ภาคผนวก

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Electrical Properties of Material Characteristics Using a Microstrip Patch Sensor

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Abstract. In this paper, the electrical properties of materials were evaluated using a microstrip patch sensor. The sensor was designed for the operating frequency in range of 1.5 to 3 GHz on a DiClad 880 substrate with the permittivity of 2.2. The resonant frequency of the design sensor ,as well as the magnitude of the reflection spectra S_{11}, were analyzed and then simulated three-dimensional finite element modeling when,. The result shows that the increase of the dielectric constant (ε_r) and conductivity (σ) of the material under test (MUT) led to the significant change of the resonant frequency. Thus, the resonant frequency may be used to evaluate the moisture content of the agricultural products.

Introduction

Nowadays, agricultural industries have become competitive and required high technology not only to produce the high quality products but also to reduce the production cost. Since the labor cost has been increasing continuously, automation systems have the great potential to solve such problem by maximizing the production with the minimum cost. This leads to the growing need of sensors and actuators. Particularly, moisture sensors play a significant role in the production of agricultural materials. The moisture content has a large effect on the storage life and product quality. The moisture measurement has therefore become necessary to the highly automated process in various industries. Although different methods have been developed to determine the moisture content, they are generally classified into two categories: direct and indirect methods. The direct method, such as the thermo-gravimetric method of sample analysis, chemical drying, azeotropic distillation, chemical method, gas chromatograph, and refractometry, can measure the precise and accurate moisture content, but such methods are complicated and required the technical expertise. In contrast, the indirect method monitors some physical parameters and then calculates the moisture content using such parameter values. In practice, these parameters are, for example, electrical conductivity, capacitance and microwave absorbance and infrared absorption [1]. In addition, it is evident that the indirect method should be non-destructive, and hence, no loss would occur from the measurement. The fact that electromagnetic waves can penetrate through the sample without damage has led to the development of the moisture measurement in agricultural products using electrical properties, such as conductivity, resistivity, or dielectric constant. Although resistance of the agricultural product can reflect the moisture content directly, many uncontrollable factors, such as an ion concentration, have the significant influence on the measured resistance. This leads to the unreliability of the method. In contrast, the dielectricity of water basically dominates the dielectric constant of the test sample due to its high dielectric constant. As a result, the other constituents with low dielectric constant in the agricultural products, such as protein, fat, oil, and starch, play a minor role in the total dielectric constant and become negligible [2]. By spanning the signal in a high-frequency range, dielectricity of the sample can be measured and analyzed. Basically, the fluctuation of the physical parameters does not have a significant effect on the dielectric property of the sample. Thus, the dielectric constant has been used to calculate the moisture content in agricultural products. Dielectric properties are highly correlated with moisture content because the permittivity of water greatly exceeds that of the dry matter of agricultural products. The technique for measuring dielectric properties of agricultural products based on microwave can be found the details in Reference 3 - 6. Some techniques to monitor the dielectric were based on the open-ended coaxial-line probes connected to the network analyzer have been reported by Tran et.al. (1984)[7], Seaman and Seals (1991) [8], and Nelson et al. (1994)[9].

The moisture measuring system is, in practice, required to be compact and user-friendly. This requirement can be satisfied using microwave because the microstrip patch sensor is small, lightweight and easy to use. Additionally, microstrip measuring systems are low-cost and easy to manufacture. Typically, microstrips are made up from high-quality printed circuit boards (PCB) because of the need of highly reliable strips. Due to the high cost of the high-graded PCBs, the microstrip are, in need, to be well designed. Therefore, the aim of this work is to design a high-performance microstrip for monitoring dielectric constants of agricultural samples. Also, the simulation has been carried out to verify its performance in the microwave region. This work reports the relationships between resonant frequency with dielectric constant and electrical conductivity of material using the three-dimensional finite element method.

Microstrip patch design and simulation setup

A microstrip patch antenna consists of a dielectric layer with a radiating patch on one side and a ground layer on another side. In theory, the width (W) and length (L) of the radiating patch, as well as the effective permittivity of the microstrip structure (ε_e), have a significant influence on the strip performance in the measuring frequency region (i.e. the free-space wavelength λ_0). Based on the electromagnetic theory, all major parameters can be used to design a strip operating within microwave region using the following equations [10].

$$W = \frac{\lambda_0}{2\sqrt{\frac{\varepsilon_r + 1}{2}}} \quad (1)$$

$$L = \frac{\lambda_0}{2\sqrt{\varepsilon_e}} - 2\Delta L \quad (2)$$

$$\Delta L = 0.412t\frac{(\varepsilon_e + 0.3)(\frac{W}{t} + 0.264)}{(\varepsilon_e - 0.258)(\frac{W}{t} + 0.8)} \quad (3)$$

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + 12\frac{t}{W}}} \quad (4)$$

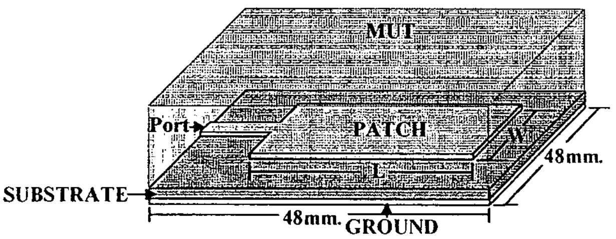
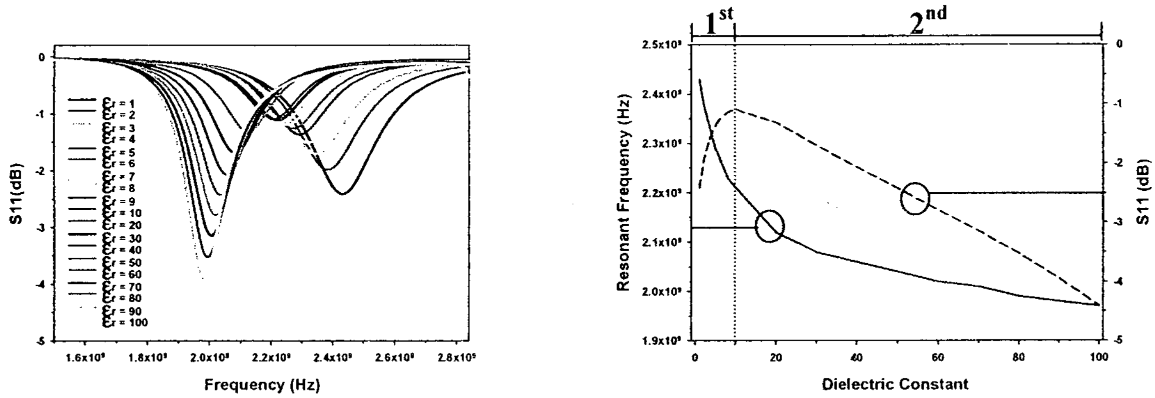


Fig. 1 A square microstrip patch sensor design

Fig. 1 shows the architecture of a microstrip patch sensor. In the operation at 2.4 GHz in air, the strip was required to have patch dimensions of 40 mm width x 40 mm length. A printed circuit board, with the permittivity $\varepsilon_r = 2.2$ (DiClad 880 substrate), was used as a dielectric substrate. The substrate was placed on top of the ground layer to form a microstrip antenna. The thickness of the substrate is 1.6 mm. A feed line (50Ω) is located at the center of the microstrip. A sample of the MUT was place over the microstrip patch sensor. The shift in the resonant frequency and magnitude of S_{11} was simulated and recorded.

Results and discussions

Fig. 2(a) illustrates the magnitude of the reflection spectra (S_{11}) of the designed sensor using the square microstrip structure. It is evident that the dielectric constants of the MUT change within the range of 1 to 100. Apart from the influence on relative permittivity, the frequency has a dominant influence on not only the magnitude of the reflection spectrum, but also the magnitude of S_{11}. In other words, the transmittance of the microwave signal changed due to the decrease of the impedance of the strip. The microstrip had a parallel-plate structure, and hence, led to the dominance of its capacitive component over the strip characteristics. With the increase of frequency, the impedance of the designed strip thus decreased.



(a) (b)

Fig. 2 Microstrip patch sensor with a frequency-dependent dielectric constant (a) magnitude of S_{11} and (b) relative shift in resonant frequency and magnitude of S_{11} (dB)

Fig. 2(b) shows the resonant frequency (red solid line) and magnitude of S_{11} (blue dashed line) versus dielectric constant.

By increasing the dielectric constant, the resonant frequency decreases significantly. However, the magnitude of S_{11} shows a maximum at the dielectric constant of approximately 10. The relation between a dielectric constant and a resonant frequency is:

$$\text{Resonant frequency} = -1\times10^{8}\ln(\varepsilon_r) + 2\times10^{9} \quad (5)$$

This equation shows the potential of the method to measure the dielectric constant using the resonant frequency. By spanning the microwave frequency over a certain region, the resonant frequency will be obtained and used to calculate the dielectric constant of samples using a calibration equation similar to the inverse of the equation (5). The magnitude of S_{11} is a function of the dielectric constant. This can be calculated using the following equations:

$$\text{Magnitude of } S_{11}[\text{dB}] = 0.593\ln(\varepsilon_r) - 2.374 \quad (1 \le \varepsilon_r \le 10) \quad 1^{st}\text{ part} \quad (6)$$

$$\text{Magnitude of } S_{11}[\text{dB}] = -0.038\varepsilon_r - 0.536 \quad (10 < \varepsilon_r \le 100) \quad 2^{nd}\text{ part} \quad (7)$$

To investigate the effect of electrical conductivity of the MUT on the strip characteristics, the dielectric constant was fixed at 10. Then, the conductivity was changed from 0 to 1000 S/cm. The simulation results are shown in Fig. 3. Fig. 3(a) illustrates the magnitude of the reflection spectra S_{11}. It is clear that the increase of the conductivity of the MUT led to the significant change of the resonant frequency.

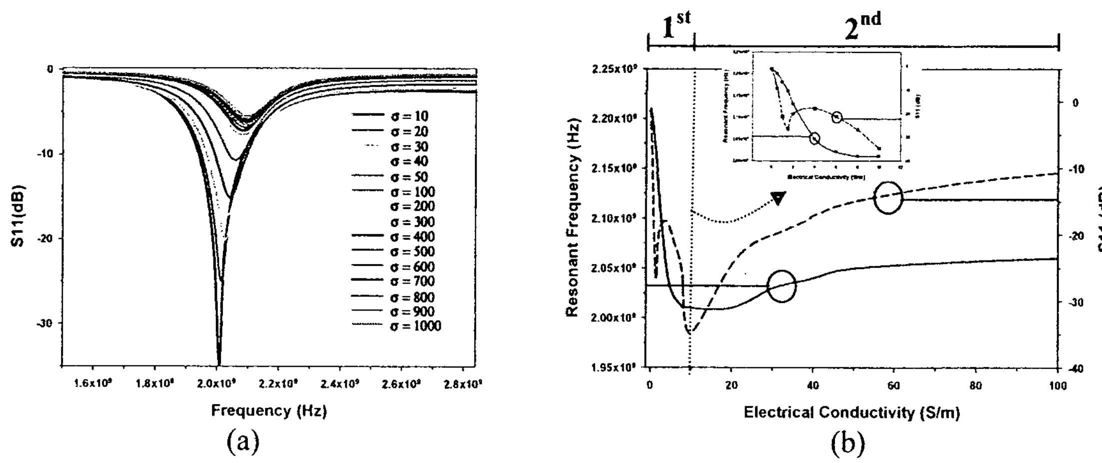


Fig. 3 The effect of electrical conductivity on the reflection spectra; (a) magnitude of S_{11} and (b) relative shift in resonant frequency and magnitude of S_{11} (dB)

Fig. 3(b) shows the effects of the electrical conductivity on the relative shift in resonant frequency (red solid line) and magnitude of S_{11} (blue dashed line).

The resonant-frequency plot shows a minimum point at the conductivity of about 10. When the conductivity is below 10, the resonant frequency decreases. In contrast, the resonant frequency increases slightly when the conductivity increases above 10. The relation between the resonant frequency and the conductivity is:

$$\text{Resonant frequency} = 3\times10^{6}\varepsilon_r^{2} - 5\times10^{7}\varepsilon_r + 2\times10^{9} \qquad (1 \le \sigma \le 10) \quad 1^{st}\text{ part} \tag{8}$$

$$\text{Resonant frequency} = 2\times10^{7}\ln(\varepsilon_r) + 2\times10^{9} \qquad (10 < \sigma \le 1000) \quad 2^{nd}\text{ part} \tag{9}$$

In this case, the magnitude of the reflection spectra S_{11} changes significantly as shown in Fig. 3(b). It is obvious that the relation between the magnitude of the reflection spectrum and the conductivity is difficult to obtain and inappropriate for the conductivity evaluation. Nevertheless, the resonant frequency shows the potential for the evaluation of both conductivity and dielectric constant. Hence, the moisture content in agricultural products may be evaluated from the resonant frequency since the moisture content has a strong relation with the dielectric property and the conductivity of the product [11-14].

Conclusions

This work has presented the relationships between resonant frequencies with electrical properties of material then simulated using the three-dimensional finite element modeling. The electrical properties of material consist of dielectric constants and electrical conductivity can be determinate using a microstrip antenna sensor based on the resonant frequency and magnitude of S_{11}. In brief, the simulation results of this work are:

(a) The increase of the dielectric constant made the resonant frequency decrease significantly.

(b) The increase of the conductivity of the MUT led to the significant change of the resonant frequency.

(c) The relation between the magnitude of the reflection spectrum and the conductivity was not adequate for the conductivity evaluation.

Nevertheless, the moisture content possesses a strong relation between the dielectric property and the conductivity, and hence, the resonant frequency may a potential parameter for the evaluation of the moisture content in the agricultural products.

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Correlation Between Morphology and Starch Content, Water Content and Electrical Properties of Fresh Cassava Root

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Abstract

This paper presents the results of a study aimed at determining a correlation between morphology and starch content, as the key indicator of raw fresh cassava root quality, water content and the electrical properties of a fresh cassava root using a Reimann scale balance, dry matter content method and bioimpedance techniques, respectively. Fresh 12 month old cassava roots from the Kasetsart 50(Ku50) cultivar with fusiform shape in three sizes of small, medium and large were tested in this. All the sizes were divided into three parts: head, middle and tail. The experimental results showed that the morphology ratio (diameter/length) of fresh cassava root was significant ($P \leq 0.01$) to the weight of the root only for the small size. Morphology correlation estimates between the size of fresh cassava root and starch and water content were significant ($P \leq 0.05$, 0.01 and 0.005) for head and tail section in the small and medium sizes, and for the middle section in the large size. Each different size had different percentages of starch content. The average percentage starch content in the large root was the highest. The middle part of the cassava root from the medium and small sizes had the highest percentage of starch. Moreover, the percentage water content in the middle part of the cassava roots from all the sizes was the highest. The water content was correlated with the starch content significantly ($P \leq 0.01$): a lot of moisture will result in a little starch and vice versa. The impedance between each size was not different. However, it was found that the impedance of the head section was less than the middle and tail sections.

Keywords

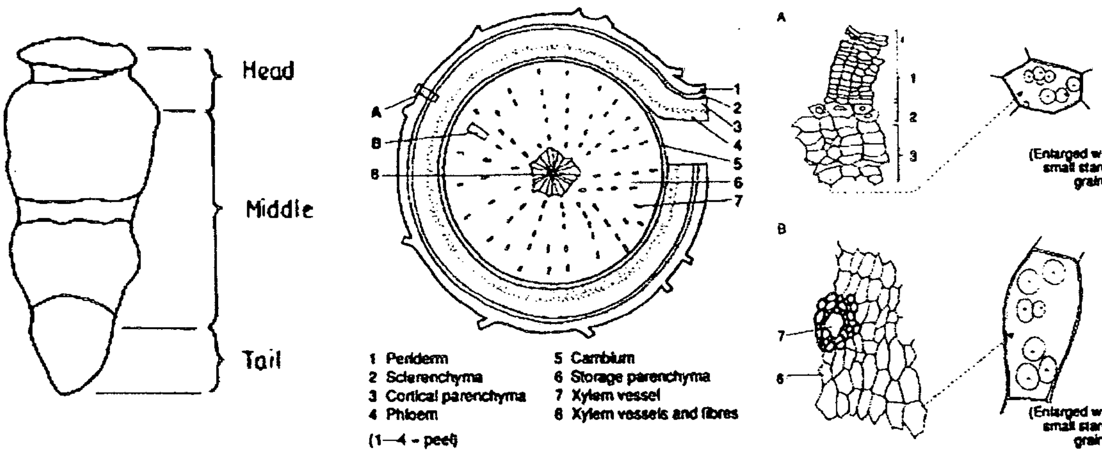
correlation, starch content, water content, electrical properties, fresh cassava root, Reimann scale balance , bioimpedance

INTRODUCTION

Cassava *(Manihot esculenta Crantz)* is a very important economic plant because of its starch production, which is a major ingredient for the ethanol and food production industries and as a raw material for animal feed. It is the third most important source of calories in the tropics after rice and maize (Rolland-Sabate et al., 2012).

The shape and morphology of a cassava root are shown in Figure 1(a) and (b). The shape of the cassava roots depends on the soil conditions under which the plants grow, and consists of cylindrical, conical, fusiform and cylindrical-conical forms. The fusiform shape is shown in Figure 1(a). It is usually elongated, has depressions and crevices along its length and tapers to one end. In most cases, the middle part has a fairly constant diameter. Whereas the head end has a relatively large diameter, and the tail end has a considerably smaller diameter when compared with the middle part. The head and tail ends are generally referred to as the proximal and distal ends, respectively (Adetan et al., 2003). At its proximal end, the tuber is joined to the rest of the plant by a short woody 'neck' (Onwueme, 1978). The cross-section of a cassava root, shown in Figure 1(b), contains the periderm, schlerenchyma, cortical parenchyma, phloem, cambium, parenchyma and fibers. The periderm, which consists of a few layers of dead cells that seals off the surface of the cassava root, varies in color and can be thick and rough or thin and smooth. The cortex is the layer of cells just below the periderm. It consists of the schlerenchyma, cortical parenchyma, phloem and cambium. The color of the cortex can vary from white or cream to pink. The peel of a cassava root consists mainly of the cortex and periderm. The parenchyma is the central portion of the cassava root and consists largely of storage parenchyma cells that derive from the cambium. The parenchyma is the main storage region of the plant where starch grains are deposited. Its color can vary from white to cream or yellow. A yellow color is an indication of high carotene. Fibers, made up of xylem bundles, form the root's central region. The fiber content and toughness depend on environmental conditions and plant age (International Institute of Tropical Agriculture, 1990).

Recently, Thailand has become the third greatest producer of cassava in the world, after Nigeria and Indonesia (Food and Agriculture Organization, 2012). There was a reported 1,479,584 hectares of cassava planted with an average production rate of 561 kg hectare^{-1} producing 29,848,491 tons per year (Office of Agricultural Economics, 2013). Most of it is planted in two seasons, the early rainy season (March-May) and the late rainy season (November-February), depending on the growing area. The harvest period is about 8-18 months after planting, with the decision on when to harvest based on market price and not the root weight or starch quantity (Prammanee et al., 2010). In general, the starch properties are significantly influenced by the stage of development of the plant and the botanical source. As verified for most cereals, amylase content is lower in the early stages of grain development (Inouchi et al., 1984; Asaoka et al., 1985). A similar trend between amylase content and developmental age is also seen in potato, where increasing root size is associated with a greater amylase content (Geddes et al., 1965). This is however not the case during development of tuberous roots such as cassava (Asaoka et al., 1992; Sriroth et al., 1999) or sweet potato (Noda et al., 1992). Moreover, the properties of cassava starch are influenced by the type of food in the soil (Editorial, 2005; Corwin, 2005), cultivation conditions at time of planting, cultivation and rainfall, water stress (Santisopasri et al., 2001), age, cultivar, temperature during growth, time of harvest and environmental conditions during cultivation (Franck et al., 2011; Sriroth et al., 1999; Defloor et al., 1998a; Defloor et al., 1998b; Asaoka et al., 1992; Moorthy et al., 1986). In addition, studies have looked at cassava roots' properties such as phytochemistry, biotechnology (Ian et al., 2010), physical and mechanical (Adetan et al., 2003). Nevertheless, reports on the correlation between morphology from various sizes and sections of a fresh cassava root and starch content, water content and electrical properties have never been published. Therefore, this work reports the correlation between various sizes and sections of a fresh cassava root and starch content, water content and electrical properties using a Reimann scale balance, dry matter content method and bioimpedance techniques, respectively.



(a) (b)

Figure 1. Morphology of cassava root: (a) general morphology (Adetan et al., 2003) and (b) transverse section (International Institute of Tropical Agriculture, 1990).

MATERIALS AND METHODS

PLANT MATERIALS

The cassava roots used for this experiment were freshly harvested from a village in Mahasarakham Province from a farm at a latitude and longitude of 16.138453° and 103.183349°. They came from the commonly grown cultivar Kasetsart 50 from plants that were about 12 months old. In the course of the experiment the roots were categorized into three different classes, namely: small, medium and large sizes, while the clustering criteria include the combined features of length and diameter.

MEASURING TOOLS AND INSTRUMENTS

Soil properties

Soil samples were collected from a village in Mahasarakham Province from a farm and analyzed for texture using the hydrometer method, pH using a pH meter and phosphorus and potassium using the Mehlich 3 method.

Physical

A variety of tools and instruments were used to carry out different measurements on the cassava roots. A tape measure was used to measure the lengths of roots while the diameters of the roots were measured using a pair of Vernier calipers. The mass of each root was measured with a digital balance.

Starch content

The cassava root samples were collected 12 months after planting. Each root was cut into small pieces before weighing using a Reimann scale balance. The principle of the Reimann scale balance technique is based on the root's specific gravity. The fresh starch content was calculated using Eq. (1):

$$Starch\ content = 210.8 \times \frac{Weight\ in\ air}{(Weight\ in\ air - Weight\ in\ water)} - 213.4 \qquad (1)$$

Dry matter content

Dry matter content was determined using the method of Benesi et al. (2004). Four undamaged roots from each size of small, medium and big were randomly selected. The various sections of the selected roots were shredded into thin slices, mixed thoroughly and duplicate 200 g samples (w_1) were dried at 65 °C for 72 h. After removal from the oven, samples were weighed immediately (w_2). Dry matter content percentage (DM %) was calculated as follows: DM % = $100*(w_2/w_1)$.

Bioimpedance

The measurement of the impedance Z of a given cassava root can be performed using two different approaches. Applying a controlled amount of AC current to the cassava peel and measuring the response AC voltage is the first approach and the most common one (Gordon et al., 2005). The second methodology is done by applying an AC Voltage to the cassava peel and measuring the response AC current. In the first approach, the excitation AC current I and the response AC voltage are known from the measurement setup. The excitation AC voltage V and the response AC current are known in the second approach. From both the approaches the known values are enough to derive the complex impedance of the cassava peel by applying Ohm's law, which is given by:

$$Z = \frac{V}{I}(\Omega) \quad (2)$$

Where $Z = R + jX$

The electrical impedance (Z) is given by a complex relation that has two components; the first real part is denoted by R that is the resistive component of the impedance and the imaginary part is denoted by X that is the reactive component of the impedance. The bioimpedance measurement system is shown in Figure 2, and it consists of a constant current, two electrode sensors and the material under test (MUT), which is cassava peel.

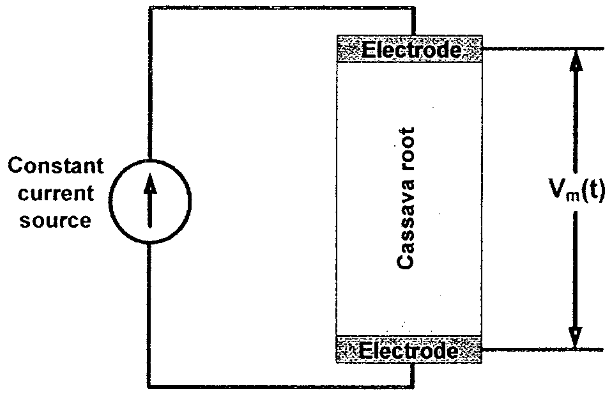


Figure 2. Bioimpedance measurement system.

Two electrode sensor

The two electrode sensor is shown in Figure 3. Two rectangular stainless plates (size 3.5cm x 8.0cm) were coated with acrylic resin (blue color). The active areas of the sensors were circle shaped (diameter 2.0cm).

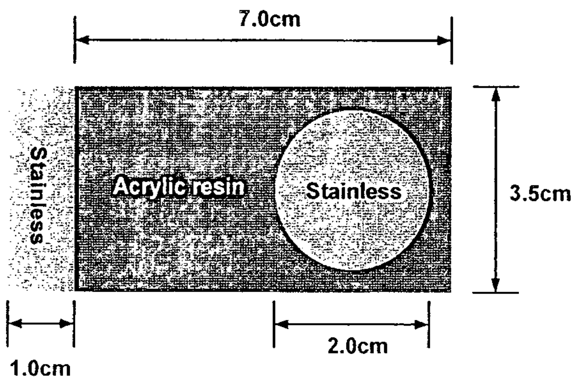


Figure 3. Schematic of the electrode.

Constant current source

A conventional method of obtaining an electrical bioimpedance measurement is by applying an AC current with constant magnitude to the biological tissue under investigation and measuring the response AC voltage across it. The current source for the stimulation of biological tissues is a basic functional part of an electrical bioimpedance measurement system. Implementing a current source that is able to deliver a constant magnitude current to the electrodes at the surface of the biological tissue is the main requirement of its design. Current sources can be divided into two categories depending on how the current is generated. In the first type, the current generation is controlled by the voltage at a point or points by an active component of the source. In the second category, active devices are in control of the generation of the current (Seoane et al., 2008). In this work the first category was implemented with the application of a single operational amplifier as a Voltage Controlled Current source (VCCS), which is an important part of Electrical Impedance Tomography (EIT) (Li et al., 2010). Many EIT applications use Howland current source models (Ross et al., 2003; Oh et al., 2007) due to the requirement for a large current output with a steady signal to noise ratio and large bandwidth as well as constant output over a wide range of resistor values. The proposed current source system in this work consisted of a voltage–to-current converter and buffer circuit as shown in Figure 4. A voltage buffer is used to significantly reduce the loading effect (Lin, 2012). The sinusoidal signal input (V_{IN}) had an amplitude of 10Vp-p and frequency of 100Hz that was converted to a current source with a Howland-base Op-amp circuit. The current signal was regulated to 1mA and supplied through the fresh cassava root. The mathematical model of the constant current is as follows:

$$I_{OUT} = \frac{-R_2}{R_1}\frac{V_{IN}}{R_X} \tag{3}$$

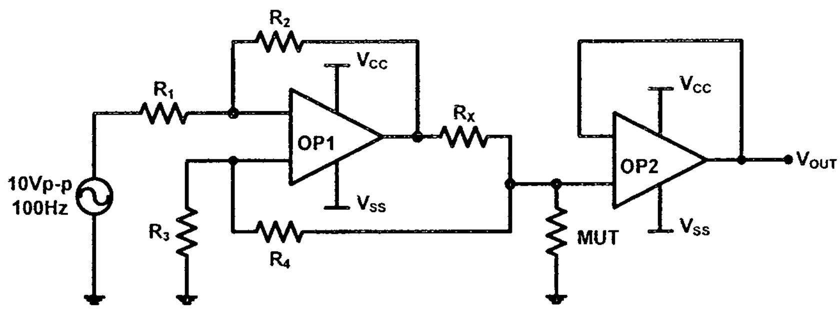


Figure 4. Current sources with the Howland-base Op-amp circuit drives grounded loads (Loe, 1967).

Experimental procedure

Fusiform shaped cassava root samples were collected and graded into small (diameter (d) < 25mm), medium (25mm≤ d ≤ 50mm) and large sizes (d > 50mm). The diameter was measured in the middle of the cassava root, which has a fairly constant diameter. For each size range 30 roots were considered during the experiment. The length and weight of each root was measured and recorded. The average of the length and weight was calculated per root. The fresh cassava roots from each size were divided into two groups. The first group was used for measuring the starch content and the second group was used for measuring the bioimpedance. Each fresh cassava root was divided into three parts: head, middle and tail. Each part had its starch content and impedance measured using the Riemann scale balance and bioimpedance, respectively. The experimental process is shown in Figure 5.

Steps when measuring starch content:

Randomly select cassava roots that weigh about 5 kg.

Weigh cassava roots in water.

Calculate starch content of cassava roots using Eq. (1).

Steps when measuring bioimpedance:

Slice cassava root in to sections 30mm thick.

Ensure diameter of slice cassava root is suitable for use with circular area of electrode.

Setup bioimpedace system by inserting the cassava peels between two electrodes and applying load.

Connect the current source to the two electrodes and measure the voltage cross it.

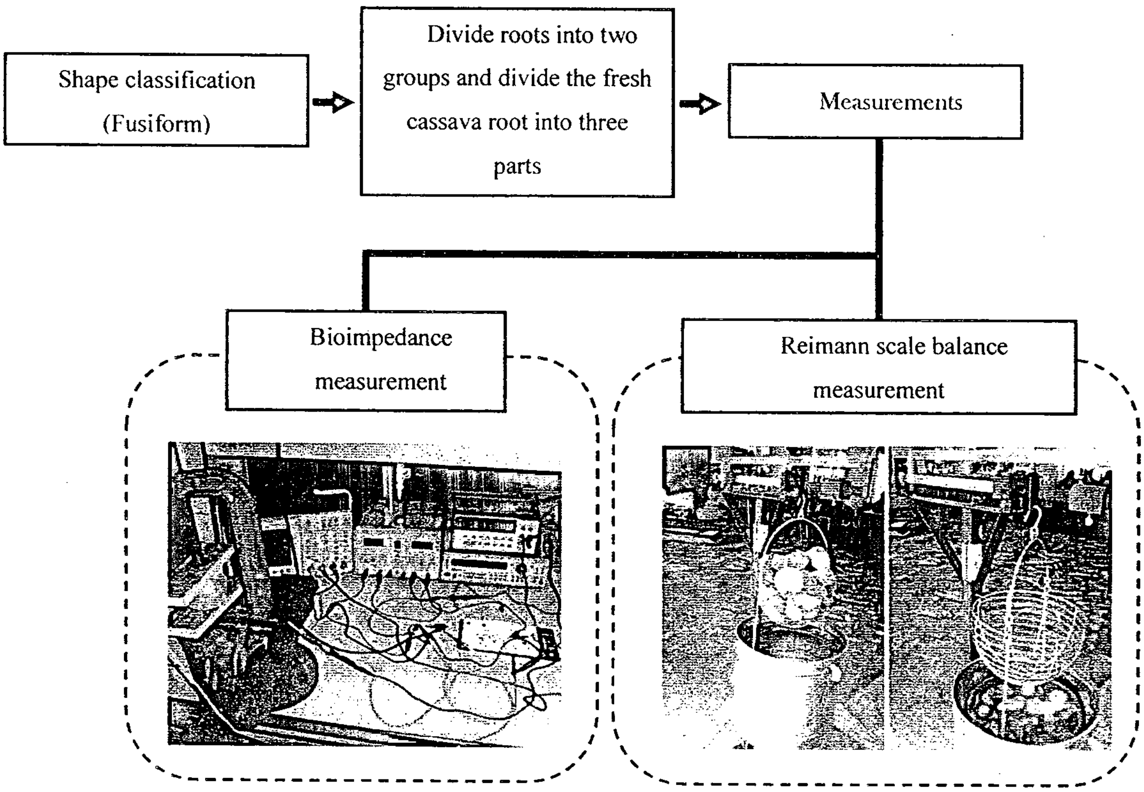


Figure 5. Flowchart of experimental process.

RESULTS AND DISCUSSION

The soils from a village in Mahasarakham province were slightly acidic sandy loam. Phosphorus (P) and potassium (K) values for the top soil as shown in Table 1.

Table 1. Soil properties of village in Mahasarakham province.

Soil level	Alt. masl	Textural class	pH	P(ug/g)	K(cmol/kg)
top soil (0-45cm)	168.03	Sandy loam soil	5.25	10.00	40.08

Alt. = Altitude; masl = Meters above sea level; P = Phosphorus; K = Potassium

In this work the size was graded using the diameter (d) with the ranges: d < 25mm for small size, 25mm<d<50mm for medium size and d > 50mm for large size. The data obtained from the experiment shows that the fresh cassava roots' average length was 21.6 cm for the small size, 25.5 cm for the medium size and 33.3 cm for the large size. The average weight of the cassava roots was 78.5 g for the small size, 280 g for the medium size and 689 g for the large size as shown in table 2.

Table 2. Average fresh root diameter, length and weight of Kasetsart 50 measured at different sizes.

Cultivar	Sizes								
	Small			Medium			Large		
	Root diameter (mm)	Root length (cm)	Root weight (g)	Root diameter (mm)	Root length (cm)	Root weight (g)	Root diameter (mm)	Root length (cm)	Root weight (g)
KU50	23.1±0.02	21.6±0.42	78.5±31.4	41.5±0.05	25.5±0.37	280±55.8	59.6±0.04	33.3±0.67	689±136.4

Table 3. Morphology ratio of cassava root and weight correlation.

Morphology ratio (Diameter/Length)	Weight
Small	-0.519*
Medium	-0.185
Large	-0.530

* Significant at 0.01 level of significance

The correlations between various sizes and parameters of the fresh cassava roots ranged from moderately high to very high (r = 0.6 – 0.99) for all three size tested and the starch content correlation was high for the small size in the head and tail sections (r = 0.948 and 0.885) and for the medium size in the tail section (r = -0.903); moderately high for the medium size in the head section (r = -0.738), for the large size in the tail section (r = -0.711) and for the small size in the middle section (r = 0.638); and low for the medium size in the middle section (r = -0.391) and for the large size in the head and middle sections (r = 0.215 and -0.376). This indicates that both small and medium sized head and tail sections are more closely related to starch content than the large size in each section and medium size in the middle section. With the three sizes tested the water content correlation was high for the small size in the head and tail section (r = 0.969 and 0.923) and for the large size in the middle section (r = -0.975); moderately high for the small size in the middle section (r = 0.628) and for the medium size in the tail section (r = -0.723); and low for the medium size in the head and middle sections (r = 0.475 and 0.294) and for the large size in the head and tail sections (r = -0.258 and 0.241). The water content correlation showed a similar trend as that of the starch content for the small size. The only difference was that the large sized middle section and water content were not correlated as with the starch content, but a weak correlation was observed with the water, as shown in table 4.

Table 4. Various sizes (below diagonal) and parameters of fresh cassava root (above diagonal) correlation matrices.

	Length	Weight	Starch content			Water content		
			Head	Middle	Tail	Head	Middle	Tail
Small (diameter)	0.919***	0.943***	0.948***	0.638	0.885**	0.969***	0.628	0.923***
Medium (diameter)	-0.023	0.893**	-0.738*	-0.391	-0.903**	0.475	0.294	0.723
Large (diameter)	0.522	-0.401	0.215	-0.376	-0.711	-0.258	-0.975***	0.241

*, **, *** Significant at 0.05, 0.01 and 0.005 levels, respectively

Figure 6 shows the percentage of starch in different sections of the fresh cassava root. The experimental results show that the average percentages of starch in the small, medium and large sizes were approximately 28.21±0.99%, 28.84±0.74% and 29.36±2.53%, respectively. It was found that the average starch percentage in the large cassava root was higher than in the medium and small roots. Moreover, it was also found that every size of root had the highest amount of starch in the middle part. For the head of the fresh cassava roots it was found that the best size and starch percentage content could be achieved in the range medium (28.03±0.35%)>small (27.23±0.30%)>large (26.53±0.54%). For the middle it could be achieved in the range large (30.15±0.44%)>medium (29.48±0.17%)>small (29.20±0.41%). For the tail it could be achieved in the range large (31.40±0.47%)>medium (29.03±0.22%)>small (28.20±0.29%).

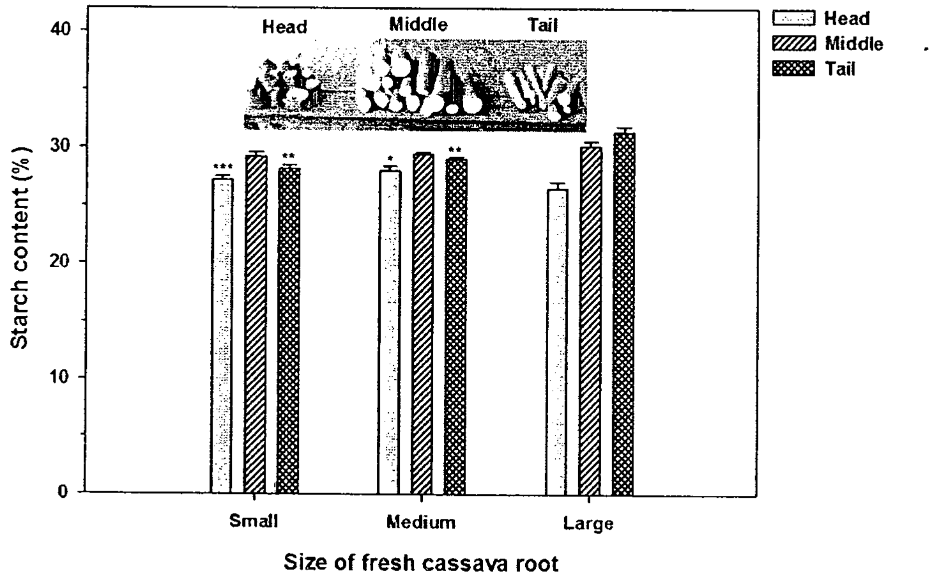


Figure 6. Correlation between size and starch content of fresh cassava roots. (*, **, *** Significant at 0.05, 0.01 and 0.005 levels, respectively)

The average moisture content in the head, middle and tail parts of the small sized cassava roots was 51.95±0.63%, for the medium sized it was 51.33±2.36% and for the large sized it was 49.76±1.40%. Moreover, it was also found that the middle part of the cassava root was the area with the highest moisture percentage in the small, medium and large sized roots as shown in Figure 7. For the small size of fresh cassava roots it was found that the various sections had the best water contents in the range middle (52.56±4.44%)>tail (51.99±4.38%)>head (51.30±2.74%). For the medium size it could be achieved in the range middle (53.65±4.80%)>head (51.41±4.65%)>tail (48.92±1.66%). For the large size it could be achieved in the range middle (50.99±1.72%)>tail (50.04±1.52%)>head (48.25±1.93%). The water content was very highly correlated with the starch content ($r = -0.955$) and was significant ($P \leq 0.01$): a lot of moisture will result in a little starch and vice versa.

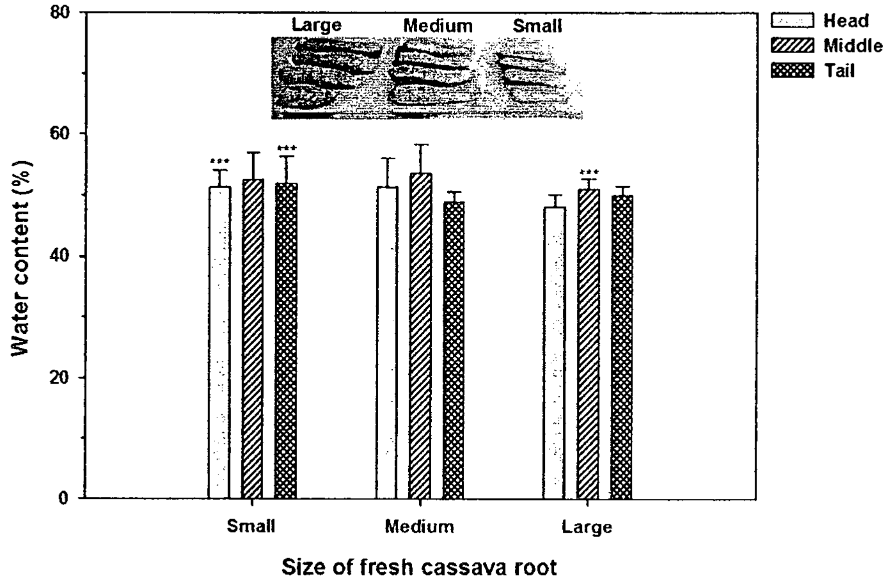


Figure 7. Correlation between size and water content of fresh cassava root. (*** Significant at 0.005 level)

Figure 8 shows the relationship between the thicknesses of the cassava root and the impedance measurements. It was found that the impedance of the cassava root was directly proportional to the thickness in a linear manner, which can be express by Eq. (4).

$$Z = \frac{\rho \cdot L}{A} \tag{4}$$

Where Z is impedance (Ω)

ρ is resistivity (Ω.m)

L is thickness of cassava peel (m)

A is area of cassava peel (m^2)

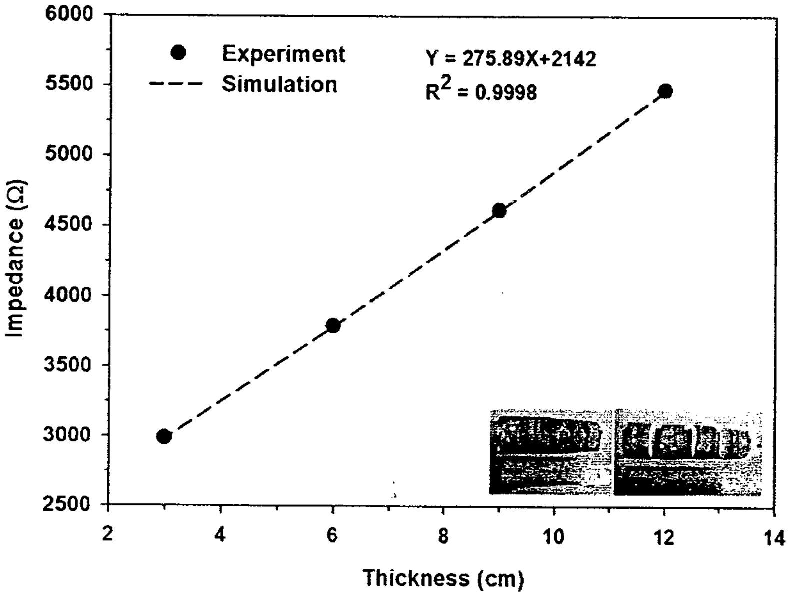


Figure 8. Relationship between the thicknesses and impedance of fresh cassava roots.

Fresh cassava roots were chosen with a diameter greater than the diameter of the sensor (2.0cm). They were divided into three sizes that consisted of small size (d < 25mm), medium size (25mm≤ d ≤ 50mm) and large size (d > 50mm). Figure 9 shows the relationship between the impedance and the various sizes and sections of the fresh cassava roots. The result shows that the average impedance of the head sections was 2.2kΩ. While the middle and tail sections were 3kΩ. The size of the cassava root did not significantly affect the impedance. The head section of the cassava roots has low impedance because the head mostly consists of fiber. The fiber is a hollow tube with water inside that can allow the electrical current to flow through the sample more easily than the middle section or tail fiber, which had smaller values.

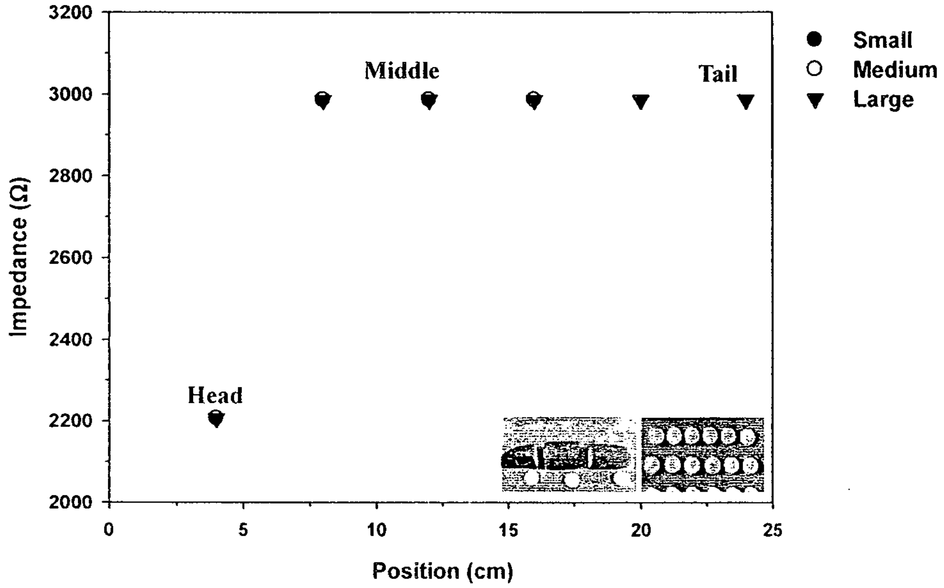


Figure 9. Relationship between the part and impedance of fresh cassava roots.

CONCLUSIONS

We have evaluated the starch content and electrical properties in various sizes and sections of fresh cassava roots. The starch content was evaluated using the Reimann scale balance method. While, the electrical property was evaluated using the bioimpedance method. Our main findings are as follows: (i) the starch content has a correlation with the size of a fresh cassava root in the order of large>medium>small, (ii) every size of root had higher amounts of starch in the middle section, (iii) the water content had a correlation with starch content where a lot of moisture results in a little starch and vice versa and (iv) the size of the cassava root was not significantly linked with the impedance but it was significantly linked with the section of the root. The head section of a fresh cassava root had lower impedance than the middle and tail sections.

ACKNOWLEDGEMENTS

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Electrical and Absorption Properties of Fresh Cassava Tubers and Cassava Starch

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ABSTRACT

The electrical and absorption properties of fresh cassava tubers and cassava starch have been studied using electric impedance spectroscopy and near-infrared spectroscopy at various frequencies. The dielectric constant, dissipation factor, parallel capacitance, impedance and absorbance of both materials were measured and analyzed. It was found that the electrical properties of fresh cassava tubers and cassava starch was a function of frequency. The dielectric constant, parallel capacitance and impedance dramatically decrease with an increasing frequency in the range of 10 kHz – 2 MHz. The dielectric constant of the fresh cassava tuber is more than that of cassava starch. However, the parallel capacitance and impedance of the fresh cassava tuber is less than that of cassava starch. The absorbance patterns of the fresh cassava tubers and cassava starch are the differences, in which the absorbance value and the absorbance peak of the fresh cassava tubers are higher and wider than for the cassava starch. The relaxation and dispersion of material was also observed in this study.

Keywords: electrical, absorption, cassava starch, fresh cassava tuber, impedance spectroscopy, near-infrared spectroscopy

1. INTRODUCTION

Cassava *(Manihot esculenta Crantz)* is a very important economic plant because of its starch production, which is a major ingredient for the ethanol and food production industries and as a raw material for animal feed. It is the third most important source of calories in the tropics after rice and maize [1]. Recently, Thailand has become the third greatest producer of cassava in the world, after Nigeria and Indonesia [2]. There was a reported 1,479,584 hectares of cassava planted with an average production rate of 561 kg hectare^{-1} producing 29,848,491 tons per year [3]. Most of it is planted in two seasons, the early rainy season (March-May) and the late rainy season (November-February), depending on the growing area. The harvest period is about 8-18 months after planting, with the decision on when to harvest based on market price and not the root weight or starch quantity [4]. The fresh cassava tubers and cassava starch have been thoroughly studied, for example, with regards to the stage of development of the plant and the botanical source [5], phytochemistry, biotechnology [6], physical and mechanical properties [7].

One of today's challenges in the study of food and agricultural products is to establish an exact relationship between the engineering properties of the food and the agricultural products' quality. The best solution would be to find some fast and non-destructive methods to determine the quality of the food and agricultural products.

The electrical properties of food and agricultural products have been of interest for many years [8] as the electrical properties of food and agricultural materials are believed to be sensitive to the product quality and could be used to follow changes in the structural properties. The electrical properties of many agricultural and food products have been studied, such as potato puree, mashed potatoes, common been, pork meat, wheat, egg, oils, cheese, cheddar cheese, cottage cheese, apples, grape juice and wine, beef meat, chickpea flour, legume flour, honey, soybean oil, watermelon, fishmeal, biscuit dough, grain, pecan, ham, tuna, edible oils, olive oil, milk, flaxseeds, safflower seed, garlic, mangoes and others [9]. Nevertheless, reports on the electrical and absorption properties of fresh cassava tubers and cassava starch have never been analyzed and published. Therefore, this work reports the comparisons between the electrical and absorption properties of fresh cassava tubers and cassava starch.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Fresh Cassava Tubers

The cassava tubers used for this experiment were freshly harvested from a village in Mahasarakham Province from a farm at a latitude and longitude of 16.138453° and 103.183349°. They came from the commonly grown cultivar Kasetsart 50 and from plants that were about 12 months old. A disc of about 5 mm thickness was cut from the middle of the tuberous root.

2.1.2 Cassava Starch

The cassava starch powder was manufactured by Kriangkrai Company Limited, Samutprakarn, Thailand. The powders were uniaxialy pressed at 3 MPa to form a disk of 20 mm diameter and 1.8 mm thicknesses.

2.1.3 Instrument

Electric impedance spectroscopy was performed with an Agilent E4980A Precision LCR meter, covering the frequency range 20 Hz to 20 MHz. The voltage had a magnitude of 1 V for all measurements. An Agilent 16451B dielectric material test fixture and guarded/guard electrode-B with a diameter of 5 mm were used. Near-infrared spectroscopy was used for the measurement absorbance.

2.2 Experimental Procedure

Cylindrical samples with a diameter of 30 mm and thickness of 5 mm were cut from the middle of fresh cassava tubers. The weights of the samples were measured by a digital balance. Both cylindrical samples were measured by electric impedance spectroscopy and near-infrared spectroscopy at various frequencies at room temperature. The dielectric constant, dissipation factor, capacitance, impedance and absorbance of both materials were measured and recorded.

2.3 Electrical Parameters

2.3.1 Dielectric Constant

The dielectric constant (ε_r) is indicative of the ability of the material to store energy and polarize when subjected to an electric field. The dielectric constant of a test material can be obtained using the following equations:

$$\varepsilon_r = \frac{thickness \times C_P}{A \times \varepsilon_0} = \frac{thickness \times C_P}{\pi \times \left(\frac{diameter}{2}\right) \times \varepsilon_0} \qquad (1)$$

where:

C_P = Equivalent parallel capacitance (F)

Thickness = Average thickness of test material (m)

A = Area of guarded electrode (m^2)

Diameter = Diameter of guarded electrode (m)

$\varepsilon_0 = 8.854\text{x}10^{12}$ (F/m)

2.3.2 Dissipation Factor

The dissipation factor (D) is the parameter that it is used to describe the quality of the components.

$$D = \frac{1}{Q} = \frac{R}{|X|} = \frac{1}{2\pi f C_p R_p} \tag{2}$$

where:

D = Dissipation factor

Q = Quality factor

R = Resistance (Ω)

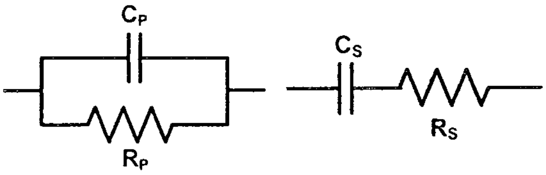
X = Reactance (Ω)

C_p = Parallel capacitance

R_p = Parallel resistance

2.3.3 Parallel Capacitance

To measure inductance (L), capacitance (C) and resistance (R), there are two equivalent circuit modes: the parallel and series modes, as shown in Fig. 1(a) and 1(b), respectively. To determine which mode is better, consider the relative impedance magnitude of the reactance and Rs and Rp. In this study, the samples were analyzed with small capacitance that yields large reactance, which implies that the effect of the parallel resistance (Rp) is relatively more significance than that of series resistance (Rs). The low value of the resistance represented by Rs has negligible significance compared with the capacitive reactance, so the parallel circuit mode should be used. The schematic structure of the electrode for the measurement of parallel capacitance is shown in Fig. 2 [10].



(a) Parallel circuit (b) Series circuit

Figure 1. Equivalent circuit modes

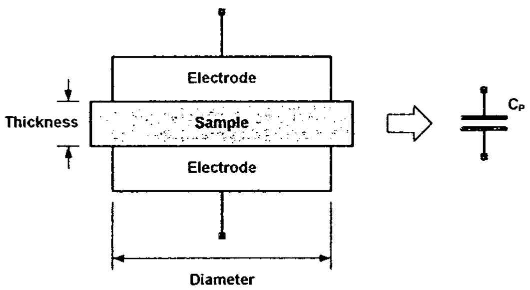


Figure 2. Schematic electrode structure for measurement of parallel capacitance

2.3.4 Electrical Impedance

The electrical impedance (Z) is given by a complex relation that has two components: the first real part is denoted by R that is the resistive component of the impedance and the imaginary part is denoted by X that is the reactive component of the impedance. The complex impedance of the test material is determined by applying Ohm's law, which is given by:

$$Z = \frac{V}{I}(\Omega) \quad (3)$$

where: $Z = R + jX$

2.3.5 NIR Absorbance

Near-Infrared (NIR) is a spectroscopic method that uses the near-infrared region of the electromagnetic spectrum and is based on overtones and combinations of bond vibrations in molecules. In NIR spectroscopy, the unknown substance is illuminated with a broad-spectrum (many wavelengths or frequencies) of near infrared light, which can be absorbed, transmitted, reflected or scattered by the sample of interest. The illumination is typically in the wavelength range of 0.8 to 2.5 microns (800 to 2500 nm). The light intensity as a function of wavelength is measured before and after interacting with the sample, and the diffuse reflectance, a combination of absorbance and scattering, caused by the sample is calculated. Light is absorbed in varying amounts by the sample at particular frequencies corresponding to the combinations and overtones of vibration frequencies of some bonds of the molecules in the sample. Specifically, the bond vibrations between oxygen and hydrogen (OH), carbon and hydrogen (CH) and nitrogen and hydrogen (NH) result in NIR absorbance bands.

3. RESULTS AND DISCUSSION

3.1 Moisture Determination

The moisture contents of fresh cassava tuber and cassava starch were 74.29±0.10 wt.% and 11.94±1.18 wt.% (wet basis), respectively.

3.2 Dielectric Constant and Dissipation Factor

The dielectric constant of the fresh cassava tubers and cassava starch as a function of frequency is presented in Fig. 3. The dielectric constant dramatically decreases with increasing frequency in the frequency range of 10 kHz - 2 MHz. At a frequency of 10 kHz, the dielectric constant of the fresh cassava tuber is 1,000 times that of the cassava starch. Moreover, the dielectric constant of the fresh cassava tuber is more than that of the cassava starch and this is caused by relaxation and dispersion of the material [11] and the moisture content is very high when compare with the cassava starch in the low frequency [12]. The dissipation factor of cassava starch dramatically increases when increasing the frequency range between 10 kHz-2MHz. The dissipation factor of fresh cassava tuber dramatically decreases when increasing the frequency range between 10 kHz-100 kHz and dramatically increases with increasing frequency in the frequency range between 100 kHz-2 MHz again. Moreover, the dissipation factor of the fresh cassava tuber is more than that of the cassava starch as determined by the Rp in the parallel circuit mode where the cassava starch is more than that of the fresh cassava tuber and this is caused by the moisture in the cassava starch that is less than in the fresh cassava tuber.

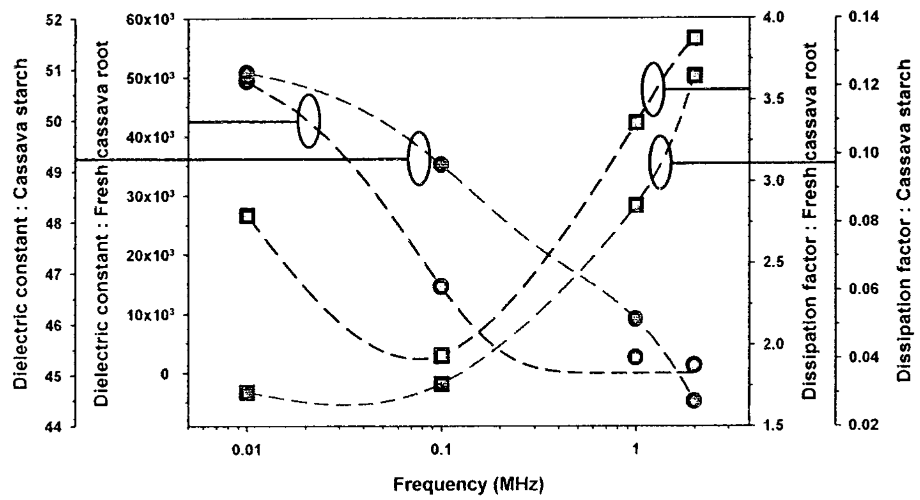


Figure 3. Dielectric constant and dissipation factor of fresh cassava tuber and cassava starch as a function of frequency.

3.3 Parallel Capacitance

Fig. 4 shows the parallel capacitance-frequency (*Cp-f*) curves of the capacitor measured with a magnitude of 1 V forward biases at room temperature. In the present study, forward bias represents that of the positive voltage that is applied to the stainless bottom electrode. The capacitance dramatically decreases with increasing frequency, especially in the frequency range of 10 kHz–2 MHz for fresh cassava tuber. Moreover, the parallel capacitance of the fresh cassava tuber is significantly more than that of the cassava starch with increasing frequency.

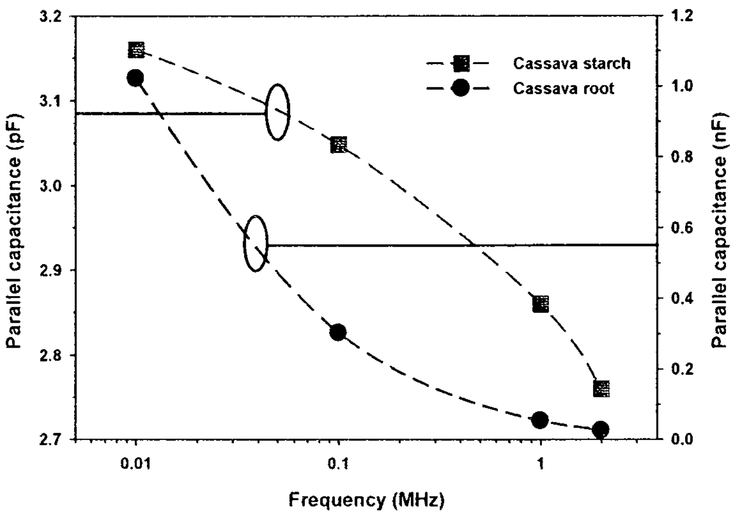


Figure 4. Parallel capacitance of fresh cassava tuber and cassava starch as a function of frequency.

3.4 Impedance

The impedance of the fresh cassava tuber and cassava starch as a function of frequency is presented in Fig. 5. The impedance dramatically decreases with increasing frequency in the frequency range of 10 kHz-2MHz. Moreover, the impedance of the fresh cassava tuber is smaller than that of the cassava starch, which is caused by the moisture content in the fresh cassava tuber being greater than in the cassava starch.

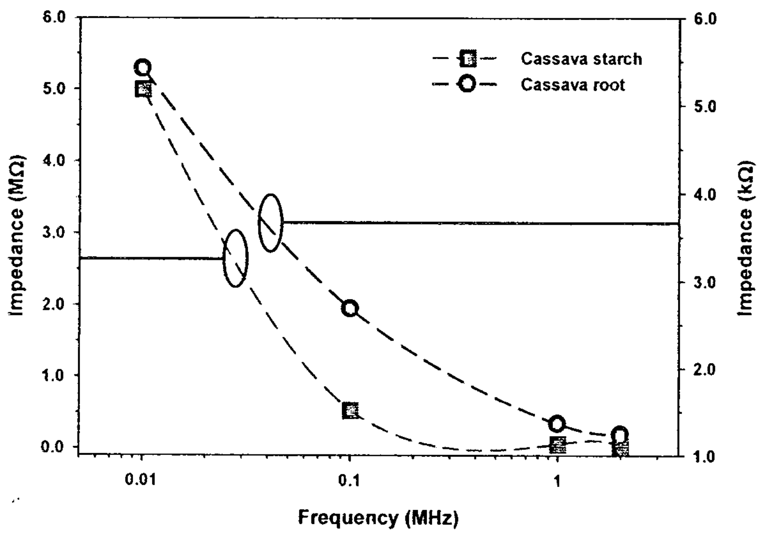
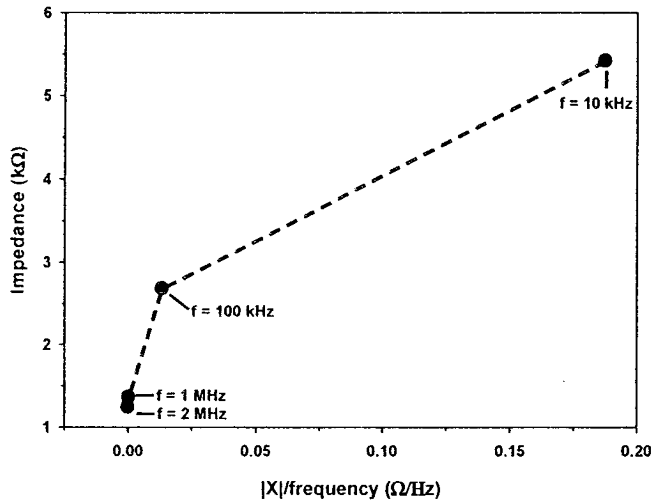


Figure 5. Impedance of fresh cassava tuber and cassava starch as a function of frequency.

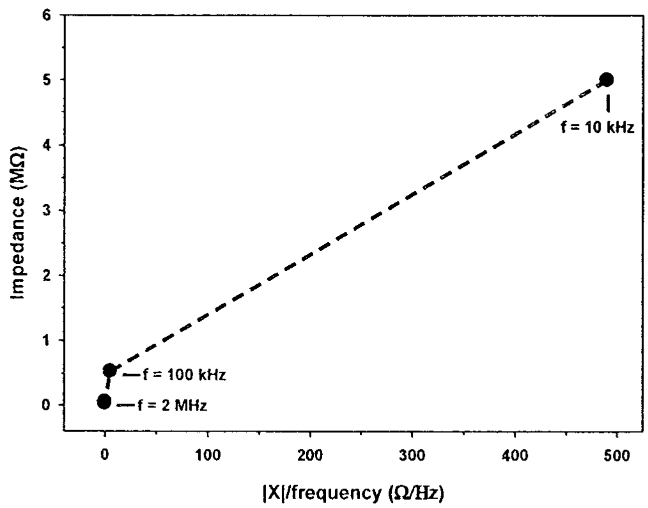
A corresponding plot of impedance versus |X|/frequency for the complex impedance spectrum under 1 V bias is shown in Fig. 6(a) and 6(b). Three well defined regions with different slopes are observed and shown in Fig. 6(a). The alternative impedance versus |X|/frequency representation, proposed by Abrantes *et al.*, [13] can distinguish the contributions from different relaxations with relatively small differences in time constants. Accordingly, the three regions in the frequency ranges of frequency < 100 kHz, 100 kHz < frequency < 1 MHz and frequency < 2 MHz may originate from three different dielectric responses, respectively. In principal, for bulk fresh cassava tuber material, the three observed responses from low to high frequencies can be attributed to the contributions from electrodes, grain boundaries and bulk, respectively. However, two well defined regions with different slopes are observed and shown in Fig. 6(b). The two observed responses from low to high frequencies can be attributed to the contributions from electrodes and bulk, respectively.

3.5 Absorbance

The spectrums of the fresh cassava tuber and cassava starch in the wave number range between 10,000 – 4,000 cm^{-1} (wavelength range between 1,000 – 2,500 nm) are presented in Fig. 7. The blue line is the spectrum of fresh cassava tuber and the red line is the spectrum of cassava starch. The wave number of 5,154.64 cm^{-1} (wavelength of 1,940 nm) shows the correlation with the moisture content of fresh cassava tuber and cassava starch, wave number of 4,329 cm^{-1} (wavelength of 2,310 nm) shows the relationship with Methylene (CH) and wave number of 4,750 cm^{-1} (wavelength of 2,105.26 nm) shows the relationship with OH combination [14]. Fig. 7 shows that the absorbance peak of fresh cassava tubers at the wavelength of 1,940 nm, which is higher and wider than cassava starch, that indicates the moisture content and molecule size of the fresh cassava tuber are larger than in the cassava starch. Moreover, both materials consist of an OH combination and Methylene (CH), which is observed from the absorbance peaks at the wavelengths of 2,105.26 nm and 2,310 nm, respectively.



(a)



(b)

Figure 6. Representation of impedance versus |X|/frequency for the complex impedance spectrum under 1 V bias. (a) Fresh cassava tuber and (b) cassava starch.

In addition, the absorbance of the fresh cassava tubers is larger than for the cassava starch in the wave number range between 1,000 cm^{-1} – 2,500 cm^{-1}.

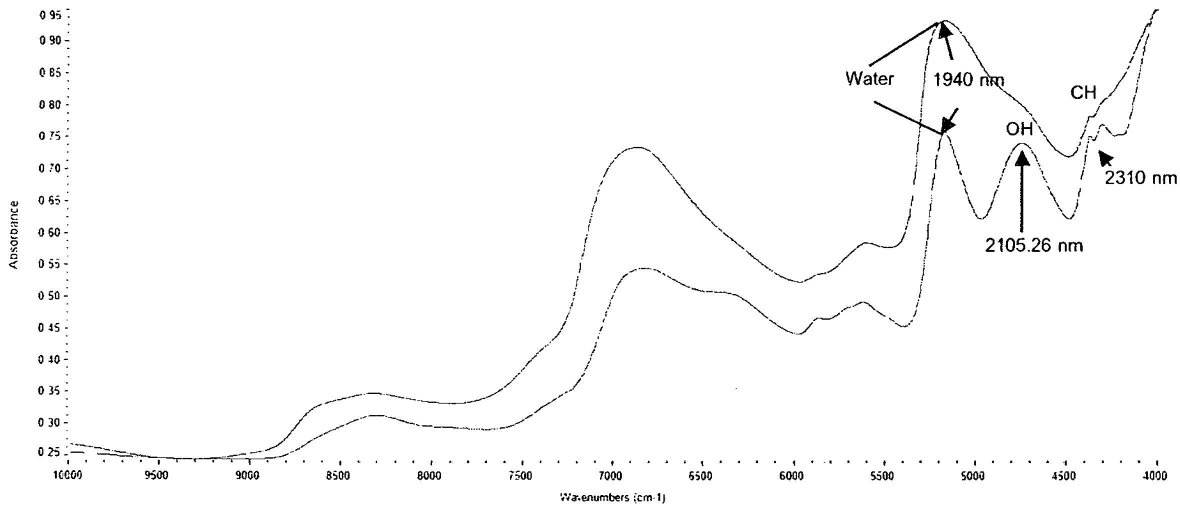


Figure 7. Absorbance of fresh cassava tuber and cassava starch as a function of wave number.

4. CONCLUSIONS

The electrical properties of food and agricultural products have been an active research goal because they are believed to be sensitive to product quality. The electrical and absorption properties of fresh cassava tubers and cassava starch have been compared and analyzed in this work. The electrical and absorption properties of fresh cassava tubers and cassava starch are a function of frequency. The dielectric constant, parallel capacitance and impedance of both materials dramatically decrease with increasing frequency, especially in the frequency range 10 kHz – 2 MHz. The dielectric constant of the fresh cassava tuber is more than that of the cassava starch. However, the parallel capacitance and impedance of the fresh cassava tuber is significantly small than that of the cassava starch. The bound and free water domains were found to affect the electrical and absorption properties as measured by impedance spectroscopy and near-infrared spectroscopy. This was due to modifications in the interactions among the macromolecular chains and with the water.

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