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*Research Article*

# EXPERIMENTAL VALIDATION OF DIELECTRIC MODELS FOR SUGARCANE VEGETATION AT C-BAND MICROWAVE FREQUENCY

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**ABSTRACT.** Monitoring vegetation using satellite data at microwave frequency is a non-conventional method and is an essential requirement for agriculture management. The interaction of the microwave signal from the satellite sensors with the vegetation is recorded in terms of the backscattering coefficient for active sensors and in terms of emissivity and brightness temperature for passive sensors. The interaction of the microwave with vegetation is greatly influenced by one of the target properties i.e., complex dielectric constant. Dielectric models of vegetation explicate the relationship between microwave response and physical characteristics of parts of vegetation. There is a great need for experimental determination of the complex dielectric constant of vegetation and validation of the complex dielectric constant with dielectric models. The present work consists of laboratory measurements of the complex dielectric constant of sugarcane vegetation at C - band microwave frequency and analysis of the variations in the complex dielectric constant with moisture content. The Von – Hippel method is used to perform these measurements at room temperature. The experimental data is then compared with dielectric models namely Carlson Formula, Matzler, and Debye Dual dispersion model to discuss the suitability of these models for the prediction of the dielectric response for sugarcane vegetation. Further, the experimentally measured data of the complex dielectric constant is used to calculate theoretically the emissivity and brightness temperature using the Fresnel equations as these parameters are significant for microwave remote sensing of sugarcane vegetation.

**Keywords:** *complex dielectric constant, sugarcane, microwave, emissivity, remote sensors.*

## INTRODUCTION

Microwave emission and backscattering from parts of vegetation are important parameters for the interpretation of remotely-sensed satellite data. A complex dielectric constant ($\varepsilon^*$) is an important parameter contributing to emission and backscattering energy. The relationship between $\varepsilon^*$ and the physical parameters of the target material provides significant information for microwave remote sensing techniques and applications.

The inversion scattering models have been developed to retrieve features of vegetation for the assessment of crop status by using remote sensing methods [1]. However, the understanding of dielectric behavior with respect to vegetation characteristics is obligatory to develop such theories. The $\varepsilon^*$ is the measure of propagation characteristics of the medium and provides the electric response of the material of interest. The $\varepsilon^*$ is comprised of $\varepsilon'$(real part) and $\varepsilon''$ (imaginary part) termed as dielectric constant and dielectric loss and are related by following Eqn.1.

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \qquad \textbf{Eqn.1}$$

Where, $j^2 = -1$, $\varepsilon'$(real part) is the ability to store electric energy in the form of charges of materials and $\varepsilon''$ (imaginary part), energy loss in the material.

Several theories for vegetation dielectric modeling have been developed with different approaches such as empirical, semi-empirical, and mixing models. Carlson formulated the empirical relationship based on dielectric measurements for Taxus, chamaecostus cuspidatus, and corn leaf at room temperature and a single frequency of 8.5 GHz (X-band) [2]. Matzler proposed the model with a semi-empirical approach where the leaf complex dielectric constant is modeled to be dependent only on two variables, namely the dry-matter fraction and dielectric constant of saline water over the frequency range up to 100 GHz [3]. Ulaby and El-Rays formulated a mixing model called the Debye Cole Dual Dispersion Model by using dielectric measurements of corn leaves in the 0.2 to 2 GHz frequency range [4]. The complex dielectric constant of the leaf is modeled as a simple mixture of three components: a Non-dispersive residual component, a free water component, and a bulk vegetation-bound water component.

Chuah H. T.et al.[5] performed the dielectric measurements for corn and rubber leaves and compared their results with all the three models stated above i.e., Carlson, Matzler, and Ulaby and El-Rays. They reported Ulaby and El-Rays mixing model has good predictability of finding complex dielectric constant, the study also reported that the accuracy agreement for corn leaves is more promising than the rubber at C-Band Chuah H. T.et al [5]. However, for corn leaves Li Z.et al. [6] reported empirical model proposed by them has higher accuracy than Ulaby and El-Rays mixing model at C-Band frequency. Itolikar et.al.[7] compared their experimental results of dielectric measurements for corn vegetation with a mixing model and reported mixing model is promising for predicting the complex dielectric constant for corn leaves at C- band frequency.

In light of the above reports Chuah H. T.et al.; Li Z. et.al.; Itolikar et.al., there seem to be different views about the promisingness of dielectric models for predicting the $\varepsilon^*$ of vegetation. It is also observed that the models are more promising to predict the $\varepsilon^*$when the sample used for experimentation and to construct the models are the same. The results of $\varepsilon^*$ calculated from the models are different from experimentally measured values qualitatively and quantitatively. It also varies from vegetation to vegetation and is more promising in the case of vegetation that is used to construct the model [5]. There is no study available for the complex dielectric constant measurement of sugarcane vegetation in the literature. This is the motivation to conduct dielectric measurements of sugarcane vegetation at C- band microwave frequency. The comparison of the measured dielectric properties of sugarcane vegetation with dielectric models will be interesting to know the suitability of these models for the prediction of dielectric properties.

The sugarcane plant is tall, perennial grass which is used mainly for sugar production. It is cultivated in tropical and subtropical climates. Sugarcane leaf consists of bulk material, air spaces, and major components as moisture content. The moisture in the plant and leaves is the core and essential content, as it plays a crucial role in physiological processes and the overall growth of the plant. Therefore, it is interesting to know the interrelationship between moisture which is the key parameter for the overall growth of plants and dielectric characteristics of sugarcane leaves for sensor development.

This paper presents experimental measurements of the complex dielectric constant of sugarcane vegetation (leaves) at room temperature ($27^0$C), at C-Band microwave frequency. These measurements were performed using a frequency domain, Von – Hippel (shorted waveguide) method for which an automated C-band microwave bench set up with a newly designed dielectric cell with a movable reflector is used. The $\varepsilon^*$ is measured for freshly cut sugarcane leaves collected from near farm locations. Measurements are taken for different moisture content ranging from natural moisture to oven-dried samples of sugarcane leaves. The dielectric constant ($\varepsilon'$), dielectric loss (ε"), and errors in their measurements are calculated by least-square fitting method. The experimental data is then used to compare with the above-described dielectric models for vegetation (Dual dispersion model, Matzler Model, and Carlson formula). The suitability of models for the prediction of dielectric properties of sugarcane leaves has been discussed based on experimental results. In addition, these experimental trends are discussed with the dielectric mechanism of dipole polarization. Estimation of dielectric-dependent emission and radiometric brightness temperature is done based on theoretical calculations using Fresnel equations which are monitoring parameters for passive Microwave Remote Sensing MWRS.

## MATERIALS AND METHODS

Freshly green leaves of sugarcane were cut from a nearby laboratory location. The leaves samples are transported to the lab wrapped in a polyethylene bag so that physical properties should not alter. The leaves were cut in the size of rectangular waveguide. The leaves are curly and not flat in their original form, so to get compactness of the sample, a newly designed sample cell with a movable reflector has been employed which is already used for several other leafy samples. The cut-sized leaves are sandwiched between a mica sheet (front end of cell) and a movable reflector (rare end of cell). The author was able to track the natural moisture content of 72.80% for sugarcane leaves considering the barrier of time spent due to transportation of samples from a farm field location to the laboratory. The dielectric measurements were performed for moist leaves (72.80%, 66.95%, 60.01%, and 51.47%) and oven-dried samples. The percent moisture is gravimetrically measured by the following Eqn. 2.

$$\% \text{ Moisture content} = \frac{\text{Ws}-\text{Wd}}{\text{Ws}} \times 100 \qquad \textbf{Eqn. 2}$$

Where,

$w_s$- weight of sample

$w_d$-weight of dry sample

There are various methods of dielectric measurement [8]. In the present work, the Von Hippel method is used for which the C-Band Microwave MW bench is automated [9]. This method is also used for measurements of Corn and Jowar, grass vegetation and has already been reported in the literature by [10-12]. This is a frequency-domain method, has good accuracy and is suitable for leaves (solid) samples. The experimental setup and assembly of components of the automated C- Band Bench for dielectric measurement are shown in Fig.1. The propagated MW is back-reflected from a reflector placed on the end of the MW bench to get a symmetrical standing wave pattern in the slot line section of the bench. The probe has a 1N23 detector that is traversed along the slot line at equal intervals and power (current) is recorded with respect to the corresponding probe positions.

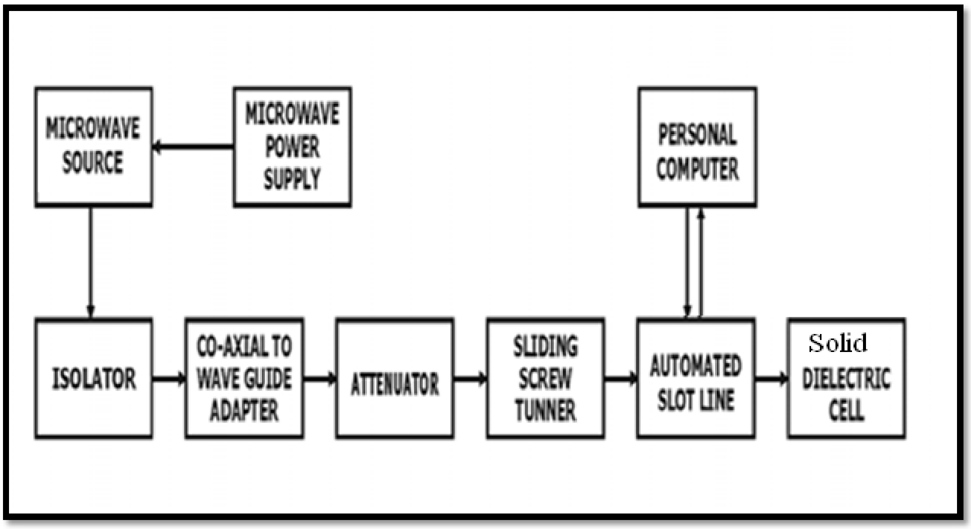


***Fig. 1.** Automated Microwave C-Band Bench Experimental Setup*

The detector is connected to a microammeter and to the Personal Computer to read and record the measured power. The symmetrical standing wave pattern is observed for empty waveguide cell and with dielectric sample (sampled sugarcane leaves) and compacted in the cell.

This data is acquired and stored in a file using a microcontroller interface system. This data utilizes $\alpha$ and $\beta$ as fitting parameters,

Where $\alpha$ = attenuation factor, $\beta$=phase shift constant. The data is stored for sugarcane leaves of different thicknesses. The guided wavelength $\lambda g$ is measured from the minima of the standing wave pattern.

$$\beta = \frac{2\pi}{\lambda_g} \qquad \textbf{Eqn.3}$$

The free space wavelength, $\lambda_0$ is determined using the relation refer eqn.4.

$$\frac{1}{\lambda_0^2} = \frac{1}{\lambda_g^2} + \frac{1}{\lambda_c^2} \qquad \textbf{Eqn. 4}$$

Where, $\lambda_c$=2×a=2×4.73=9.46 cm, 'a' being the broader side of the C-band rectangular waveguide. The real and imaginary parts of the complex dielectric constant are calculated using the relations given in eqns.5 and 6.

$$\varepsilon' = \lambda_0^2\left(\frac{1}{\lambda_c^2} + \frac{(\alpha^2-\beta^2)}{4\pi^2}\right) \qquad \textbf{Eqn. 5}$$

$$\varepsilon'' = \frac{\lambda_0^2\alpha\beta}{2\pi^2} \qquad \textbf{Eqn. 6}$$

The dielectric constant has been computed by the source code developed for this purpose.The number of data files, for different thicknesses (in this case measured for three thicknesses of 0.7, 1.4 and 2.1 cm) of the samples are combined to get a single input data file, which can be used, in the source code for calculating dielectric constant ($\varepsilon'$) and loss ($\varepsilon''$) with errors in the measurements as $\Delta\varepsilon'$and $\Delta\varepsilon''$.

To compute dielectric properties along with the errors in the measurements, the least square fitting technique is used. The measured data makes use of $\alpha$ and $\beta$ as fitting parameters, where $\alpha$ = attenuation factor, $\beta$= phase shift constant.

When the program code is run for computation of the ε' and ε'' using "inp.dat" as the input file, multiple solutions are obtained for different values of the coefficient of propagation constant "AP (2)" corresponds to a difference factor. The difference factor refers to the difference between the experimental and theoretical calculations. The multiple solutions for dry sugarcane leaves are expressed in Fig.2 and a detailed procedure for finding optimum results along with errors has been reported in [11]. The errors of the present measurements are given in Table 1.

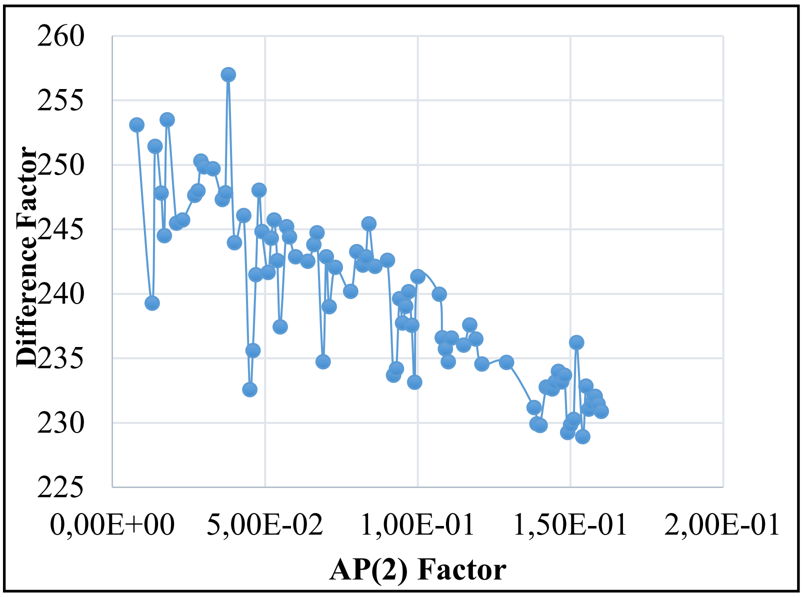


***Fig. 2*** *Multiple solutions for optimization of errors for dielectric constant and loss*

***Table. 1****. Errors in measurements of ε' and ε''*

| **% Moisture Content of Sugarcane Leaves** | Error in Dielectric Constant $\Delta\varepsilon'$ | Error in Dielectric Loss $\Delta\varepsilon''$ |
|---|---|---|
| 72.8 | 3.49E-02 | 4.47E-02 |
| 66.95 | 4.46E-02 | 5.06E-02 |
| 60.01 | 4.10E-02 | 4.87E-02 |
| 51.47 | 3.71E-02 | 3.67E-02 |
| 0(Oven dried) | 1.22E-02 | 1.05E-02 |

***Models for Prediction of Dielectric Properties of Vegetation***

***Carlson Formula***

This is an empirical model based on experimental data on grass, Taxus, cuspidatus, and corn leaf at room temperature and a single frequency of 8.5 GHz.

$$\varepsilon = 1.5 + \{[\mathrm{Real}\varepsilon_w/2] + j[\mathrm{Imaginary}\varepsilon_w/3]\}m_g \qquad \textbf{Eqn. 7}$$

Where, mg is the fractional moisture content of leaves and $\varepsilon_w$ is the dielectric constant of water which is calculated by Eqn.8.

$$\varepsilon_w = \left[4.9 + \frac{73.5}{1+\frac{jf}{19.7}}\right] \qquad \textbf{Eqn. 8}$$

Where, $j^2 = -1$ and f- Frequency in GHz

***Matzlers Model***

This is a semi-empirical formula where the leaf dielectric constant is modeled to be dependent only on two variables, namely the dry-matter fraction $m_d$ (the ratio of dry mass to the fresh mass of leaf), and $\varepsilon_{sw}$, the dielectric constant of saline water. The leaf dielectric constant is expressed as

$$\varepsilon = 0.522(1 - 1.32m_d)\varepsilon_{sw} + 0.51 + 3.84m_d \qquad \textbf{Eqn. 9}$$

Where, $m_d = 1 - m_g$. This model is valid for $0.5 < m_g < 0.9$ $m_g$ is the fractional moisture content.

***Debye Cole Dual Dispersion Model***

This model has a physical basis for formulation. The complex dielectric constant of the leaf is modeled as a simple mixture of three components.

(i) Non –dispersive residual component, $\varepsilon_s$;

(ii) A free water component $v_{fw}\varepsilon_w$, where $v_{fw}$ is the volume fraction of water and $\varepsilon_w$ the free water dielectric constant; and

(iii) A bulk vegetation bound water component $v_b\varepsilon'_b$, where $v_b$ is the volume fraction of bulk vegetation bound water component and $\varepsilon'_b$ its dielectric constant.

$$\varepsilon' = \varepsilon'_s + v_{fw}\varepsilon'_w + v_b\varepsilon'_b \qquad \textbf{Eqn. 10}$$

The values of $\varepsilon'_w$ can be estimated using Debye Equation. Substituting the equation for εw and εb in Eqn.10.

$$\varepsilon = \varepsilon_s + V_{fw}\left[4.9 + \frac{73.5}{1+\frac{jf}{19.7}} - j\frac{18\sigma}{f}\right] + V_b\left[2.9 + \frac{55.0}{\left(1+\frac{jf}{0.18}\right)^{0.5}}\right] \qquad \textbf{Eqn. 11}$$

$$\varepsilon_s = 1.7 - 0.74M_g + 6.16{M_g}^2 \qquad \textbf{Eqn. 12}$$

$$V_{fw} = M_g(0.55Mg - 0.076) \qquad \textbf{Eqn. 13}$$

$$V_b = \frac{4.64{M_g}^2}{1+7.36{M_g}^2} \qquad \textbf{Eqn. 14}$$

$$\sigma = 1.27 \qquad \textbf{Eqn. 15}$$

Where, $j^2 = -1$, f is the frequency in GHz, Mg- Gravimetric moisture content and σ- Ionic conductivity.

***Estimation of emissivity and brightness temperature***

The emissivity is expressed as given in eqn. 16.

$$e_{s(p)} = (1 - R_{s(p)}) \qquad \textbf{Eqn. 16}$$

Where $R_{s(p)}$ is the smooth-surface reflectivity. For a homogeneous leaves sample with a smooth surface, the reflectivity at vertical and horizontal polarizations, $R_{sV}$ and $R_{sH}$, is given by the Fresnel expressions given by Eqn. 17 and 18.

$$R_{sV} = \left|\frac{K\cos u - \sqrt{K - \sin^2 u}}{K\cos u + \sqrt{K - \sin^2 u}}\right|^2 \qquad \textbf{Eqn. 17}$$

$$R_{sH} = \left|\frac{\cos u - \sqrt{K - \sin^2 u}}{\cos u + \sqrt{K - \sin^2 u}}\right|^2 \qquad \textbf{Eqn. 18}$$

Where 'u' is the incidence angle and 'K' is the absolute value of the dielectric constant of sugarcane leaves, which is a measure of the response of the leaves to an electromagnetic wave and is largely determined by the moisture content of the leaves. The emissivity of the leaves for different moisture content, for different angles of incidence, is calculated using Fresnel equations. Passive MWRS is based on the measurement of thermal radiation in the centimeter wave band of the electromagnetic spectrum $T_b$. This radiation is determined largely by the physical temperature and the emissivity of the radiating body and can be approximated by using Eqn. 19.

$T_{b(p)} \approx e_{s(p)} T$ **Eqn. 19**

Where $T_{b(p)}$ observed brightness temperature; T physical temperature of the emitting layer; p refers to vertical or horizontal polarization; $e_s$ smooth-surface emissivity.

## RESULTS AND DISCUSSION

The $\varepsilon'$ and $\varepsilon''$ of complex dielectric properties of sugarcane leaves and their variation with respect to moisture content are shown in Fig.3 and 4. From these Figures it is observed that the experimentally $\varepsilon'$and $\boldsymbol{\varepsilon''}$increases with the increase in percent moisture content. These trends are exponential which justifies the polarization of electric dipoles for the free water molecules and their bounding with the leaf bulk material. The water molecule is polar in nature which shows orientation polarization with respect to the applied electric field at C-band microwave frequency. The increase in complex dielectric constant with moisture content may be due to the more polarizability of dipoles. For lower moisture content, these water molecules are tightly bonded to the bulk, resulting in less polarizability of electric dipoles so the change in dielectric properties at lower moisture is not rapid with respect to moisture content. On the contrary for higher moisture content the water molecules are comparatively free, resulting in more polarizability of the dipoles so the change in dielectric properties at higher moisture is rapid.

Comparing our experimental findings of $\varepsilon'$ and $\boldsymbol{\varepsilon''}$ for sugarcane leaves with Carlson and Matzler models, it is observed that the estimated dielectric properties provide linear trends between moisture content and $\varepsilon'$ and $\boldsymbol{\varepsilon''}$. These models have not taken into consideration the freeness of water molecule from the bulk with respect to an increase in moisture, its effect on polarizability and hence on the dielectric properties.

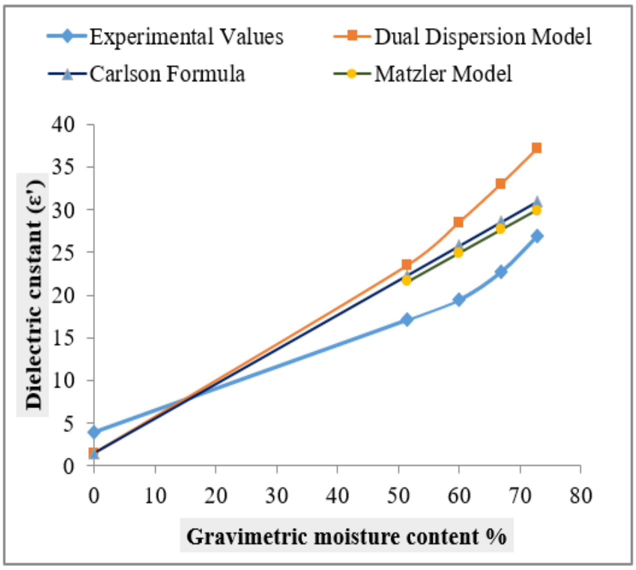


***Fig.3.*** *Variation of Dielectric constant (ε') with percent gravimetric moisture content*

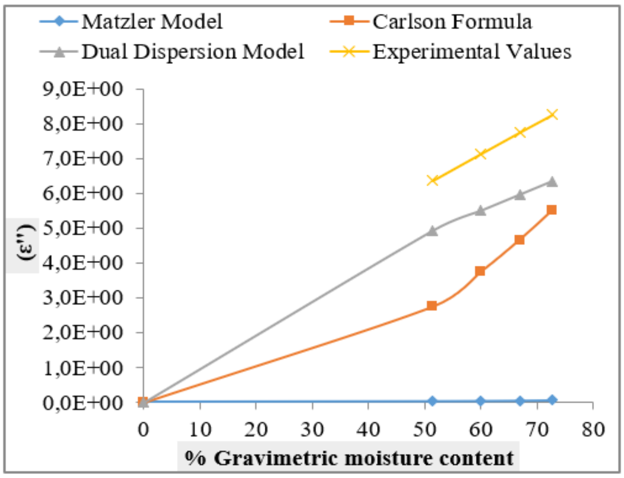


***Fig.4.*** *Variation of Dielectric loss (ε'') with percent gravimetric moisture content*

Trend-wise, the dual dispersion model is more promising to explain the dielectric behavior of sugarcane vegetation as the measured data and calculated results from this model show an exponential increase as a function of moisture content. All the models quantitatively overestimate the $\varepsilon'$ and $\boldsymbol{\varepsilon''}$ of sugarcane leaves at C- band frequency. This may be due to the type of vegetation that we used being sugarcane other than that was used to construct any of the above-mentioned models. However, the measured values of $\varepsilon'$agree to a certain extent with the dual dispersion model by Ulaby and El-Rayes. The measured $\boldsymbol{\varepsilon''}$ is not agreeable with any of the above models.

The emissivity and brightness temperature for horizontal and vertical polarization estimated from measured dielectric properties at a different angle of incidence for dry and moist sugarcane leaves are shown in Fig.5 and 6. The impact of moisture on the leaves is clearly shown in the emission and the change of emission due to the angle of incidence for horizontal and vertical polarization has been displayed in Fig.5 and 6. These parameters are significant for the study of vegetation in passive microwave remote sensing.

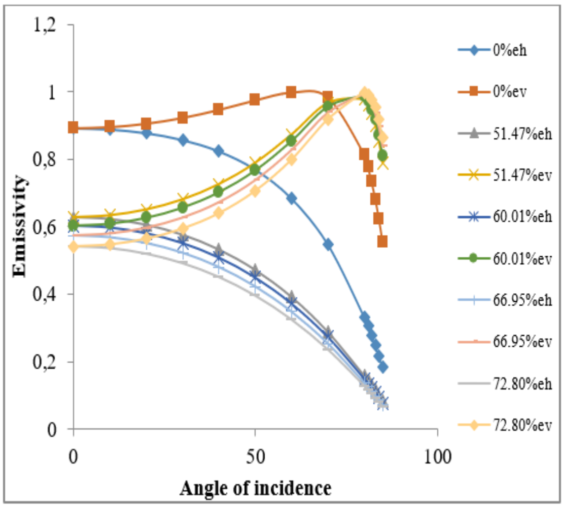


***Fig.5.*** *Emissivity at different angles of incidence of sugarcane leaves for different moisture*

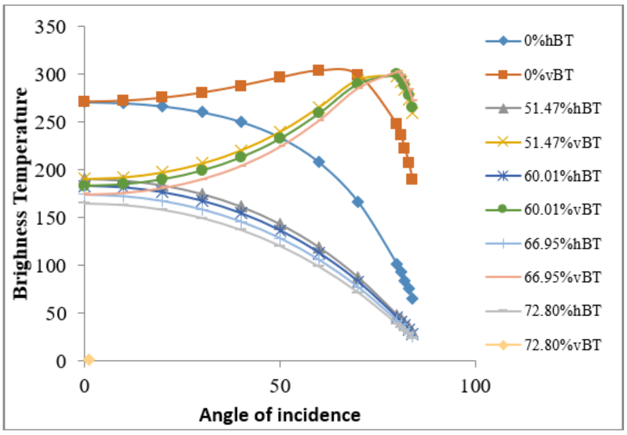


***Fig.6.*** *Brightness Temperature at different angles of incidence of sugarcane leaves for different moisture*

## CONCLUSION

The laboratory validation of dielectric properties is very important for remote sensing techniques, interpretation, and applications. The dielectric behavior of sugarcane leaves has been studied at C- band microwave frequency and at room temperature. The estimated emissivity and brightness temperature from measured data of dielectrics is graphically expressed as these parameters are interpreting parameters in passive microwave sensors. The impact of sugarcane leaves moisture on $\varepsilon'$ and $\varepsilon''$ have been presented and discussed which is a significant link for microwave sensor development to monitor the moisture of leaves. This relationship is exponentially increasing which supports the dielectric polarization theory for free water molecules and their bounding with the vegetation bulk matter. The experimental data are compared with available dielectric models and results from the comparison have been expressed and discussed. It seems to a certain extent the dual dispersion model is suitable to predict dielectric properties of sugarcane vegetation at C- band frequency. The deviation of experimental data from the models for dielectric behavior suggests conducting more measurements of the complex dielectric constant of different vegetations and coming up with an optimal model which will be suitable for all types of vegetation.

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**CompliancewithEthicalStandards**
The authors declare that they have no conflict of interest.

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