

Estimation of Leaf Moisture Content by Measuring the Capacitance

A. Afzal¹, S. F. Mousavi^{2*}, and M. Khademi²

ABSTRACT

Water is one of the most vital constituents in plants. In this research, for an estimation of leaf moisture content, the variation of capacitance was employed. The variations were measured *via* designed and manufactured capacitive sensors. The objective of the research was to estimate leaf moisture content by measuring its capacitance for five agronomic crops. Experiments for measuring leaf capacitance were performed on maize, sorghum, capsular bean, white bean and sunflower at two frequencies of: 100 kHz and 1 MHz. The results showed that in all cases the best fitted curve for variations of the capacitance in relation to leaf moisture percentage was in the form of an exponential function namely: $y = ae^{bx}$ (where y is capacitance, x is leaf moisture content, a is the linear coefficient, and b is the exponential coefficient). Parameters a and b for different plants of each crop and each frequency were not significantly different at 1% probability level. However, these coefficients were significantly different among different crops. Coefficients of determination were higher at 100 kHz than at 1 MHz. It was also observed that the higher the leaf moisture the more the data points scattered around the best-fit line, although the scattering was more uniform at 1 MHz.

Keywords: Dielectric constant, Moisture sensors, Real-time measurement.

INTRODUCTION

Water is one of the indispensable parts of a plant's growth needs. Water deficiency brings about low quality and quantity of the yield and finally results in plant death (Noggle and Fritz, 1976). Over-irrigation on the other hand also causes low water use efficiency and low plant resistance to water shortage, increasing the damages by some pests and diseases, and as well as the reduction of soil aeration. Thus, calculating or measuring the appropriate time for irrigation is of crucial importance in agricultural applications. For this purpose, if the amount of internal water content of a plant can be assessed, the detection of

stress due to water deficit would be possible. A variety of methods exist for estimating the internal water content in plants. However, methods that do not use the plant directly cannot provide one with a precise estimation (Kramer, 1983) and direct methods on the other hand are not applicable in real-time mode.

One of the characteristics of liquid water is the relative high dielectric constant among its molecules that is substantially different from that in other materials (Elliott, 2000). The dielectric constant of water (80 at room temperature) is considerably greater than that of air (1) or soil solids (2–5) (Jones *et al.*, 2002). As a result, this parameter is employed to measure moisture in soil (Seyfried and

¹ Department of Agricultural Machinery, College of Agriculture, Isfahan University of Technology, Isfahan 84156-83111, Islamic Republic of Iran.

² Department of Water Engineering, College of Agriculture, Isfahan University of Technology, P. O. Box: 84156-83111, Isfahan, Islamic Republic of Iran.

* Corresponding author; e-mail: mousavi@cc.iut.ac.ir



Murdock, 2004), biological substances (Stuchly and Stuchly, 1980), and in food (Li *et al.*, 2003). In general, the dielectric constant of a leaf sample is a function of the water content within the leaf and the measurement frequency (Chuah *et al.*, 2003). Chuah *et al.* (2003) measured dielectric constants of leaves of two tropical crops, rubber palm (*Heavea brasiliensis*) and oil palm (*Elaeis guineensis*) at the microwave frequency region.

A semi-empirical formula for the complex dielectric permittivity of leaves from different plants has been found by Matzler (1994), covering the frequency range of 1 to 100 GHz. The formula is applicable to fresh leaves. These two methods are more applicable in remote sensing applications. An electrostatic free-space system acting as a parallel plate capacitor has been designed and tested to estimate water content and biomass in situ using greenhouse grown spinach by Jones *et al.* (2006). The attenuation of the transmitted signal through the system was strongly correlated with water content and dry biomass.

Real-time non-invasive moisture content sensing techniques are needed for online moisture measurement and control in food products. A dielectric spectroscopy-based system has been used for moisture determination in cookie dough by Li *et al.* (2003). Experiments were conducted with a concentric ring dielectric capacitive sensor in the frequency range from 10 Hz to 10 kHz.

Most of the sensors used in dielectrometry are capacitive in nature. Capacitive sensors have the advantage of high measurement accuracy and non-invasiveness. The simplest example of a capacitive sensor is a parallel-plate capacitor (Mamishhev *et al.* 1999; Shay and Zhan, 2002).

Any factor that causes changes in consisting materials and physical shape of a substance can result in change in its dielectric constant (Dunlap and Makower,

1945; Elliott, 2000). Thus, the dielectric constant of leaves is assumed as the following function:

$$\epsilon_r = f(\omega, T, I, M, L, C) \quad (1)$$

where ϵ_r is leaf dielectric constant, ω is the applied frequency, T is leaf temperature, I is the type and amount of ions, M is moisture content, L is the type of leaf tissue, and C represents the chemical composition of the leaf. Factors that may have impacts in this regard are type of the 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 on the surface of the leaf (dust and dew).

Capacitance (C , in Farad) in an ideal flat capacitor is obtained by the following relation (Reitz *et al.*, 1979; Scaife, 1998):

$$C = \epsilon_r \epsilon_0 A / d \quad (2)$$

Where ϵ_0 is the permittivity of vacuum ($8.854 \times 10^{-12} \text{ F m}^{-1}$), A is the area of a capacitor sheet in m^2 , d is the distance between the sheets in m, and ϵ_r is dielectric constant of the material between the sheets of the capacitor. If the dielectric material has two parallel layers with capacitor sheets, which have dielectric constants ϵ_{r1} and ϵ_{r2} (thickness of d_1 and d_2), the capacitance relation is (Reitz *et al.*, 1979):

$$\frac{1}{C} = \frac{1}{\epsilon_{r1} \epsilon_0 A / d_1} + \frac{1}{\epsilon_{r2} \epsilon_0 A / d_2} \quad (3)$$

The objective of this research was to develop a non-destructive, real-time measuring method by using the capacitance to estimate leaf moisture content. This method is simple and economical, leaves are not damaged and real-time measurements as well as closed-loop control systems are possible. Through this method, water stress in plants could be determined and the optimum time of irrigation be calculated.

MATERIALS AND METHODS

Two semi-oval isolated copper plates (diameters of 4 and 3 cm) were attached to

two firm plastic plates, so that the space between the two plates remained constant (1.3 mm). The combination of plastic plates and the copper plates forms the capacitive sensor (Figure 1). The dielectric materials included the plant leaf and the air between the copper plates. Therefore, the equation that was used for capacitive sensor resembles Equation (3). A Keithly 590 C-V Analyzer was used as the capacitance-measuring instrument, which had the ability of measuring capacitance at two frequencies of 100 kHz and 1 MHz. In all cases, the leaves were sampled neither from water-filled parts (main vein) nor from parts void of water (leaf edge).

Experiments were performed on five field crops of maize (*Zea mays*), sorghum (*Sorghum sp.*), capsular bean (*Phaseolus vulgaris*), white bean (*Phaseolus vulgaris*), and sunflower (*Helianthus annuus*). Seeds were sown in late May 2006 in 40×40×60 cm pots and irrigated regularly until emergence of 15-25 leaves on each plant.

Plants were fully irrigated three hours before the initiation of the experiments. From each crop, three plants and from each plant three leaves were randomly picked (as replications). Samples were taken from the middle part of a leaf. Leaf samples were inserted into the sensor and the capacitance was measured every hour. Samples were weighed following the readings. This procedure was continued until the samples were dehydrated at ambient conditions. Finally, leaf samples were completely dried out in an oven of 70°C for 24 hours to find

out their dry weights. Leaf moisture content was calculated on a wet basis. Air temperature in the laboratory was 20°C.

During the research, the effective factors to alter the dielectric constant of the capacitor were limited to variations in the leaf moisture content. Moreover, the methodology of the experiment was designed as to be close to applicable conditions. So, in all experiments the diversity of leaf thickness was ignored.

The statistical design of the experiments was Randomized Complete Blocks. SAS software was employed to analyze the data.

RESULTS AND DISCUSSION

Figures 2 and 3 show the measured capacitances versus leaf moisture content for the five crops and at 100 kHz and 1 MHz. In all cases, among different types of fitting lines to data points (*e. g.*, linear, polynomial, power, logarithmic, etc.) the best-fit curve was found out to be in the form of an exponential relationship:

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

where y is capacitance in pF , x is leaf moisture content in percent weight, a is the linear coefficient, and b is the exponential coefficient. Based on different sections of these figures, the measured capacitance was increased by an increased in the moisture content. Early measurements of carrots' dielectric properties by Dunlap and Makower (1945) at frequencies in the range of 18 kHz to 5 MHz showed that the

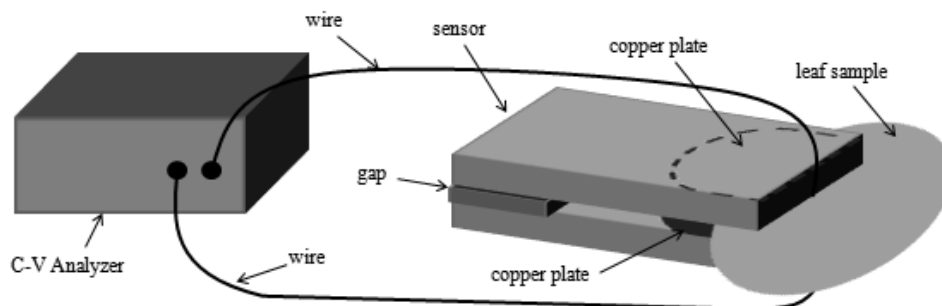


Figure 1. Schematic of the capacitance measuring system.



dielectric constant was largely dependent on moisture content as influenced by frequency, temperature, density, and particle size. In their research, the dielectric constant was essentially constant at moisture contents up to 6-8% and increased rapidly at higher moisture levels.

It is seen that moisture content increased the scattering of the points around the lines. The cause for this observation might be the amount and type of ions in different samples (in Equation 1, the type and amount of ions was predicted to have an effect on dielectric constant). Polarization of free ions leads to a

decrease in the internal electric field and consequently increases the dielectric constant (Elliott, 2000; Scaife, 1998). But by reducing moisture, ions' freedom decreases and as a result hinders polarization. Thus, the impact of diversity in quantity and type of ions increases at higher moisture contents. The intensity of this variation in scattering is lower at 1 MHz. Water molecules rotate around their axes for polarization. In contrast, ions move during polarization and they also need more time (Elliott, 2000; Forlich, 1990). Consequently, by increasing the frequency the time for polarization of

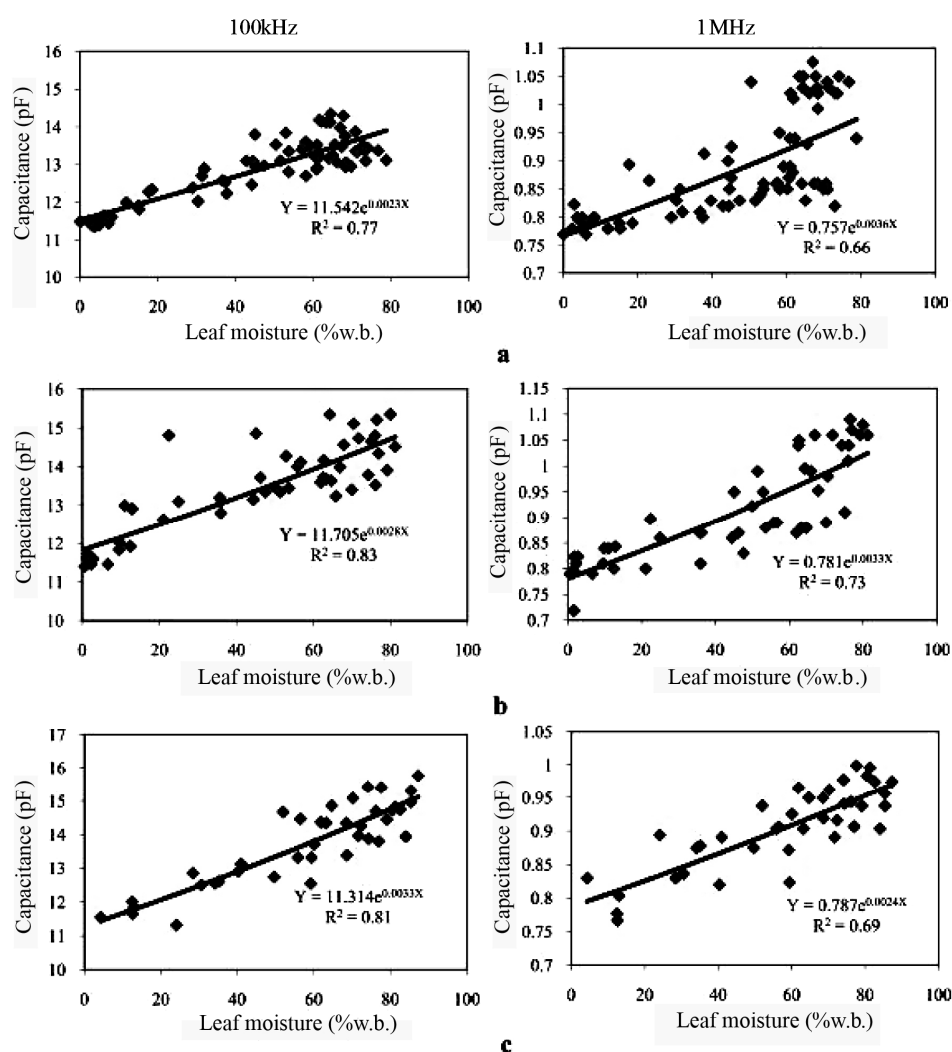


Figure 2. Graphs of all measured points of 3 types of crops at frequencies of 100 kHz and 1 MHz: (a) Maize; (b) Sorghum, (c) Capsular bean. In the equations inside the figure sections, y is capacitance, x is leaf moisture content, and R^2 is the coefficient of determination.

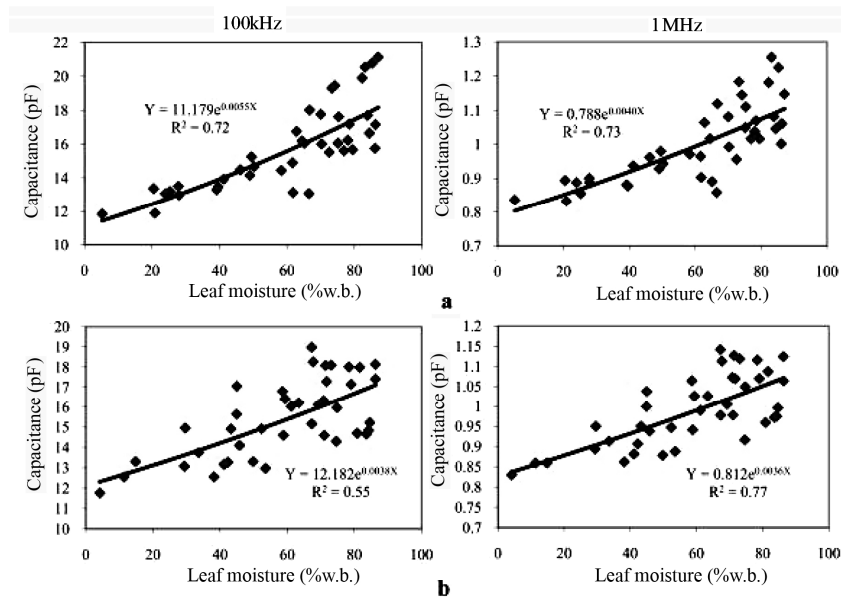


Figure 3. Graphs of all measured points of 2 types of crops at frequencies of 100 kHz and 1 MHz: (a) White bean, (b) Sunflower.

ions decreases. Therefore, it is likely that the impact of the diversity of the quantity and types of ions is lower at a higher frequency.

In most cases of Figures 2 and 3, the coefficient of determination was higher at 100 kHz than at 1 MHz. The possible cause for this observation is reduction of scale, and as a result, an increase in measurement errors at 1 MHz.

Statistical analysis on different parameters of Equation (4) for the five types of crops is shown in Table 1. Based on this table, parameters a and b for different plants of each crop and at each frequency are not significantly different. In Table 2, the analysis of all five types of crops and two frequencies are shown. At frequency of 100 kHz, there is no significant difference between the values of $\ln(a)$. In contrast, a subtle difference is observed for this parameter at 1 MHz, which may be due to measurement errors. It is therefore expected that the dielectric constant of dry leaves for these crops are similar.

At 100 kHz, sorghum exhibited the highest coefficient of determination (83%), while

sunflower showed the lowest (55%). At 1 MHz, sunflower exhibited the highest coefficient of determination (77%), while maize showed the lowest (66%). These four values were significantly different at 1% probability level. Meanwhile, the range of b coefficient for 1 MHz is smaller than 100 kHz. These comparisons support our finding that although the coefficients of determination at 100 kHz were higher than those at 1 MHz, it seems that 1 MHz should be preferred for a general equation relating leaf moisture content and capacitance.

At 1 MHz, there was very little difference observed among the b coefficients. At 100 kHz, this coefficient was very high for white bean. This crop bears small leaves. As a result, the number of lateral veins on leaves was higher than those for other crops' leaves. Thus, the average thickness of wet leaves of white bean samples was higher than that for other samples and the coefficient b of white bean at 1 MHz was also higher than that for other crops.

**Table 1.** Statistical comparison of the parameters of Equation 4 for different plants of each crop at frequencies of 100 kHz and 1 MHz.

Crop	Plant No.	100 kHz ^a			1 MHz ^a		
		$Ln(a)$	b	R^2	$Ln(a)$	b	R^2
Maize	1	2.438	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
Sorghum	1	2.454	0.0030	0.92	-0.275	0.0040	0.75
	2	2.477	0.0023	0.67	-0.215	0.0029	0.84
	3	2.440	0.0032	0.91	-0.274	0.0036	0.69
Capsular Bean	1	2.440	0.0029	0.88	-0.250	0.0021	0.74
	2	2.440	0.0034	0.70	-0.197	0.0021	0.56
	3	2.349	0.0040	0.80	-0.187	0.0016	0.60
White Bean	1	2.470	0.0045	0.55	-0.198	0.0035	0.69
	2	2.378	0.0057	0.57	-0.248	0.0036	0.62
	3	2.381	0.0059	0.90	-0.253	0.0046	0.86
Sunflower	1	2.469	0.0043	0.44	-0.294	0.0035	0.62
	2	2.494	0.0041	0.77	-0.222	0.0040	0.85
	3	2.629	0.0031	0.33	-0.189	0.0031	0.79

^a Each value is obtained from the best fitted curve for the plant. For each crop, values of $Ln(a)$ and b in each column are not significantly different ($P < 0.01$) based on Duncan Multiple Range Test. In the table, $Ln(a)$ is natural logarithm of coefficient a , b is exponent, and R^2 the coefficient of determination.

The exponential functions of Table 2 show relatively reliable estimates of leaf moisture content by measuring the capacitance. However, this may only be true for one stage of the considered crops. These models should be expanded for different vegetative and reproductive stages of the crops. Then, by relating type and age of plant to leaf moisture content, the time of irrigation may be determined by measuring leaf capacitance.

Although leaves were detached from the plant in this study, there is no need to cut the leaves off the plants for measuring their dielectric constant. This type of measurement could be performed whilst the plants are standing alive. To apply the findings of this research to field situation, one more relation [other than Equation (4)] should be sought namely: the relation between leaf moisture content and leaf moisture potential. This relationship is

Table 2. Statistical comparison of the parameters of Equation 4 for different crops at frequencies of 100 kHz and 1 MHz.

Crop	100 kHz ^a			1 MHz ^a		
	$Ln(a)$	b	R^2	$Ln(a)$	b	R^2
Maize	2.446 a	0.0023 c	0.77	-0.279 a	0.0036 a	0.66
Sorghum	2.460 a	0.0028 bc	0.83	-0.247 ab	0.0033 ab	0.73
Capsular Bean	2.426 a	0.0033 b	0.81	-0.240 b	0.0024 b	0.69
White Bean	2.414 a	0.0055 a	0.72	-0.239 ab	0.0040 a	0.73
Sunflower	2.500 a	0.0038 b	0.55	-0.208 ab	0.0036 a	0.77

^a Each value is obtained from the best fitted curve for the plant. In each column, values followed by the same letter are not significantly different ($P < 0.01$) based on Duncan Multiple Range Test. In the table, $Ln(a)$ is natural logarithm of coefficient a , b is exponent, and R^2 is the coefficient of determination.

unique for every crop. Then, it would be possible to set the irrigation time.

CONCLUSIONS

Under the conditions of this research, the achieved models provide us with a relatively suitable estimation of leaf moisture content by measuring the dielectric constant of leaves in five different types of crops. The thickness of the leaves was ignored in the models. The accuracy of this estimation was higher at 100 kHz as compared to 1 MHz. However, it seems that if a general model is required, for different types of plants 1 MHz should be a better choice of frequency. According to the results, it appears that except for type and amount of ions and the leaf thickness, the remaining factors contribute little to the error in this method. It is hoped that by adding coefficients to consider plant age, plant type, type and amount of ions, a generalized precise model can be developed to estimate leaf water content of different plants. This method can be employed for the detection of water stress and for adjusting the time of irrigation in real-time mode without damaging the plant.

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تخمین رطوبت برگ با اندازه گیری ظرفیت خازنی

۱. افضل، س. ف. موسوی و م. خادمی

چکیده

آب یکی از حیاتی ترین نیازهای گیاه است. در این پژوهش برای تخمین رطوبت برگ از تغییرات ظرفیت خازنی استفاده شده است. این تغییرات توسط یک حسگر خازنی که طراحی و ساخته شده است اندازه گیری شد. هدف این پژوهش تخمین رطوبت برگ با استفاده از اندازه گیری ظرفیت خازنی حسگر بوده است. تحقیق روی پنج نوع گیاه زراعی که عبارتند از ذرت، سورگوم، لوبیا کپسولی، لوبیا سفید و آفتابگردان در دو فرکانس 100 kHz و 1 MHz انجام پذیرفت. نتایج نشان داد که در همه موارد بهترین مدل برازش داده شده برای توصیف تغییرات ظرفیت خازنی بر حسب درصد رطوبت برگ به شکل فرمول نمایی $y = ae^{bx}$ است که در آن y ظرفیت خازنی، x درصد رطوبت برگ، a ضریب خطی و b ضریب نمایی است. پارامترهای a و b برای بوته های مختلف هر نوع گیاه و در هر دو فرکانس، در سطح احتمال 1% تفاوت آماری نداشتند. ولی این ضرایب برای نوع گیاهان مختلف متفاوت بودند. ضرایب تبیین مدل در 100 kHz بیشتر از 1 MHz بود. همچنین مشاهده شد که با افزایش رطوبت برگ پراکندگی نقاط داده در حول منحنی برازش داده شده افزایش یافت. ولی این پراکندگی در 1 MHz یکنواخت تر بود.