) of banana.

2.3. Measurement of quality indices

One of the most important quality indices of banana fruit is total soluble solids (TSS). To measure TSS, 10 g of flesh was sampled from a whole banana (along the length of the fruit) and diluted in 50 g of distilled water in a blender for 1 min. TSS was measured using a hand held refractometer with three replications for each level of ripeness.

Another quality index is firmness of banana fruit. For many fruits, firmness is measured by a destructive puncture test or compressions test. Firmness is defined as the maximum force in (N) required until tissue failure is occurred. Fruit firmness was measured using an Instron Universal Testing Machine (Model SANTAM ST-5) with an 8 mm cylindrical probe. The head speed was set at 50 mm/min. The firmness was measured at 2 cm away from the middle of the fruit.

2.4. Statistical analysis

Comparison of a new measurement technique with an established one is often needed to see whether they agree sufficiently for the new to replace the old (Bland and Altman, 1999). Such investigations are often analyzed inappropriately, notably by using correlation coefficients. The use of correlation is misleading. An alternative approach, based on graphical techniques and simple calculations was used. Bland–Altman approach (Bland and Altman, 1999) was used to plot the agreement between the measured

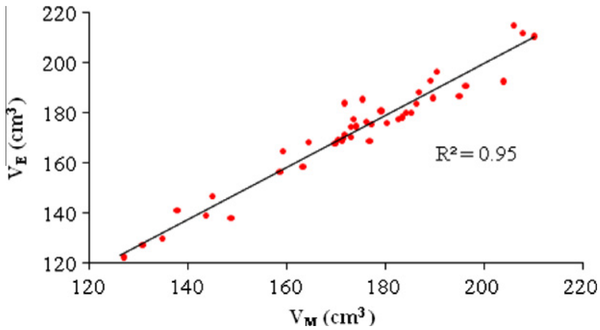

Fig. 4. Banana volume measured using mass of banana (V_M) and estimation method (V_E) with the line of equality.

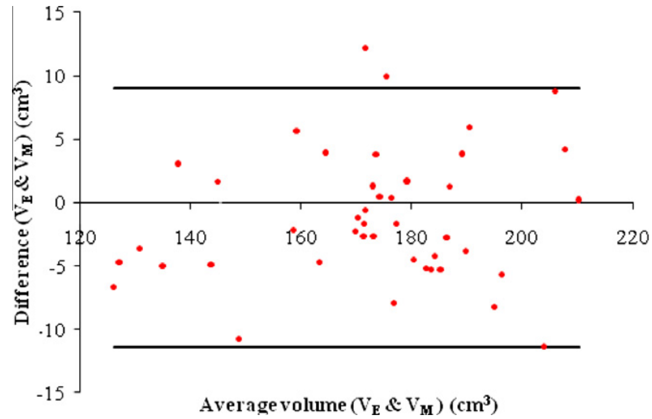

Fig. 5. Bland–Altman plot for the comparison of banana volumes measured with mass of banana and estimated volume by mathematical approximation; outer lines indicate the 95% limits of agreement (−11.42; 9.06) and center line shows the average difference.

parameters with the mathematical approximation. The paired *t*-test and the mean difference confidence interval approach were used to compare the volume of banana determined from mathematical approximation with the measured volume of fruit by Eq. (12). The paired *t*-test was used for testing whether the difference between the two measurements was significantly different. The important feature of this test is its ability to compare the measurements within each subject. These validation methods were also employed by previous researchers (Koc, 2007; Khojastehnazhand et al., 2009; Omid et al., 2010). These analyses were performed using the Excel Analysis Toolpack option (MS Corporation, Redmond, WA, USA).

3. Results and discussion

The volume estimated by mathematical approximation was compared with the volume calculated by Eq. (12). A plot of the volumes determined by mathematical approximation and measured volume is shown in Fig. 4. The coefficient of determination (R^2) was obtained as 0.95.

It means that this method is sufficiently reliable to predict the volume of banana fruit. The mean value of volume difference between estimated volume and measured volume was 1.18 cm^3 (95% confidence interval: −2.74 cm^3 and 0.038 cm^3). The standard deviation (SD) of the volume difference was 5.22 cm^3. The paired samples *t*-test results showed that the banana volume estimated with mathematical approximation was not significantly different from the volume computed by Eq. (12) ($P = 0.145$). The volume differences between two methods were normally distributed and 95% of the volume differences were expected to lie between d−1.96 SD and d+1.96 SD, known as 95% limits of agreement (Bland and Altman, 1999). The 95% limits of agreement for comparison of volumes measured with mass of banana and mathematical estimation were calculated at −11.42 and 9.06 cm^3 (Fig. 5). Volume estimated by mathematical approximation may be about 11.42 cm^3 lower or 9.06 cm^3 higher than volume calculated with Eq. (12). Statistical analysis showed that mathematical estimation method is able to model the banana with a good estimation. This method was applied to estimate the volume and projected area of banana for computing effective thickness (t).

Mean values of banana dielectric constant at various frequencies vs. ripening time is plotted in Fig. 6. As Fig. 6 shows variation in dielectric constant occurred at all frequencies, at 10 kHz and 10 MHz the slope of curves are irregular. At 100 kHz and 1 MHz frequencies, slope of variation is consistent. At these frequencies, a decrease in dielectric constant was perceived during ripening treatment of banana.

Fig. 7 presents the mean values of TSS of banana fruits during ripening. TSS was increased from 7.8 (±1.04)% Brix at stage 1 (green-mature) to 18.6 (±0.6)% Brix at stage six (full-ripe). The R^2 of quadratic regression was obtained as 0.99. It can be presumed that TSS increased in quadratic form during ripening treatment reliably. Medlicott et al. (1990) also reported a quadratic relationship between the TSS and the level of banana ripeness that is indicated by color chart (Fig. 1). Since most of the TSS is sugar, an increase in the TSS is because of hydrolysis of starch into soluble sugars such as glucose, sucrose and fructose that occurred as a result of ripening treatment (Marriott et al., 1981).

The banana pulp TSS curves revealed different shapes at different frequencies (Fig. 8). The resemblance of 10 kHz with 10 MHz curve and 100 kHz with 1 MHz curve is noticeable. Also at 100 kHz and 1 MHz, variations of TSS are more regular than at 10 kHz and 10 MHz. Thus 100 kHz and 1 MHz sine signals are more appropriate for predicting the TSS of banana fruit.

We attempted to model TSS as a function of dielectric constant for various frequencies. The model considered included one output variable (TSS of the banana fruits) and one input dielectric constant (ε); i.e., TSS $\propto F(\varepsilon_r, f)$. Accordingly, the relationship between TSS and ε_r was obtained for 100 kHz and 1 MHz frequencies by regression analysis (Table 1 and Fig. 9). The experimental data were fitted to a quadratic model as

$$\mathrm{TSS}(f) = a \cdot \varepsilon_r^2(f) + b \cdot \varepsilon_r(f) + c \tag{13}$$

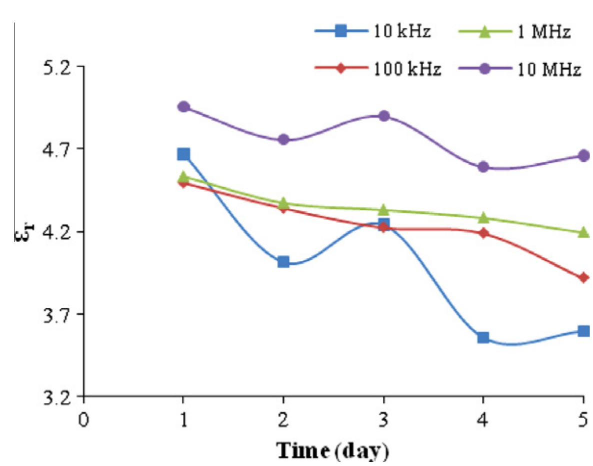

Fig. 6. Dielectric constant of banana fruits at different frequencies during ripening treatment.

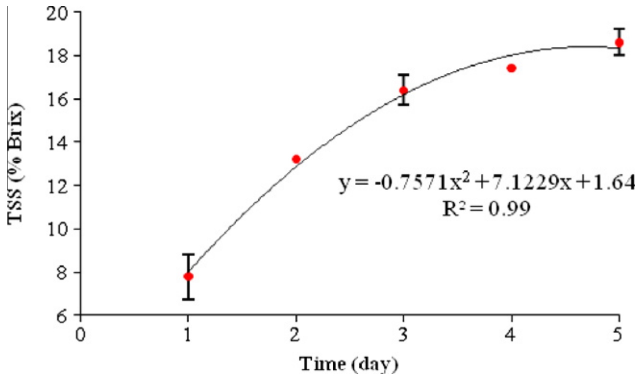

Fig. 7. Change in total soluble solids of banana pulp during ripening treatment. Each point represents the mean value of three bananas. Vertical lines represent the standard deviation. Broken line is regression curve fitted to data.

The parameters of the model (a, b, and c) are given in Table 1. The R^2 was attained 0.998 and 0.97 for 100 kHz and 1 MHz, respectively.

Fig. 10 represents the change in the firmness of banana fruits as a result of ripening time. A linear decrease in firmness was observed due to ripening treatment ($R^2 = 0.97$). When banana fruit is ripened, the text of banana softens. Its softening is due to alteration in cell wall structure by degrading enzymes (e.g. polyglacteronase) and also to degradation of starch (Seymour, 1993). Softening occurs rapidly. It is principally the result of the conversion of pectic substances which represent 0.5–0.7% of the ripe pulp (Marriott and Lancaster, 1983; Stover and Simmonds, 1987). This rapid softening corresponds to a conversion of pectic substances (Marriott and Lancaster, 1983). This decline corresponds to tissue softening by pectin solubilization in cell wall that occurs during fruit ripening (Hultin and Levine, 1963; Smith et al., 1990).

To predict the firmness of banana, variations of this parameter was plotted vs. dielectric constant at different frequencies. Variations of firmness against dielectric constant are different at various frequencies (Fig. 11). At all frequencies, the slopes of curves are positive, but this variation was not regular at 10 kHz and 10 MHz. So these frequencies were eliminated from ripeness prediction process. The relationship between firmness and dielectric constant of banana fruits was investigated at 100 kHz and 1 MHz (Fig. 12).

Table 1
Results of the quadratic model of TSS as a function of dielectric constant fitted by regression analysis to the experimental data.

$\mathrm{TSS}(f) = a \cdot \varepsilon_r^2(f) + b \cdot \varepsilon_r(f) + c$				
Frequency (kHz)	a	b	c	R^2
100	−44.226	353.08	−658.80	0.998
1000	−45.75	366.31	−712.67	0.97

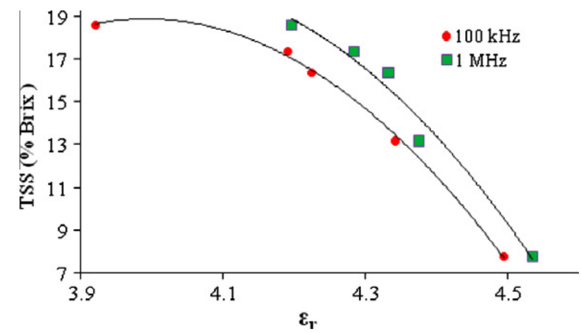

Fig. 9. Quadratic curve estimation to predict the soluble solids content of banana fruits.

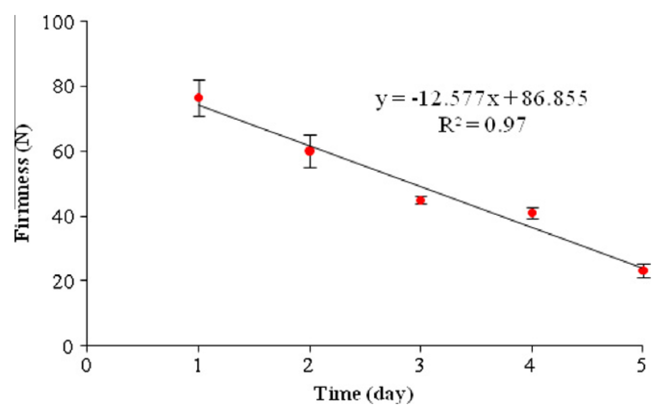

Fig. 10. Change in firmness of banana fruit during ripening treatment. Each point represents the mean value of three bananas firmness. Vertical lines represent the standard deviation. Broken line is regression curve fitted to data.

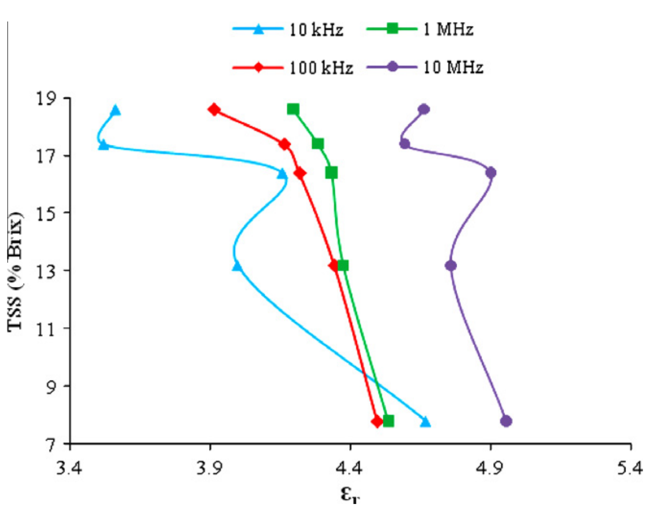

Fig. 8. Decrease in TSS of banana pulp as a function of dielectric constant at different frequencies.

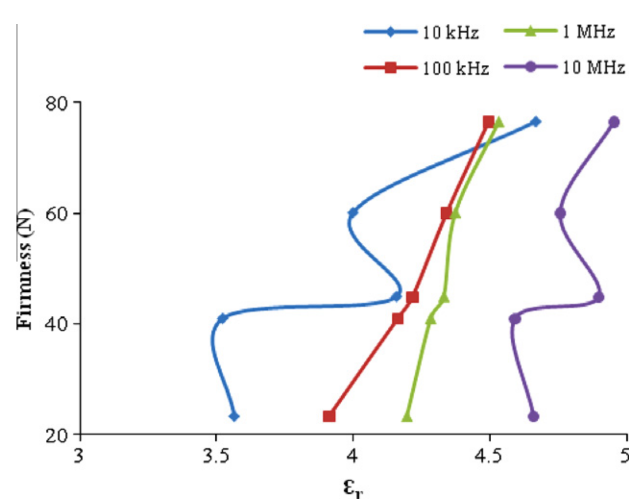

Fig. 11. Increase in firmness of banana fruits versus dielectric constant at different frequencies.

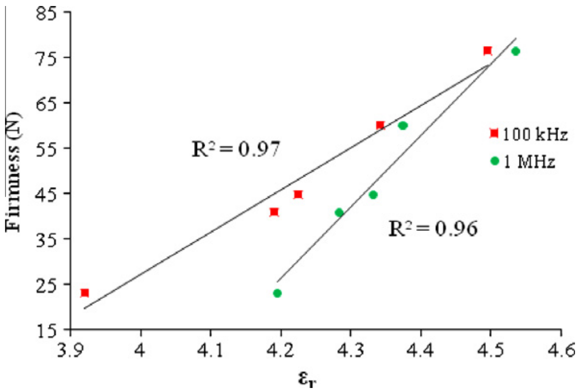

Fig. 12. Relationship between firmness and dielectric constant of banana fruits.

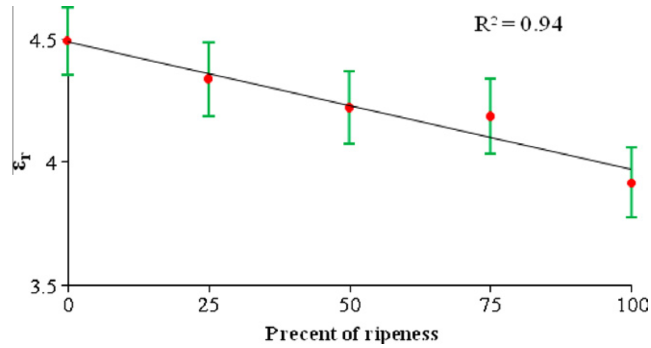

Fig. 13. Relation between percentage of banana ripeness and dielectric constant. Each point represents the mean value of 43 banana fruits. Straight line is data fitted line. Vertical lines represent the 95% confidence intervals.

The R^2 were attained 0.97 and 0.96 for 100 kHz and 1 MHz, respectively.

Estimation power of dielectric constant at 100 kHz is more appropriate than 1 MHz to predict the TSS and firmness of banana fruit, thus 100 kHz sine wave is proposed to apply for predicting the level of fruit ripeness.

Many consumers use the terms mature and ripe interchangeably to describe the state of a fruit when it is ready for consumption, Reid (2002) notes that fruit producers and postharvest produce technologists consider these terms to have distinct meanings. Reid indicates that the term "mature" is best described by the Webster's dictionary definition as "having completed natural growth and development". Reid further elaborates that the term mature describes the stage at harvest that will ensure that the fruit's quality will meet or exceed the minimum level acceptable to the consumer at the time it is consumed. In a climacteric fruit, such as banana, the fruit is not considered to be of desired eating quality at the time it initially becomes mature, but requires a ripening period before it achieves the taste and texture desired at the time of consumption. In this context the term ripe is best described by the Webster's dictionary definition as "having attained a final or desired state".

As concluded from the preamble above, we can find the ripeness degree of green-mature banana fruits before ripening treatment, 0%, because in this stage, banana fruit does not have the quality indices for consumption. When banana reaches full-ripe stage, the degree of ripeness can be presumed 100%, because the fruit achieves the favorite quality indices. On the fifth day of ripening treatment, banana fruits reach full-ripe stage. The change in dielectric constant against percentage of ripeness is shown in Fig. 13. The linear regression fitted to data, satisfies the prediction of ripeness at the level of 5%, so this method can be calibrated to predict the ripeness level of banana fruit using dielectric constant.

To obtain the calibration coefficient, the percent of ripeness was plotted against the dielectric constant values (Fig. 14). The slope of line was found through regression analysis. Since the initial values of dielectric constant differed between samples, to obtain calibration equation, the first day's dielectric constant, ε_{r0}, was used as the abscissa. The level of ripeness can be computed from Eq. (14):

$$P_r = -180.72(\varepsilon_r - \varepsilon_{r0}) \tag{14}$$

where P_r is the percent of ripeness, the calibration coefficient was obtained -180.72, ε_r is dielectric constant of banana, and ε_{r0} is dielectric constant of banana on the first day.

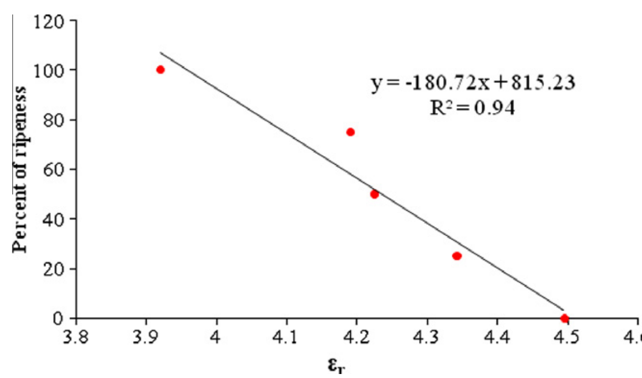

Fig. 14. Calibration of electrical impedance system to predict level of ripeness.

4. Conclusion

In this research, an impedance sensing system was developed and employed to predict the ripeness level of banana fruit. This paper studied the ability of this method to predict the quality of bananas during ripening treatment. Results showed that this technique, which is based on dielectric property, was able to estimate changes in the quality parameters of banana fruits during ripening period. Linear regression at 100 kHz provides an acceptable correlation for both TSS and firmness with dielectric constant. So this frequency was selected to develop the sensing system. Further works are needed to conduct researches on this method at higher frequencies to develop a more reliable prediction of banana quality when the ripening treatment is carried out on banana fruit.

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