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Full Length Article

Estimation of Moisture in Maize Leaf by Measuring Leaf Dielectric Constant

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ABSTRACT

Leaf moisture of maize was estimated by variation of dielectric constant. These variations are measured via designed and manufactured capacitive sensors. Capacitance was measured at two frequencies (100 kHz & 1 MHz). The results showed that in all cases the best fitted curve for variations of dielectric constant in relation to leaf moisture percentage was in the form of $y=ae^{bx}$ exponential function (y is capacitance, x is leaf moisture content, a is coefficient & b is exponent). As leaf moisture increased, the dispersion of points around the line increased. Parameters '*a*' and '*b*' for different plants, different places of samples on each leaf and each frequency were not significantly different (p = 0.01). Coefficient '*b*' and coefficient of determination (R^2) decreased from top to bottom of the plants in 100 kHz frequency. The R^2 in 100 kHz frequency were higher than 1 MHz.

Key Words: Capacitance; Real-time measurement; Plant water stress

INTRODUCTION

Water is one of the indispensable parts of a plant's need. Water deficiency affects quality and quantity of crop yield and finally results in plant death (Noggle & Fritz, 1976). Over-irrigation ends up in low water use efficiency and plant resistance to water shortage, increases the damages by some pests and diseases and reduces soil air. So, irrigation scheduling is of crucial importance. For this purpose, if the amount of internal water content of plant is known, recognition of water stress would be possible. Different methods exist for estimating the internal water content of plants. But those methods that do not use the plant directly cannot give proper estimation (Kramer, 1983) and direct methods are not applicable in real-time mode.

One of the characteristics of liquid water is the existence of relative high dielectric constant among its molecules (80 at room temperature) that is utterly different from most materials (Elliott, 2000; Jones *et al.*, 2002). As a result, this parameter is used to measure moisture in soil (Seyfried & Murdock, 2004) and other substances. Generally, the dielectric constant of a leaf is a function of water content and frequency (Chuah *et al.*, 2003).

Chuah *et al.* (2003) measured dielectric constants of leaves of rubber (*Heavea brasiliensis*) and oil palm (*Elaeis guineensis*) at microwave frequency region. A semi-empirical formula for the complex dielectric permittivity of leaves from different plants is found covering the frequency range of 1 to 100 GHz (Matzler, 1994). The formula is applicable to fresh leaves. These two researches are more applicable in remote sensing.

Most of the sensors used in dielectrometry are capacitive in nature. Capacitive sensors have the advantage of high measurement accuracy and noninvasiveness. The simplest example of a capacitive sensor is a parallel-plate capacitor (Mamishev *et al.*, 1999).

In the present research, capacitive method is utilized to measure dielectric constant of maize leaves. This method is easier and cheaper, leaves are not damaged and real-time measurements as well as closed-control systems are possible.

Any factor that causes changes in materials and physical shape of a substance can end up in change in its dielectric constant (Elliott, 2000). Thus, leaf dielectric constant is assumed as:

$$K_L = f(\omega, t, I, M, T, C) \tag{1}$$

where, K_L = leaf dielectric constant, ω = applied frequency, t = leaf temperature, I = type and amount of ions, M = moisture content, T = type of leaf tissue and C = chemical composition of leaf. Factors that may have impacts in this regard are type of plant, plant age, leaf location on the plant, place of sampling on the leaf, leaf diseases, pests, air temperature, nutritional level in the soil and external substances (dust & dew) on the leaf surface.

Capacitance (Farad) in an ideal flat capacitor is obtained by the following relation (Reitz *et al.*, 1979):

$$C = K\varepsilon_0 \frac{A}{d} \tag{2}$$

where ε_0 = permittivity of vacuum (8.854 × 10^{-12} F m^{-1}), A = area of a capacitor sheet (m^2) and K = dielectric

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constant of the material between the sheets of capacitor. If the dielectric material has two parallel layers with capacitor sheets, which have dielectric constants K_1 and K_2 (thickness of d_1 & d_2), the capacitance relation is (Reitz *et al.*, 1979):

$$\frac{1}{C} = \frac{1}{K_1 \varepsilon_\circ \frac{A}{d_1}} + \frac{1}{K_2 \varepsilon_\circ \frac{A}{d_2}} \qquad (3)$$

Therefore, if the dielectric constant is measured by capacitive method, the thickness of dielectric material is important. So, thickness of the leaf is influential in this method.

Objective of this research is estimation of leaf moisture content by measuring its dielectric constant. The hypothesis of this experiment was that since dielectric constant of water is high, as leaf moisture increases, its dielectric will increase too.

MATERIALS AND METHODS

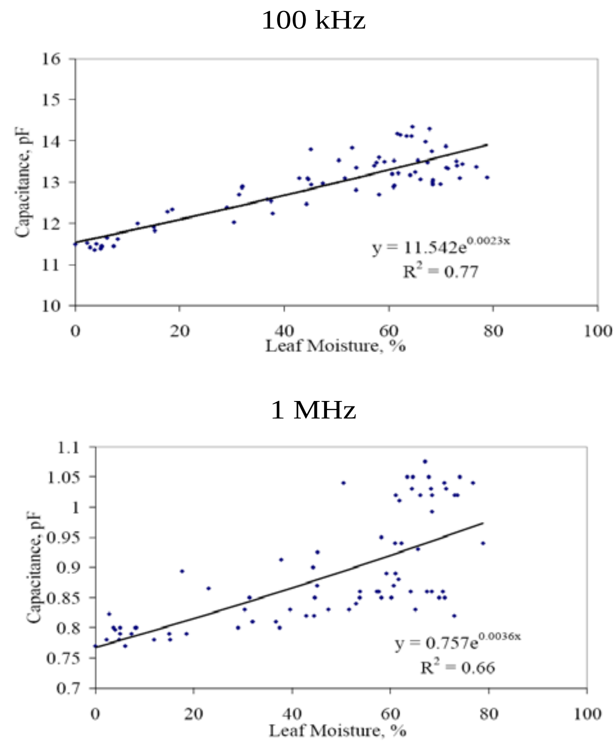
Two semi-oval isolated copper sheets (principal diameters of 4 & 3 cm) were stuck to two firm plastic plates, such that the space between the two sheets remains constant (1.3 mm). The combination of plastic plates and the copper sheets forms the capacitive sensor. The dielectric materials were plant leaf and the air between the sheets. Therefore, the equation that is used for capacitive sensor resembles Eqn 3. Keithly 590 was used as the capacitance-measuring instrument, which had the ability of measuring capacitance in two frequencies (i.e., 100 kHz & 1 MHz). Leaves were sampled neither from water-filled parts (main vein) nor from parts empty of water (leaf edge).

Experiments were performed on maize (*Zea mays*). Seeds were sown late May, 2006, in 40 × 40 × 60 cm pots and irrigated regularly until there were about 15 leaves on each plant. When measuring of dielectric constants started, all plants were at grain-filling stage.

Three hours before the initiation of the experiments, plants were fully irrigated. Three plants of maize were picked randomly. In each plant, one leaf was picked from top, middle and bottom sections. In one of the plants, samples were taken from tip, middle and close to petiole. In other cases, samples were taken from middle of the leaves. At every hour, leaf samples were inserted into the sensor and the capacitance was measured. Leaves were weighed after the readings. This procedure was continued until the samples became completely dry. Finally, leaf samples were put in 70°C oven for 24 h and their dry weight was measured thereafter. Air temperature in the laboratory was 20°C.

In this research, the effective factors on leaf dielectric constant were limited to variation of leaf moisture content and thickness of leaves was ignored. The statistical design of the experiments was Randomized Complete Blocks. SAS software was used to analyze the data.

Fig. 1. Graphs of all measured points of leaf moisture vs. capacitance for maize in two frequencies of 100 kHz and 1 MHz



RESULTS

In Fig. 1, all measured quantities of leaf moisture and capacitance are shown for 100 kHz and 1 MHz frequencies. In both cases, among different types of fitting lines to points (*e.g.*, linear, polynomial, power, logarithmic, etc.) the best-fit curve is in form of:

$$y = ae^{bx} \qquad (4)$$

where, y = capacitance (pF), x = leaf moisture content (percent weight), a = coefficient and b = exponent. It is seen from this figure that as the moisture content increases, the capacitance increases too. As moisture content increases, the dispersion of the points around the line increases.

In Tables I to III, statistical analysis of parameters of Eqn 4 for different plants, leaf location and sample location on the leaf are shown. The parameters for plants and location of leaf sample, in each frequency, were not significantly different ($p = 0.01$). The R^2 in 100 kHz is higher than 1 MHz frequency. This might be due to reduction of scale and as a result, an increase in measurement errors in 1 MHz frequency. In 100 kHz frequency, '*b*' decreases from top to bottom of plant.

DISCUSSION

The cause for variation of dispersion of points along the best-fit line (Fig. 1) might be the amount and type of ions in different leaf samples. Scaife (1998) states that

Table I. Statistical comparison of the parameters of Eqn 4 for different plants of maize

Plant	100 kHz			1 MHz		
Number	Ln(a)	b	R^2	Ln(a)	b	R^2
1	2.438[1]	0.0027	0.86	-0.235	0.0032	0.60
2	2.440	0.0022	0.78	-0.270	0.0029	0.58
3	2.450	0.0026	0.79	-0.310	0.0043	0.66

[1]Each value is obtained from the best fitted curve for each plant. Values of '*ln(a)*' and '*b*' in each column are not significantly different (p=0.01) based on Duncan Multiple Range Test

Table II. Statistical comparison of the parameters of equation 4 for different leaf locations

Leaf	100 kHz			1 MHz		
Location	Ln(a)	b	R^2	Ln(a)	b	R^2
Top	2.420[a]	0.0029[a]	0.86	-0.262[a]	0.0034[a]	0.75
Middle	2.460[a]	0.0020[b]	0.65	-0.309[a]	0.0031[a]	0.59
Bottom	2.471[a]	0.0017[b]	0.53	-0.295[a]	0.0043[a]	0.74

Each value is obtained from the best fitted curve for each leaf location. Values of '*ln(a)*' and '*b*' in each column followed by different letters are not significantly different (p=0.01) based on Duncan Multiple Range Test

Table III. Statistical comparison of the parameters of Eqn 4 for different sample locations on leaf

Sample Location	100 kHz			1 MHz		
	Ln(a)	b	R^2	Ln(a)	b	R^2
Tip	2.440[1]	0.0022	0.78	-0.251	0.0025	0.58
Middle	2.430	0.0025	0.82	-0.298	0.0035	0.60
Close to Petiole	2.470	0.0025	0.36	-0.275	0.0031	0.54

[1]Each value is obtained from the best fitted curve for each sample location. Values of '*ln(a)*' and '*b*' in each column are not significantly different (p=0.01) based on Duncan Multiple Range Test

polarization of free ions leads to a decrease in the internal electric field and consequently increases the dielectric constant. But by reducing moisture, ions' freedom decreases and as a result hinders polarization. So, the impact of diversity in quantity and type of ions increases in higher moisture contents. The intensity of this variation in dispersion is lower in 1 MHz frequency. By increasing the frequency, the time for polarization of ions decreases. Therefore, it is likely that the impact of diversity of the quantity and type of ions in higher frequency is lower.

Decrease in '*b*' at 100 kHz frequency might be the result of higher ion concentration in top leaves, which affects the dielectric constant (Table II). Generally speaking, dynamic ions were more available in top leaves (Gardner *et al.*, 1985; Fageria *et al.*, 1997). So it is possible that the effect of dynamic ions in increasing dielectric constant was more than stationary ions. This induction will be more pronounced as there was no significant difference between different locations of maize leaf in 1 MHz frequency.

The R^2 decreased from top to bottom of plant (Table II). Leaves from top to bottom get older and wrinkle more, while losing moisture. So, it is assumed that leaf wrinkling resulted in less accurate measurements of dielectric constant. It is likely that the difference between exponent '*b*' of leaf location was due to this error. By decreasing the space between the two capacitor sheets, this problem can be manipulated.

The results of this experiment were in accordance with our hypothesis. In all cases, as leaf moisture increases, the dielectric constant increases too. Jones *et al.* (2006) using a parallel plate capacitor found a strong relationship between moisture content and dielectric constant for greenhouse grown spinach.

One point was clear. There was no need to cut the leaves off the plants to measure dielectric constant. It could be performed, whilst the plants are standing alive. To apply the findings of this research to field situation, one more relation (other than Eqn 4) should be sought: the relation between leaf moisture content and leaf moisture potential. This relationship was unique for every crop. Then, it is possible to set the irrigation time.

CONCLUSION

The achieved regression model gives a relatively simple and suitable estimation of maize leaf moisture content by measuring dielectric constant. Estimations are more accurate in 100 kHz as compared to 1 MHz frequency. However, if a general model is required, 1 MHz frequency is more desirable. It appears that except for type and amount of ions and the leaf thickness, the rest of the factors make a very subtle error in this method. If plant age and type and amount of ions are considered, a generalized precise model will be developed to estimate leaf water content. This method can be employed to recognize water stress and time of irrigation in real-time mode without damaging the plants.

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