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Effect of Light and Water on *Schefflera* Plant Electrical Properties

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

The electrical parameters of *Schefflera arboricola* as a function of time and plant water uptake were monitored and reported here. Electrodes clamped and attached to the plant leaf, stem and soil along with a temperature sensor, a light sensor and a 10 GHz microwave sensor were used to simultaneously measure the electromagnetic properties of the plant and relate it to water uptake, light level, and temperature. The data collected was correlated with light intensity, temperature and moisture content of the soil. The leaf capacitance periodically decreased by 51 pF/hr during the night and increased by 62.3 pF/hr during the day. The plant stem capacitance, on the other hand, decreased by 0.8 pF/hr at night and increased by 18 pF/hr during the day. Its resistance increased by 3.6 KΩ/hr at night and decreased by 92.3 KΩ/hr during the day. The microwave reflection also changed periodically during the night and day. These experiments were repeated over extended period of time (4 days) with watering and drought cycles. The wet and the dry phases for the measurements gave distinct signature data that can be used to devise a sensor to optimize watering of the plant.

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Keywords: Capacitance; dielectric; light intensity; metabolism; microwave reflection; Schefflera arboricola; temperature.

1. INTRODUCTION

The plants electrical properties is expected to change as a function of water intake, light level, CO_2 and oxygen concentrations and aging. There have been numerous attempts to relate these parameters to the plant metabolism, stress and drought resistance. Afzal et al. [1] used capacitance to measure the moisture content in plant leaf. They reported a value of 14 pF, 15 pF and 16 pF as highest capacitance for maize, sorghum and capsular bean respectively for a fresh leaf at 100 KHz and 11.5 pF for a completely dried leaf of all the plants under the study. Their experiment was destructive and used a leaf that was cut. Other studies used inserted electrodes into the plant tissue. Plants tend to perspire a significant amount of water from the petiole. Zhang and Willison [2] calculated the amount of damage an electrode insertion can do to the plant tissue. They found that a 0.35 mm radius electrode could damage 0.4-0.5 mm collar of a leaf. Here we discuss plant measurement techniques that are non-intrusive and non-destructive and that can be potentially used to develop stand-alone sensors that can provide signals for plant watering.

For our study we used a common house plant *Schefflera arboricola* [3] also known as the dwarf umbrella tree. *Schefflera* is a genus of the flowering plants in the Araliaceae family. These plants are trees, shrubs and lianas which can grow 1-30 meters tall with woody stems. *Schefflera* consists of palmately compound leaves which allow equal distribution of water and food from the main vein. To correlate the plant's electrical properties with the soil moisture, we used gold electrodes inserted inside the soil and measured its resistance. The plants electrical properties were measured using a copper electrode strapped to its stem, two electrodes contacting the plant leaf and forming a capacitor, and microwave horn antennas that measured reflection and transmission of 10 GHz signals through the plant foliage.

All the plant measurements we developed here, measure the electrical (capacitance and resistance) and electromagnetic (complex permittivity) of the plant. These parameters, on the hand, are affected by the plant water uptake on an hourly basis. It is well known that the energy stored in the plant is related to the water potential ($\varPsi$) that varies as a function of light, time, temperature and moisture content of the soil [4]. The water potential can be represented as the change in chemical potential or the free energy per mole of water at a given temperature and pressure per partial molal volume of water. The water potential quantifies the amount of work needed to move 1 mole of water from one point to other and has a unit of pressure (Pa).The capacitance and resistance or the complex permittivity that were measure in our experiments can be directly related to the water potential variations that also determines the plant transpiration [5]. A simple electrical model of water potential was shown by Zhuang *et al.* where the plant can be seen as an electrical circuit with a potential Ψ_s at the soil and Ψ_l at the leaf. Due to the potential difference Ψ_l - Ψ_l , the water flows through different parts of the plant. The resistance of a path in the plant (R) and the corresponding capacitance (C) can be used to relate the water potential to the current (j_v) through a simple relationship: $j_v(t) = \frac{\varPsi_s - \varPsi_l^*}{R} - C\frac{d\varPsi_l^*}{dt}$ [6,7]. As the water content of the soil decreases, osmotic potential in the leaf is balanced by a decrease in stomatal conductance [6,7] that reduces photosynthesis and the plant growth rate. A dual mode microwave resonator [8] was used to show that the osmotic potential (Ψ_l) decreased from -0.55 Mpa to -1.55 Mpa as the plant was dehydrated losing 50% w/w water content in its leaf.

2. METHODOLOGY

2.1 Electrical Parameters of Leaf

The schematic and picture of the experimental set-up are shown in Fig. 1. The capacitance electrodes were 2 cm diameter copper tapes. We noticed that to enable the leaf to breath, we needed to have 0.1 mm diameter holes on these copper electrodes. The number of holes made on the bottom electrode was more than the upper electrode as the plant leaf contains more stomata at the lower portion [9]. This allowed the plant to exchange CO_2, O_2 and light for respiration and photosynthesis. The electrodes were supported by a thin plexiglass layer with matched holes. Álvarez-Arenas et al. [10] in their studies showed the relation between the ultrasound waves and the water content of the leaf and its thickness by

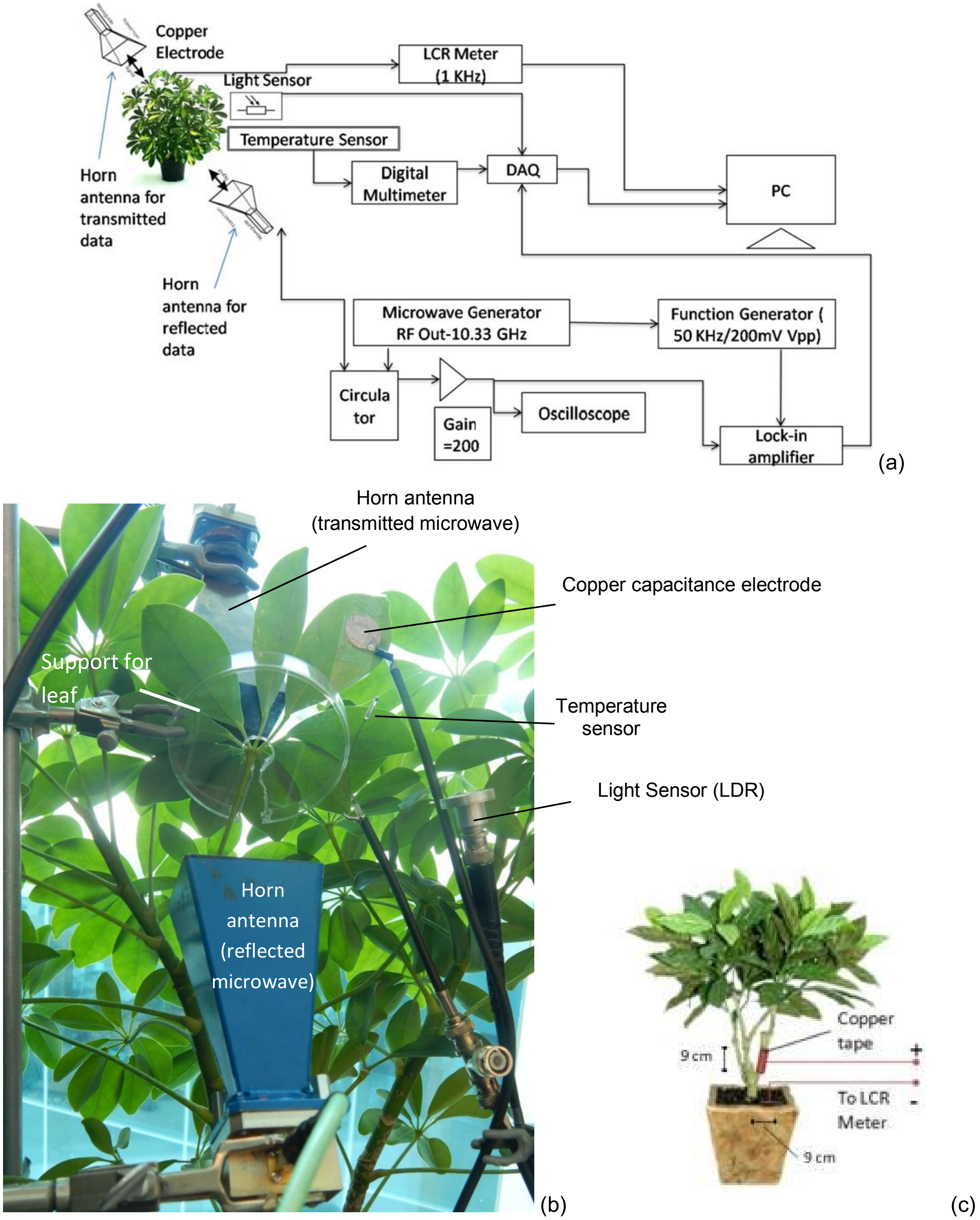


Fig. 1. a) Schematic of the experimental set-up used for the measurement of electrical parameters of the *Schefflera* plant. b) Optical picture of the experimental setup. c) A copper electrode wrapped around the plant stem and a gold electrode inserted in the soil nearby were used to measure the stem-soil capacitance and resistance

relating velocity variation to explain the water content. The capacitance (C) measured in our experiment can be related to the electrode area (A), permittivity of the plant ($\varepsilon_0\varepsilon_r$) and the leaf thickness (d) as:

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \tag{1}$$

Where $\varepsilon_0 = 8.854 \times 10^{-14}$ F/cm is the permittivity of the vacuum and the relative permittivity is a function of leaf temperature (T (θ)) [11], light (L) [12], humidity, soil moisture [13] (humidity and soil moisture together produce the potential ψ) and to some extent wind speed (V_w) [14].

$$\varepsilon_r = f(T(\theta), L, \Psi, V_w) \tag{2}$$

It is reasonable to assume that ε_r increases monotonously as a function of the leaf water content under normal and moderately stressed conditions. Thus, by measuring the capacitance, the moisture content of the leaf can be estimated provided that the variations in the leaf thickness can be assumed to be small. The experiment was done in the laboratory and we did not consider the wind speed that in the field can change the water evaporation rate leading to the modification of the permittivity.

The stem capacitance and resistance were measured between an electrode that was wrapped around the plant stem and a gold electrode that was inserted in the soil near the plant (Fig. 1). The stem capacitance/resistance is related to its water content as discussed above.

The microwave transmission and reflection through the plant leafs and foliage is related to the complex permittivity of the leaf, distance and volume. As the plant goes through hydration and dehydration, its structural properties change that modifies its posture. These physical changes can affect the stand-off distance between the foliage and the microwave receiver/transmitter. To alleviate this problem, we used a plexiglass (does not affect the 10 GHz microwave) to prop up plant leafs as shown in Fig. 1. The plexiglass prevented leafs from sagging as the plant went through the drought cycles. The leaf volume was more or less constant throughout our studies. Thus, the only parameter that modified the microwave reflection/transmission was the change in the complex permittivity of the plant that similar to its low frequency value shown in eq. 2 is affected by the leaf water content (Ψ, V_w), temperature ($T(\theta)$), and light level (L).

2.2 Calibration

The calibration procedure involved resetting the microwave reflected/transmission signals with a known object to cancel the electronic drift in the system, calibrating the photodetector output using a calibrated optical meter, and making sure that the fringing fields do not contribute to the leaf capacitor measurements. We used a light sensor that gave -2.24×10^{-3} V/0.03 Klux output for indoor lighting. The photodetector was characterized and we found that for a change of 2.32 Klux there was a change of 9.768×10^{-3} V. The horn antenna emitting and receiving the reflected microwave radiation at 10 GHz (modulated at 23 KHz) was placed directly below the portion of the plant with maximum foliage while the horn antenna detecting the transmitted microwave was placed above the foliage as shown in Fig. 1. The temperature sensor was sensitive to 0.1ºC variation and was placed near the plant. An Agilent LCR meter at 1 KHz was used to measure capacitance and resistance of the leaf and the stem.

2.3 Electrical Parameters of Plant Stem

The measurement at the stem was used as control experiment to understand the way plant takes water from the soil. The plant stem was wrapped with copper tape and was covered with an electrician black tape to avoid any external shorts and field effects. The copper electrode was attached to the stem at 9 cm above the soil level (Fig. 1c). The counter electrode was inserted in the soil near the plant. The stem-soil and leaf electrodes were connected to the LCR meter. The data from all the sensors were obtained using the LabVIEW interface on the PC. In some cases the sensor output was fed through a DAC board and in some other cases we used the parallel interface board to acquire the sensor data through a digital multi-meter.

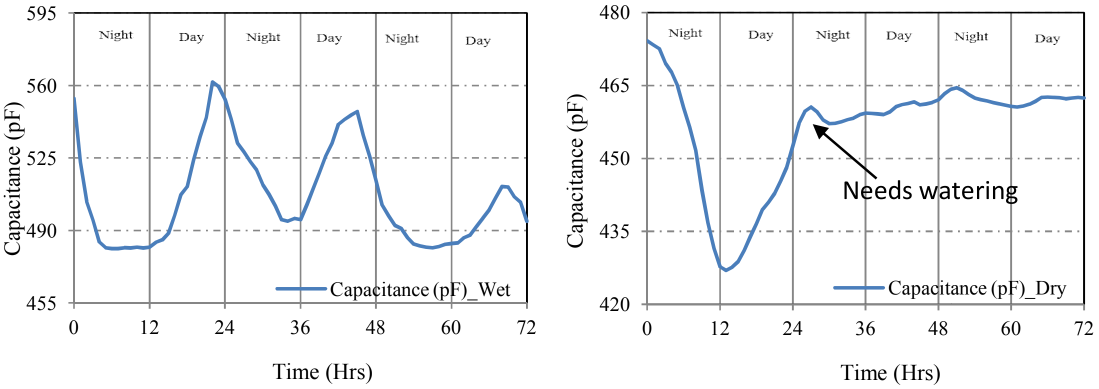
3. RESULTS

3.1 Leaf and Stem Capacitance/ Resistance

Fig. 2 shows the leaf capacitance variations as a function of time. First set of measurements was for the wet phase. After the initial drop from 640 pF down to 580 pF, the capacitance variation was periodic with around 24 hour period. The initial drop was observed with many different electrodes with different areas. The glued electrodes had a larger initial capacitance drop than the dry-pressed electrodes. The initial change can be attributed to the physical and electro-chemical stresses that the placement of the copper electrode induces in the leaf. In the wet phase the capacitance increased during the day time and decreased at nights. Assuming that the leaf capacitance is directly proportional to the water content of the leaf, the periodic variation of the leaf capacitance directly shows the hydration/dehydration of the leaf during the day/night cycles. Thus, when photosynthesis commences during the day, the plant water uptake increases and the leaf's moisture content increases as well.

We then measured the capacitance variation for the dry phase. In this set of measurements we did not water the plant regularly. The initial results were quite similar to those with regular watering due to the presence of moisture in the soil. However, as time passed and the soil started drying up and there were significant changes in the response of the plant. It can be clearly seen from Fig. 2b that the plant strongly reacts to the dehydration. This can be related to drought-induced lowering of the plant metabolism. In the drought phase, the plant was watered at 4 PM and 24 hours before the measurement shown in Fig. 2b was taken. For day 1 we observed the capacitance of 476.7 pF during the evening, about the time of sunset. As observed earlier too, the capacitance falls during the night and the value was 425.2 pF during the sunrise. At the time of sunrise the plant metabolism becomes prominent and the capacitance begins to rise. This rise was observed until the evening again with 462.7 pF being the capacitance at sunset. There was a decrease of 51.5 pF, as shown in Table 1, during the night and an increase of 37.4 pF during the day. However, this was drastically changed in the next few days. For the day 2 there was only a change of 4.5 pF which was a decrease of 86.69 % compared to day 1 and during the night the change observed was 95.15 % compared to the first night. The day/night capacitance cycles recover reversibly upon resuming the hydration cycles.

The capacitance value obtained at the leaf had opposite variation to the data obtained at the stem. During the day when plant undergoes rapid transpiration and photosynthesis, the bulk water content is in the leaves and that leads to an increase in the capacitance at the leaf. The stem during this duration acts as the supplier of water and nutrients to the leaves and hence shows a continuous decrease in capacitance.



(a) (b)

Fig. 2. Variation of the leaf capacitance as a function of time over 4 days. (a) The leaf capacitance is nearly periodic with 24 h period for the wet phase. Plant was watered every day at 4 PM and t=0 hour is at 5:30 PM and at 7:30 PM it was completely dark. (b) Variations of the capacitance as a function of time during the dry phase

Table 1. The table below compares the value of capacitance for the plant as the plant started to dry up

	*Day-1	*Night-1	Day-2	Night-2	Day-3	Night-3	Day-4
Capacitance (pF)	476.7	425.2	462.7	460.2	465.2	460	462.1
ΔC (pF)-Day	+37.4		+4.9		+2.1		
ΔC (pF)-Night	-51.5		-2.5		-5.1		

**Day here represents the value of capacitance at the sunset; Night represents the value of capacitance at sunrise*

The stem capacitance and resistance variation was found to be almost opposite to each other. We observed that the stem resistance during the day was 1108.06 KΩ as compared to 43.07 KΩ during the night. The average resistance during day was 3398.9 KΩ whereas it was 2738.8 KΩ during the night. Thus, the rate of change of resistance was found to be much larger during the day than night. This clearly indicated that in the presence of light plant performs photosynthesis and draws much larger amount of water from the soil. The rate of change of resistance was found to be approximately 28 times larger during the day. The same pattern was found for the capacitance variation at the plant stem. During the day the capacitance change was 216 pF whereas during night it was just 10 pF and similarly, average capacitance during day was 88.2 pF, due to large change and 107 pF during night. There was a change of 18 pF per hour during day and only 0.8 pF during the night, giving the same conclusion as obtained using the data for resistance. The calculation for the values obtained in the Table 2 was done using an approximation that the day started at 7:00 AM and night started at 7:30 PM. Both the day and night consideration are done keeping in mind the data obtained from the light sensor. Thus, the day and night variation was finalized by the duration of sunlight.

The resistance between the gold electrodes inserted into the plant soil was nearly constant around 10 KΩ during the day and night for the wet phase. The value dipped right at the time the plant was watered however it recovered its average value shown in Fig. 3. The data was however different for dry phase with a variation of 12 KΩ, 15 KΩ, 16 KΩ, 17 KΩ and 17 KΩ (the current being 10 μA) which was a clear indication of dehydration. Though this data can be useful for the sensor algorithm the electrode in the soil has disadvantages and hence we focused on the data from leaf for capacitance and the microwave reflection voltage.

Table 2. The table below shows the comparison of the change and average electrical parameters at the plant stem

Duration	ΔC* (pF)	Cavg* (pF)	ΔC/hr* (pF\hr)	ΔR* (KΩ)	Ravg* (KΩ)	ΔR/hr* (KΩ/hr)
Day	216	88.2	18	1108.06	3398.9	92.34
Night	10	107	0.833	43.07	2738.8	3.59

**ΔC/ΔR is the change in capacitance/resistance, Cavg/Ravg is the average capacitance/resistance, ΔC/hr, ΔR/hr is the change in capacitance\resistance per hour*

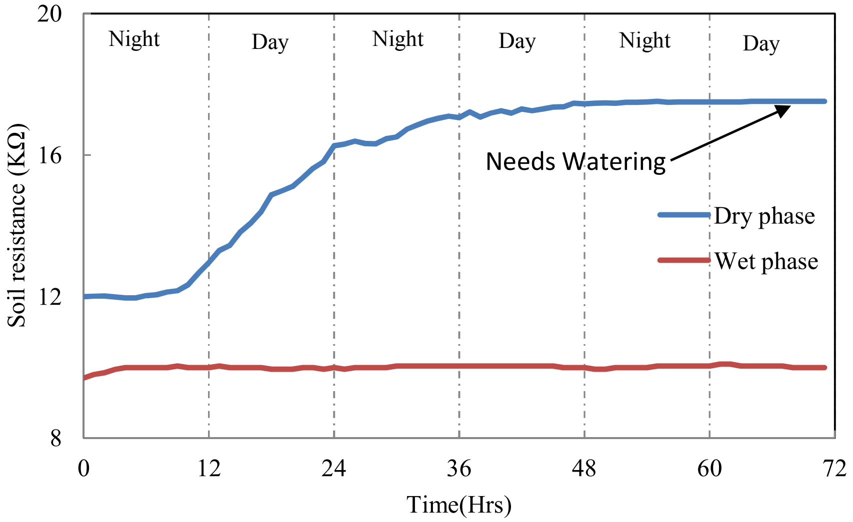
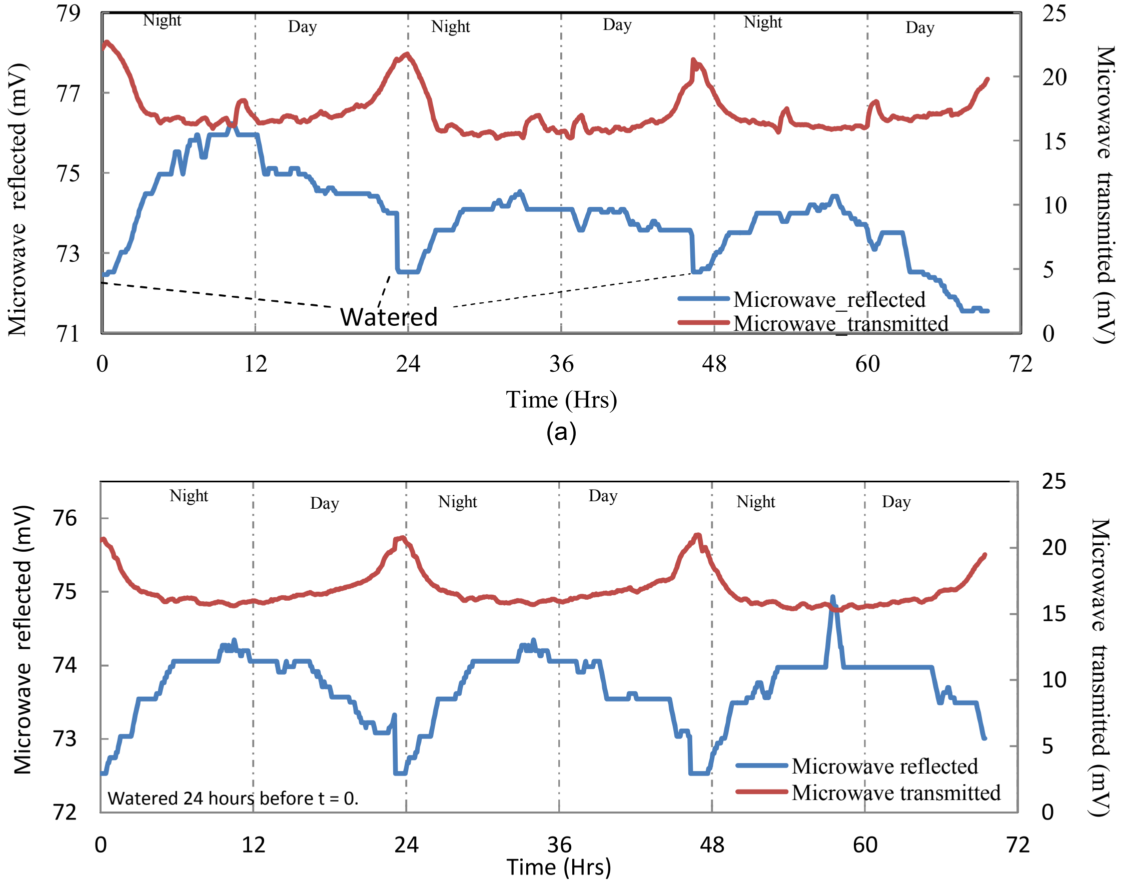


Fig. 3. Variation of the voltage between the gold electrodes for the soil during the wet and dry phase

3.2 Microwave Reflection / Transmission Measurements

Microwave reflection and transmission measurements are extensively used in remote sensing and provide information regarding the complex permittivity of the sensed medium. Microwave measurements can be done at exceedingly small power (1 μW) to not cause any harm and they do not require electrodes or other structures that may stress the plant in any way. Fig. 1 shows the microwave reflection/ transmission experimental setup. Two X-band (8-12 GHz) horn antennas were used and the 10 GHz signal was amplitude modulated at 23 KHz to enable using a lock-in amplifier to detect the reflected/transmitted waves. The transmitted microwave through the foliage periodically decreased (~6 mV) at nights and increased (~5 mV) during the day tracking the periodic changes we observed in the leaf capacitance during the hydration phase with regular watering at 4 PM every day. During the dry phase (stopped watering the plant), the transmitted microwave signal decreased (~ 4 mV) at nights and increased (~4 mV) during the day. The reflected microwave also changed regularly with day/night cycle and closely tracked the transmitted signal with an opposite sign as shown in Fig. 4.

Plant dehydration for 72 hrs did not change the variations of the transmitted microwave through the plant foliage. An important distinction between the dry and wet phase was large variations in the microwave reflection/ transmission at the sunset which was present in wet phase but not in the dry phase. This variation can be attributed to a reduction in transpiration and stomatal closure as shown by Brodribb et al. [16]. The plant was watered at 0 hrs (4 PM), 24 hrs and 48 hrs for the wet phase and there was no watering for the dry phase as shown in Fig. 4.



(a)

(b)

Fig. 4. Variation of the reflected/transmitted microwave from the plant leaf for (a) Wet phase, (b) Dry phase, with plexiglass-supported foliage to prevent mechanical motion

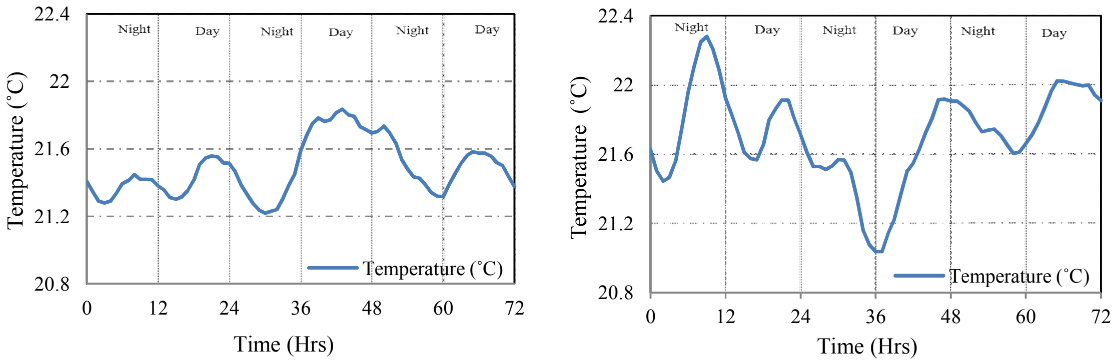
3.3 Temperature and Light Intensity Measurements

The temperature was slightly higher during the day and lower at night as shown in Fig. 5. Temperature variations near the plant is probably affected by the moisture levels that are affected by plant transpirations. Since moist air has higher thermal mass, its temperature will not have as much variations due to the external temperature fluctuations (air conditioner) compared to the dry air as can be clearly seen in Figs. 5a and 5b.

The graph presented in Fig. 6 shows the variation of light intensity and it can be observed that for the dry and the wet phases it was almost the same. Thus, the effect of light variations from day-day on the electromagnetic properties of the plant can be ignored.

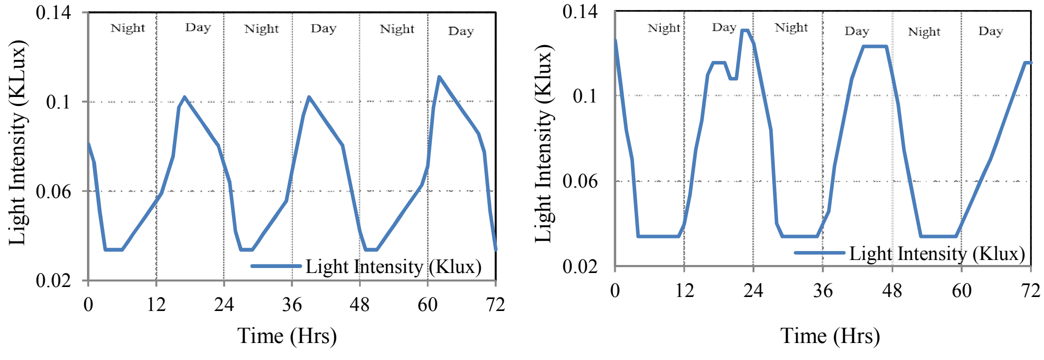
3.4 Capacitance and Microwave Measurements

In order to come up with a sensor that does not corrode with time and is independent of the soil texture, we focused on the leaf capacitance and microwave reflection/transmission by the foliage. The capacitance variation gave a very distinct pattern for the wet and dry phase. Combination of wet and dry phase data can be used to water the plant exactly when it needs. The microwave transmission data showed similarity to the capacitive data. As shown in Fig. 7 as the rise and fall in capacitance and microwave transmission repeats every 12 hours. The dry phase data is, however, distinct as with the initial change for a day in capacitance the parameters the value starts to saturate as the soil dries up whereas the transmission data does not saturate. A control setup for the microwave was used to understand the effect of desiccation on the plant.



(a) (b)

Fig. 5. Temperature variations as a function of time (a) Wet Phase (b) Dry Phase. The variation was small however average temperature during the day was more than night (change of 0.1°C = change of 4.88×10^{-3} V)



(a) (b)

Fig. 6. Photosensor output as a function of time (a) Wet Phase (b) Dry Phase. The photo-sensor used was less sensitive to the indoor lighting and that helped in providing data. (2.33 Klux = 9.768×10^{-3} V)

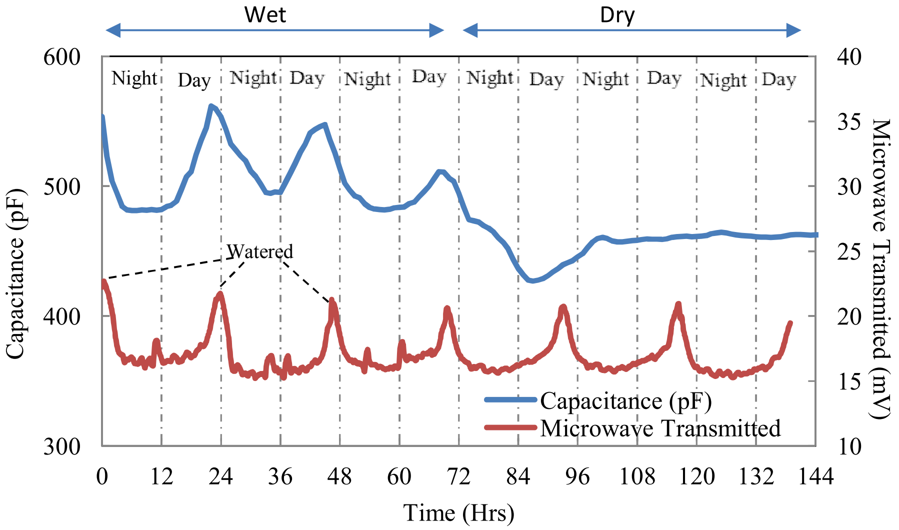


Fig. 7. Comparison of the capacitance variation for the dry and wet phase with the microwave transmitted at the plant leaf. Watering done at T = 0, 24 and 48 Hrs

4. DISCUSSION

The plant's biological parameters and their dependence on light, water/nutrients and temperature are well known [17]. The microwave reflection pattern in our experiment was similar to Wang et al. using a microwave sensor for orchid/azalea [15]. The point of watering the plant was found to be near 3 days. Usually plants are watered in 1-2 days but it was clear from our data that there is not much change in our plant health till around 3-4 days. It has been shown that plants can recover from 50-90% water loss in 1-100 day time span by Brodribb et al. [16]. The Capacitance variation in our study was similar to variation of transpiration shown by Brodribb *et al.* An increase from 0 mmol m^{-2} s^{-1} to 5 mmol m^{-2} s^{-1} during day and decrease from 5 mmol m^{-2} s^{-1} to 0 mmol m^{-2} s^{-1} during the night was shown. This indicates that the capacitance variation in our case gives an inverse relation of the transpiration rate in the plant leaf. The capacitance obtained for the plant under stress showed a very small variation as also reported by Brodribb et al. As water potential in leaf decreased from -1.15 Mpa to -2.85 Mpa (>80% stomatal closure) the variation in transpiration was reduced from 5 mmol m^{-2} s^{-1} to 0.5 mmol m^{-2} s^{-1}. Jones HG's [17] study indicated water potential (Mpa) variation over 3 day period which was similar to our capacitance variation.

The capacitance and soil data gave very distinct results for the dry and wet phase and hence they can be used for plants water need easily. Using capacitance data ideally the plant needs to be watered at a gap of around 54 hrs. The resistance variation at the soil however indicated that the plant needs to be watered at around 56 hrs since last watered, as the value saturated. Hence the capacitance variation gives a better understanding of plants water requirement. All plants will not have the same variation as shown in this study, hence if needed for agricultural purpose the experiment can be repeated to get the exact electrical parameter variation for plant under examination. The microwave reflection/ transmission data however had minute variations for the two phases. Hence, we extended the dry phase study to 5 days. The mechanical support to the leaf was still present and that ensured any change in the microwave reflected or transmitted was only due to the water content. As seen in Fig. 8 the extended microwave reflection dry phase data gives a very distinct point for the plant to be watered. The ideal time for watering in this case was found to be 69 hrs. There was a decrease of 1 mV in the average value of the microwave reflected after 3 days as compared to 0 - 0.2 mV. That indicated the effect of desiccation in the plant. There was no sign of necrosis even after 142 hrs of dry phase. Hence, physical examination would bluff that the plant is healthy. Given that the precision in the watering time all the cases were ±12 hrs, they surely hold promises of producing accurate and precise sensors for agricultural needs.

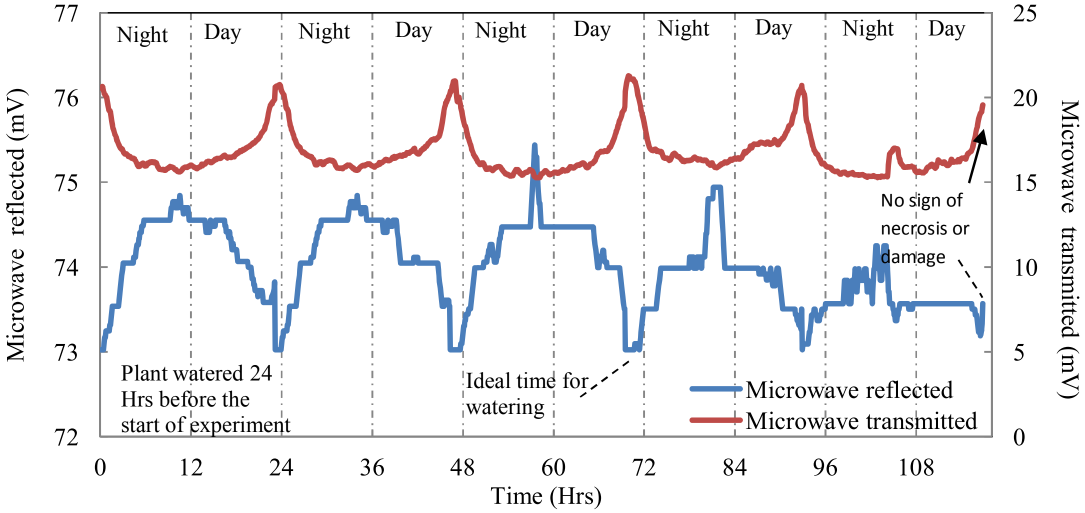


Fig. 8. Variation of the microwave for the extended dry phase of 5 days

5. CONCLUSION

The electrical parameters of *Schefflera* leaf and stem were studied as a function of time using capacitance, resistance and microwave measurements. These studies revealed that the plant leaf's moisture content, that changes dramatically during hydration/dehydration and day/night cycles, directly affect its capacitance, resistance and microwave transmission/reflection signals. These signals varied nearly periodically as a function of day/night cycles and tracked each other reproducibly and reliably. Microwave measurements are non-intrusive and can be performed at a stand-off distance to assess the moisture content of plant leaf to determine the time for hydration.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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