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A new semiempirical model determining the dielectric characteristics of citrus leaves for the remote sensing at C band

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Abstract: Dielectric parameters (i.e. permittivity) are fundamental to the simulation, design, modeling, and developing of microwave applications. For targeted objects, the complex permittivity is an essential parameter that affects its characteristics of scattering and microwave radiation. Thus, in microwave remote sensing applications, the knowledge of the dielectric property of vegetable materials is used not only to detect planting areas for monitoring and to able to specify the growth stage of them in seasonal variations, but also to determine the water requirement of the plant for controlling (water stress). This paper focuses on determining the dielectric parameters of orange and lemon leaves, grown in the Mediterranean coasts of Turkey, depending on the moisture content (MC) and frequency by measuring the samples (leaves) with waveguide transmission line technique in the larger part of the C band frequency range (4.90–7.05 GHz) (compatible with WR159) in order to propose a novel model based on curve fitting method for estimating the real part of dielectric constant (ϵ') and the imaginary part of dielectric constant (ϵ''). Using dielectric measurement results of orange leaves, our model based on frequency and MC is compared with the dielectric measurement results of the lemon leaves, which is in the same family with orange species, to specify the accuracy of the proposed model. The determination coefficient, R^2, and mean square root of errors values are also obtained as 0.966 and 0.824, respectively.

Key words: Dielectric constant, moisture content, citrus leaves, remote sensing, C band

1. Introduction

The complex dielectric constant, an essential property of materials, determines the interaction and behavior of the material with electromagnetic (EM) waves. The dielectric characteristics of the material directly affect the storage and heat conversion rates of applied EM waves into the material. With the development of microwave technology, microwave remote sensing (RS) and microwave heating/drying applications have become widespread. However, for effective use of these technologies, the dielectric parameters of the material should be firstly determined. In lossy mediums, the complex dielectric constant (ϵ^*) is complex, while the real part (ϵ') shows how much energy is stored in the material, while the imaginary part (ϵ'') affects propagation speed, attenuation and transmission parameters [1]. In general, the complex dielectric constant for a homogeneous, isotropic, and

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lossy medium is defined as follows.

$$\epsilon^* = \epsilon_0 \; [\epsilon_r' - j\,\frac{\sigma}{\omega\epsilon_0}], \tag{1}$$

where ϵ_0 is the dielectric constant of the free-space, σ is the conductivity, ω is the angular frequency, and ϵ_r' is the real part of the relative complex dielectric constant.

$$\epsilon' = \epsilon_0 \epsilon_r', \tag{2}$$

$$\epsilon'' = \frac{\sigma}{\omega}. \tag{3}$$

Here the loss tangent of the material is expressed as in Eq. (4) since it is equal to the ratio ϵ''/ϵ'. It is seen that the power loss in the material depends on the frequency and the dielectric constant.

$$tan\delta = \frac{\sigma}{\omega\epsilon_r'\epsilon_0}. \tag{4}$$

Currently, the dielectric measurements of plant materials (leaves, branches, fruits etc.) are used in microwave applications such as heating, drying, and RS. This is the motivation of this study for measuring and determining dielectric parameters in plants. The EM waves to the plant cluster penetrate the leaves, stem, branches, and fruit surfaces and perform the behaviors such as reflection, refraction, absorption, and scattering on the plant surface. The predominant factor in these behaviors originates from the leaves [2, 3]. RS applications can be performed by a variety of methods in the microwave. However, microwave techniques have some advantages over other methods. These advantages are the penetration of microwaves into vegetation and soil, being sensitive to water content in soil and plants, and spreading in cloudy weather and at night. Moreover, RS applications are widely used for vegetation monitoring and various military purposes. There are several studies on the effects of plant leaves and stems on RS and EM scattering models [4, 5]. According to these studies, dielectric parameters in the plant depend largely on the moisture content (MC) of the plant. Thus, the needs of plants and soil to water can be determined to make irrigation processes efficient. In this way, irrigation applications of plants with microwave applications can be done effectively by the remote control [6]. In addition, the ripening status and quality of the fruit can also be determined by the dielectric measurement of the plant [7, 8].

Unlike the aforementioned applications, dielectric parameters of plants are also used to determine the absorption properties of materials. Nowadays, the most absorbing materials are polymer-based and their absorption properties decrease with time. These polymer-based materials also pose certain risks to the environment and health. To minimize these risks, various plants can be utilized as absorbing material. Dielectric characteristics of absorbing fibrous plants such as bananas are obtained. According to [9–11], the banana leaves can be used as an absorber material since it contains 43.5% of carbon.

In microwave heating/drying processes, the EM energy that penetrates the plant tissue is absorbed to a certain extent and converted into heat. The amount of power emitted per volume in the material is given in Eq. (5) [12].

$$P = E^2\sigma = 55.63 \; \cdot \; 10^{-12} \cdot f \cdot E^2 \cdot \epsilon'', \tag{5}$$

where P is the absorbed power in the material and E is the electrical field. Accordingly, the power absorbed in the material is directly dependent on the dielectric constant of the material. It is stated that both energy and time savings are obtained compared to traditional methods [13, 14]. There are many techniques to have the dielectric properties of plants. While the parallel plate and lumped elements methods are used in the frequency band below 100 MHz, transmission line, coaxial probe, cavity resonator, waveguide, and free-space measurement techniques are used in the upper frequency region [15–17]. It is significant to measure dielectric parameters at certain frequencies depending on the water content of the plants. Dielectric measurements can be made both before and after the plant leaves are removed from the branch [18]. Moreover, there are dielectric measurements of the leaf completely in powder form.

According to the data of Food and Agriculture Organization in 2018, Turkey ranks 7th and 2nd in the world production of oranges and lemons, respectively. Oranges and lemons are densely grown in the southern coast of Turkey in the Mediterranean. The MC of the leaves in orange and lemon plants is one of the most important parameters in determining the storage conditions, usage areas, and processing of these plants. Main motivation in this study is to determine the dielectric parameters required for microwave technologies that increase yield and quality in orange and lemon production.

In this study, the dielectric characteristics of the orange and lemon leaves from the same family (Rutaceae) are obtained depending on the MC and frequency at 24 ºC. A new model is proposed based on curve fitting method using measured S_{11} and S_{21} of orange leaves. Then, the accuracy of the model is tested with measurements data of the lemon leaves. For the measurements, waveguide transmission line (WTL) method is utilized with WR159 waveguide in the frequency band of 4.90–7.05 GHz. This paper is organized as follows: in Section 2, measurement test set-up is given. Section 3 presents the measurement results and the proposed model, and Section 4 evaluates the results.

2. The process of the dielectric measurement

For the measurements, WR159 (4.90–7.05 GHz) waveguide, RF coaxial cable, two flanges, and Anritsu MS4624B (10 MHz to 9 GHz) vector network analyzer are used with the WTL method. The sample (leaves) is placed between the flanges and made ready for measurement. It is important for the accuracy of the dielectric measurement to prevent bending and breakage of samples during drying process. Therefore, in order to eliminate this negative effect, transparent plastic glasses (plexiglass) compatible with flange sizes are used on both sides of the leaf. On the plastic glass, 8 $\times$ 4 numbers of 1-mm holes are drilled by computer numerical control (CNC) milling machine in order to ensure homogeneous drying of the leaves. The samples are soaked in distilled water for 48 h prior to measurement and saturated with water. During this time, their weights are measured every 12 h. The change in weight measurements at the end of 48th h is found to be $\pm$ 0.3%. The measurements last approximately 3 days per leaf, unless the 48 h period in water is taken into account.

Before the measurement, the water-saturated leaves are cut with a scalpel for the WR159 waveguide size. S_{11} and S_{21} parameters are measured and their weights are obtained with a precision balance with μgr sensitivity after each measurement step. The water-saturated leaves are dried step by step in a microwave oven. The drying and measuring steps continued until the leaves are completely dry. After the final drying step, the samples are kept in this oven for 24 h while the temperature in the oven is 70 ºC. The last weight changes of the leaves did not change after the final drying step. Therefore, it is determined that the water in the leaf is completely evaporated. Then, the weight and S-parameters of the completely dried samples are obtained and the measurement process is completed. The temperature of the room where the samples are measured is 24 ºC.

Figure 1 demonstrates the measurement environment. Figure 1a shows the ready-to-measure system with waveguides. Figures 1b and 1c show hollow flanges and the plexiglass for WR159, respectively. Figures 1d and 1e show the waveguide-coaxial adapter and plastic glass-filled flanges, respectively.

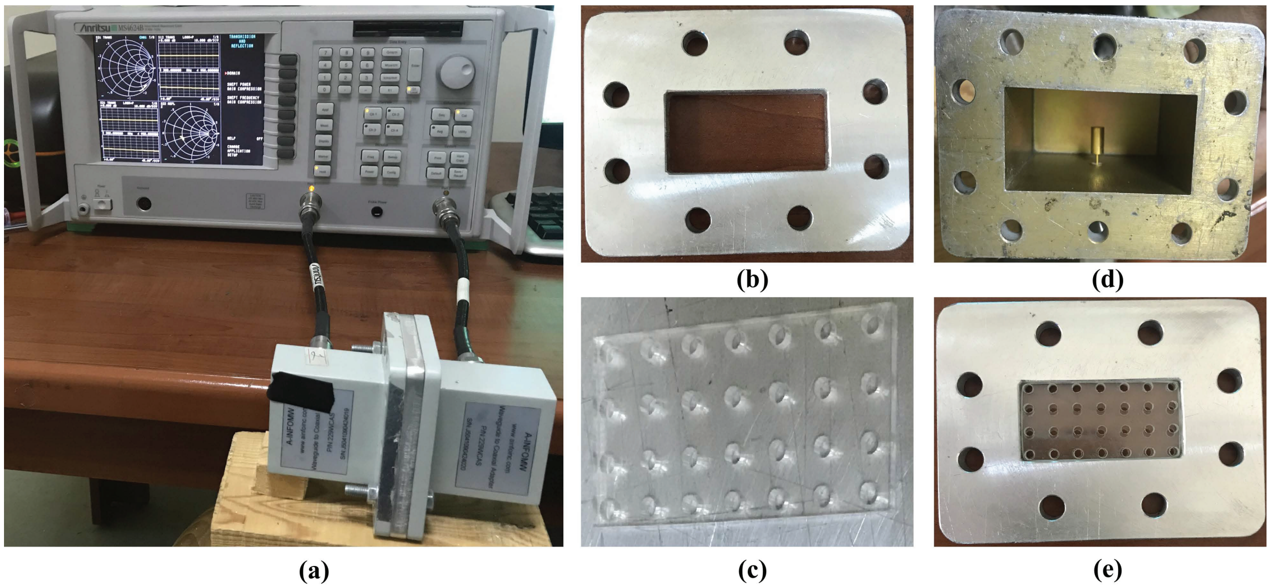

Figure 1. a. Test and measurement set-up, b. Hollow flanges, c. Plexiglass for WR159, d. Waveguide-coaxial adapter, e. Plastic glass-filled flanges.

Figure 2 gives the necessary steps to prepare the orange and lemon leaves for measurement. Figure 2a shows the fresh orange leaves that are kept in the water for 48 h. This leave is cut in accordance with the corresponding waveguide dimensions shown in Figure 2b. While the orange leaf with plexiglass is shown in Figure 2c, after the last drying step, a fully dried leaf is left in the oven at 70 ºC for 24 h in Figure 2d. Moreover, Figure 2e gives the fresh lemon leaf. The sample is given with and without flange in Figures 2f and 2g, respectively. In each drying step, the leaves are weighed with a microscale with a sensitivity of μgr in Figure 2h to calculate the MC of the leaf.

As mentioned earlier, the drying of the samples is carried out step by step. Tables 1 and 2 show the MC calculated during the drying stages of orange and lemon samples for WR159. The weight of the fresh orange and lemon leaves is 287 mg and 232 mg before drying process. At each step of the drying, the weight of the sample decreased and remained constant at 113 mg and 85 mg, respectively. These weights are obtained by keeping the sample in the oven at 70 ºC for 24 h and are completely dried. In the literature, different methods and temperature values are used to determine the moisture content of vegetative materials. In the literature, different methods and temperature values are used to determine the moisture content of vegetative materials. In this study, the drying temperature and duration is determined as 70 ºC and 20 s, respectively because thin and easily dried leaves are selected as samples [6, 18]. Due to this weight reduction, the moisture amount and the MC also decreased. The MC of the fresh leaf before drying is 100%, while the MC of the fully dried sample is calculated as 0% according to the formula given in Eq. (6).

The MC of the fresh leaf is assumed to be 100% and the MC is determined using the following statement with the dry leaf [19]:

$$WaC = m_{fresh} - m_{dry}. \tag{6}$$

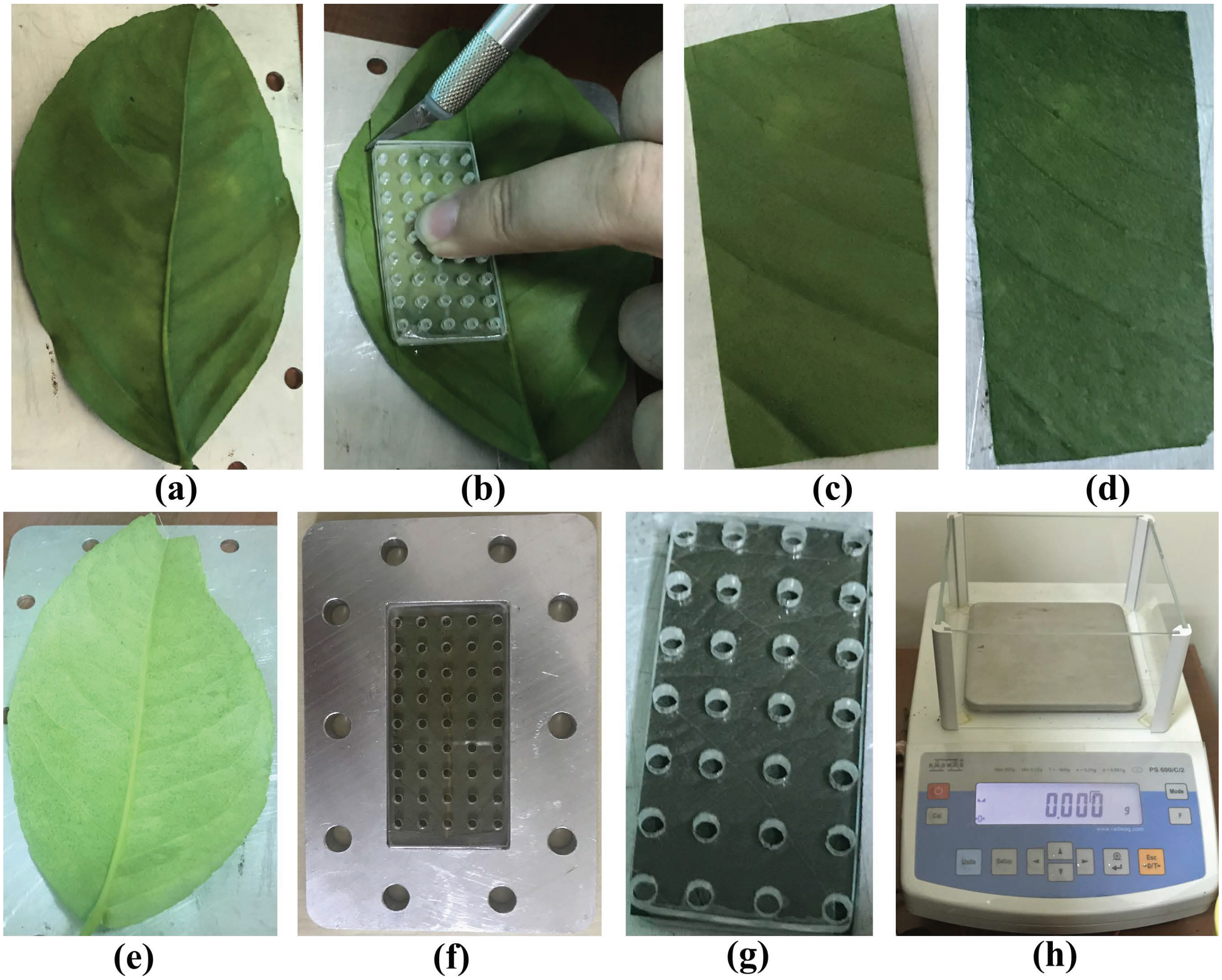

Figure 2. Preparation of orange and lemon leaves for the measurement.

Table 1. The change of MC of orange leaves.

Total weight (mg)	Dried weight (mg)	Moisture amount (mg)	Moisture content (%)
287	113	174	100
177	113	64	36.78
134	113	21	12.07
130	113	17	9.77
121	113	8	4.60
113	113	0	0

Using Eq. (6), the relative MC of the leaves (M_r) can be determined using Eq. (7).

$$M_r = \frac{m_{measure} - m_{dry}}{WaC}.100 \tag{7}$$

where $m_{measure}$ is the measured weight of the sample.

Table 2. The change of MC of lemon leaves.

Total weight (mg)	Dried weight (mg)	Moisture amount (mg)	Moisture content (%)
232	85	147	100
122	85	37	25.17
108	85	23	15.65
101	85	16	10.88
90	85	5	3.40
85	85	0	0

The real part of dielectric constant (ϵ') and the imaginary part of dielectric constant (ϵ'') should be calculated from the measured S-parameters to understand the effect of MC on the dielectric constant. The most widely used method in the literature is the Nicolson-Ross-Weir (NRW) algorithm [20]. In this paper, dielectric parameters of leaves are calculated using the NRW algorithm. According to this algorithm, the samples should have a certain thickness and measurement and as the accuracy of measurement errors increases with increasing frequency. The dielectric constant is calculated as a complex number using the NRW algorithm using Eq. (8-14) [21].

$$S_{11} = \frac{\Gamma(1-T^2)}{(1-\Gamma^2 T^2)}, \tag{8}$$

$$S_{21} = \frac{T(1-\Gamma^2)}{(1-\Gamma^2 T^2)}, \tag{9}$$

$$X = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}}, \tag{10}$$

$$\Gamma = X \pm \sqrt{X^2 - 1}, \tag{11}$$

$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11}S_{21})\Gamma}, \tag{12}$$

$$\frac{1}{\Lambda^2} = -\left[\frac{1}{2\pi L} In(\frac{1}{T})\right]^2, \tag{13}$$

$$\epsilon^* = \frac{\lambda_0}{\mu_r}\left(\frac{1}{\lambda_c^2} - \left[\frac{1}{2\pi L} In(\frac{1}{T})\right]^2\right), \tag{14}$$

where Γ is the reflection coefficient, T is the transmission coefficient and L is the thickness of the sample.

2.1. Removing errors in the measurement set-up

Common methods for eliminating systematic errors in the measuring set-up are deembedding method and thru reflect line (TRL) method. The method uses mathematical expressions to eliminate the errors of the model used in the test. This method is preferred in noncoaxial devices where calibration techniques are not necessary and utilizes the S-parameters [22]. Therefore, this method can only be applied with testing the errors in the model. Since the plexiglass used in dielectric measurements behave like equipment under test (EUT), the S-parameters of that should be determined. Therefore, the effects of both flange and these plexiglass on the dielectric measurement should be eliminated. In addition to the deembedding method, the TRL method is a widely used and accurate method [23]. This technique is also known as a reference method that can demonstrate accuracy in measurement methods. Thus, the causes of errors that may directly affect the accuracy of this method should be considered. Negligible error rates at low frequencies further affect measurement accuracy at higher frequencies. Teflon material is widely used as a sample because of its easy accessibility and low cost to ensure that the measurement accuracy is sufficient. The ϵ' and ϵ'' values of the material having a thickness of 2.5 mm are almost constant versus the frequency and measured as 2 and 0, respectively.

3. Results and proposed model

As mentioned earlier, ϵ' (the real part of dielectric constant) and ϵ'' (the imaginary part of dielectric constant) parameters of orange and lemon samples are measured for each MC depending on the frequency at 24 ºC room temperature. Dielectric parameters are calculated using measured S_{11} and S_{21} parameters by NRW algorithm. The number of measurement steps for this frequency band is approximately 2.7 MHz and measurements are performed at 801 different frequency points. Figure 3 shows the measured ϵ' values for orange leaves. It is shown that the value of ϵ' decreases with increasing frequency, while the value of ϵ' increases with increasing MC. Figure 3 shows that at 6 GHz, MC is 100%, 12%, 0%, and ϵ' is 15.14, 10.44, and 6.43, respectively. It is seen in Figure 4 that these similar changes are valid for ϵ'' values. According to Figure 4, MC is 100%, 12.1%, 0%, while the value of ϵ'' is 15.52, 11.22, and 8.20 at 6 GHz.

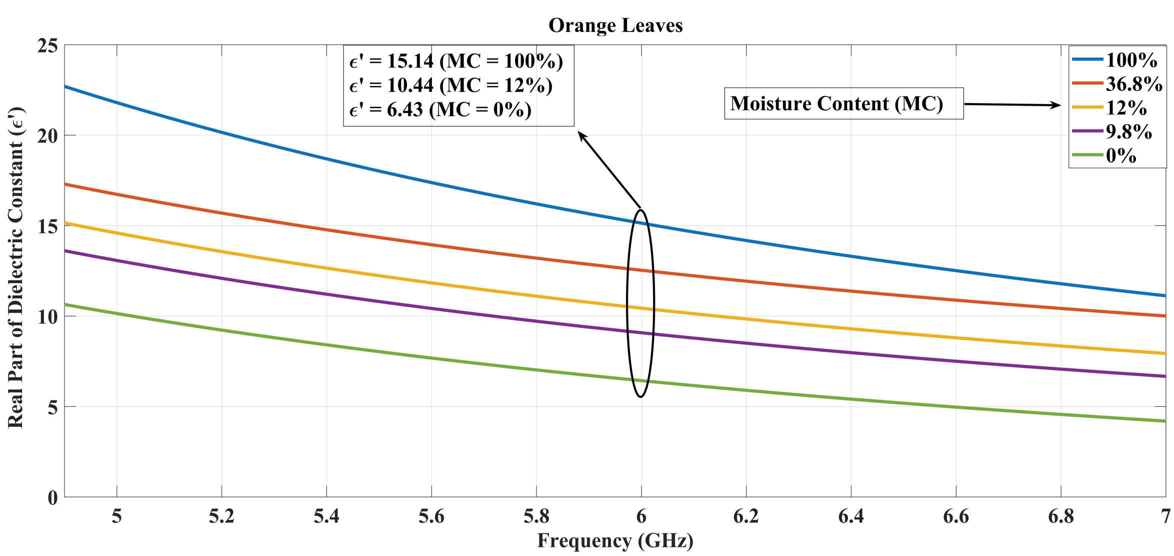

Figure 3. Measured relative dielectric constant for orange leaves in 4.90–7.05 GHz.

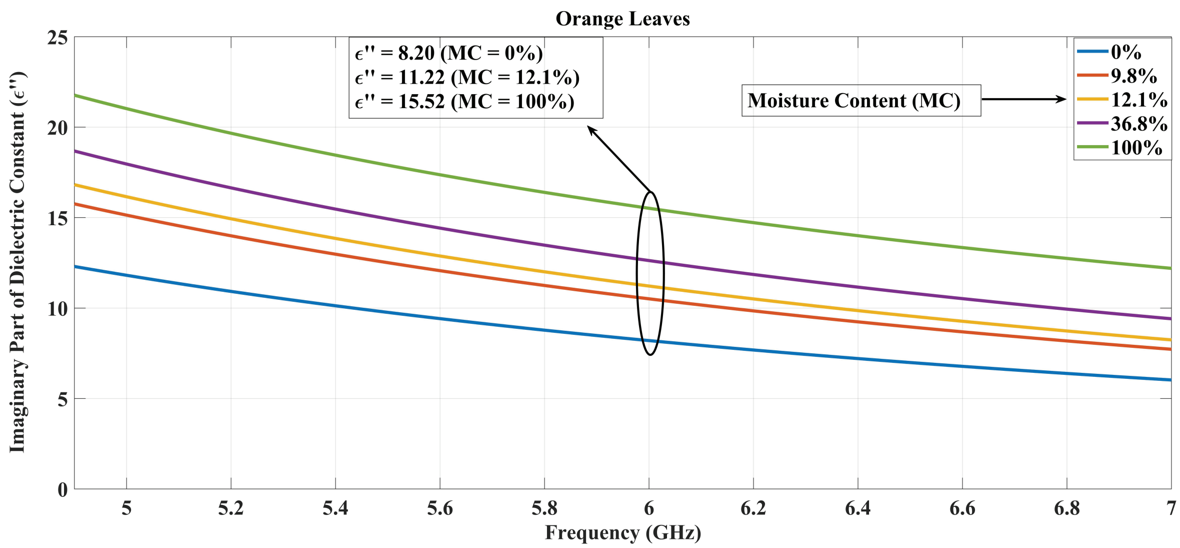

Figure 4. Measured dielectric loss for orange leaves in 4.90–7.05 GHz.

Figure 5 shows the variation of lemon leaves ϵ' values with frequency and MC. It is seen that ϵ' decreases with frequency increase and MC decrease. At 6 GHz, MC is 100%, 15.6%, 0%, and ϵ' is 16.87, 11.48, and 7.94, respectively. Similar changes can be seen in Figure 6 for ϵ''. At 6 GHz, MC is 100%, 15.6%, 0%, while the value of ϵ'' is 15.29, 10.30, and 3.33. According to these results, these values decreased on the vertical axis due to MC. In the literature, ϵ' and ϵ'' values of pure water vary between 74 and 70 and 25 and 18 for the 4.90–7.05 GHz band, respectively [5]. For the results obtained in this study, the ϵ' and ϵ'' values of the fresh leaf are much higher than those of the dry leaf, which is expected due to MC.

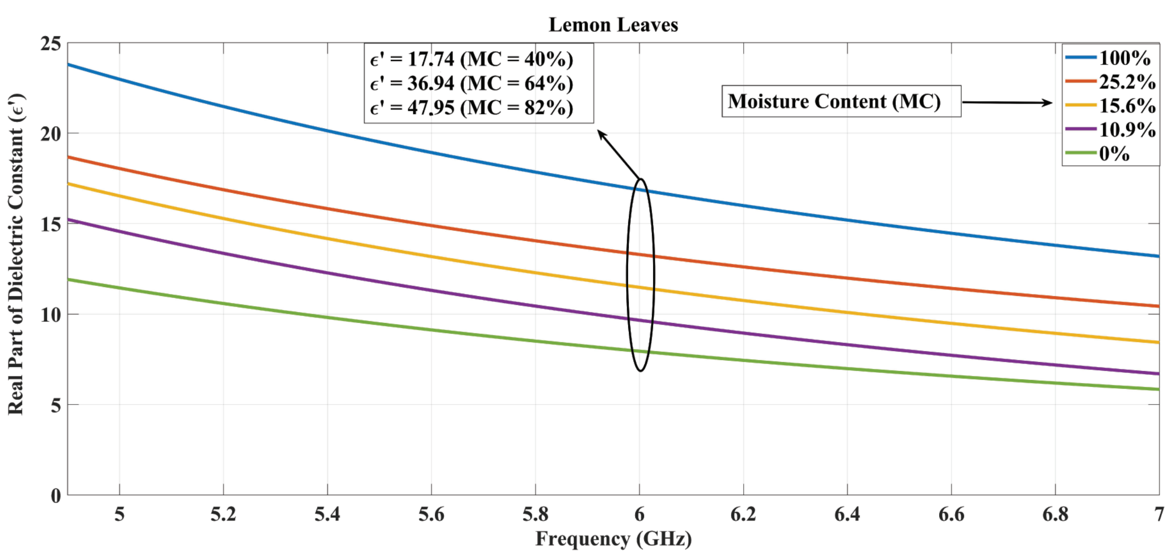

Figure 5. Measured relative dielectric constant for lemon leaves in 4.90–7.05 GHz.

The proposed model is obtained by curve fitting method using the data obtained from the measurement results of the orange leaves. This model is compared with the dielectric measurement results of lemon leaves

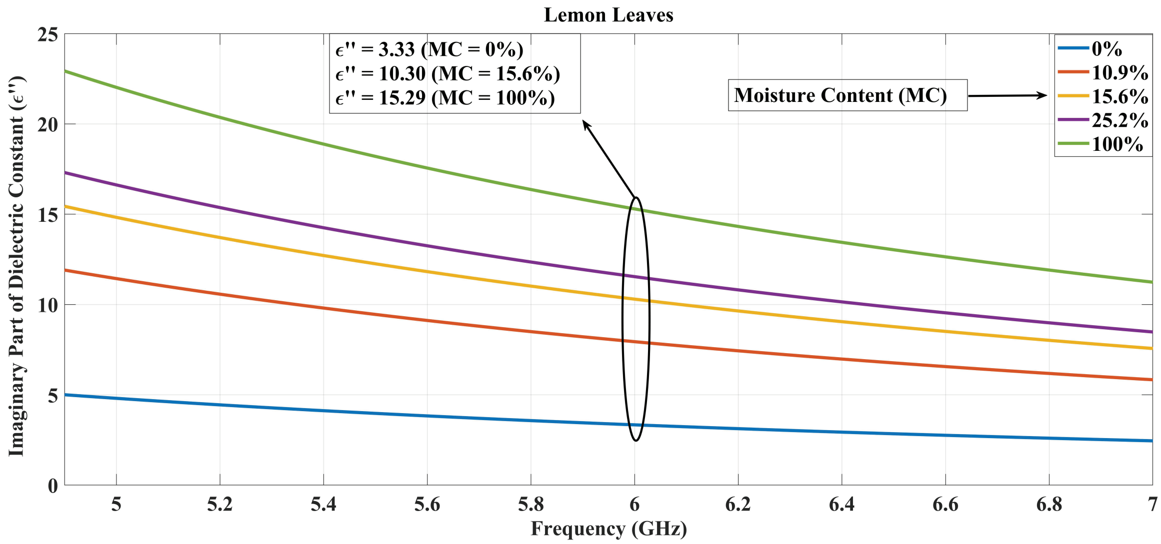

Figure 6. Measured dielectric loss for lemon leaves in 4.90–7.05 GHz.

which belong to the same family with orange type to determine the accuracy of the proposed model which is tested. This gives an idea about having similar dielectric characteristics of the different species in the same family. The model aims to calculate the magnitude of complex dielectric constant (the dielectric constant) depending on the frequency and MC. In Eq. 16 contains a second-order function with two variables.

$$\epsilon = \sqrt{(\epsilon')^2 + (\epsilon'')^2}, \tag{15}$$

$$\epsilon(f, m) = a + b.f^{-c} + d.m^e + g.f^{-c}.m^e, \tag{16}$$

where ϵ is the dielectric constant, f is the frequency in GHz, and m represents MC ranging from 0 to 100. The dielectric constant in Eq. 15 is preferred in the model since it contains both the real and the imaginary part of the complex dielectric permittivity of the material. In this way, instead of two different models, only one model is proposed. The coefficients of the model obtained for WR159 waveguide for orange leaf are $a = 86.9$, $b = -20.75$, $c = 36.5$, $d = 1.361$, $e = -2.426$, $g = -11.62$. In order to create this model, 6 different MC values calculated in the drying steps of orange leaf are used as data in Table 1. Another orange leaf with 29 % MC is selected as the test sample in order to test the accuracy of the model. The m value in Eq. 16 is determined as 29 so that the MC value in the model is the same as the measurement. In Figure 7, the measured dielectric constant of the orange leaf which is selected for the test is compared with the model. The results comply well with each other. The determination coefficient, R^2, and RMSE values are calculated with respect to the frequency and MC values by MATLAB® program to specify the performance of the model. Accordingly, R^2 and RMSE values of the model are obtained as 0.966 and 0.824, respectively.

The usability of the model is tested by using the measurement data of orange leaf for lemon leaf. Here the results of the proposed model having the same MC ($m = 24$) are compared with a lemon leaf having an MC value of 24%. It is seen in Figure 8 that there is an agreement between the results. The model derived from the leaves of a plant of the same family is also valid for another species of the same family. Even if the genus

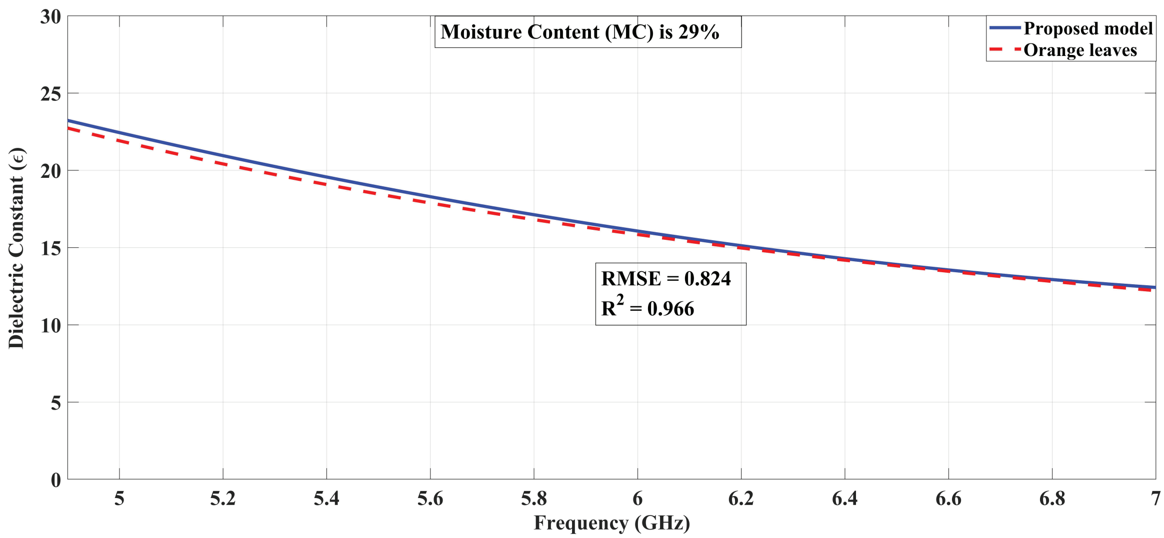

Figure 7. Comparison of the measured dielectric constant and proposed model for orange leaves.

and subfamilies of oranges and lemons are different, they both belong to the family Rutaceace and dicotyledons (Magnoliopsida) class. Therefore, the model obtained with the measurement data of the orange leaf is compared with the lemon leaf measurement results.

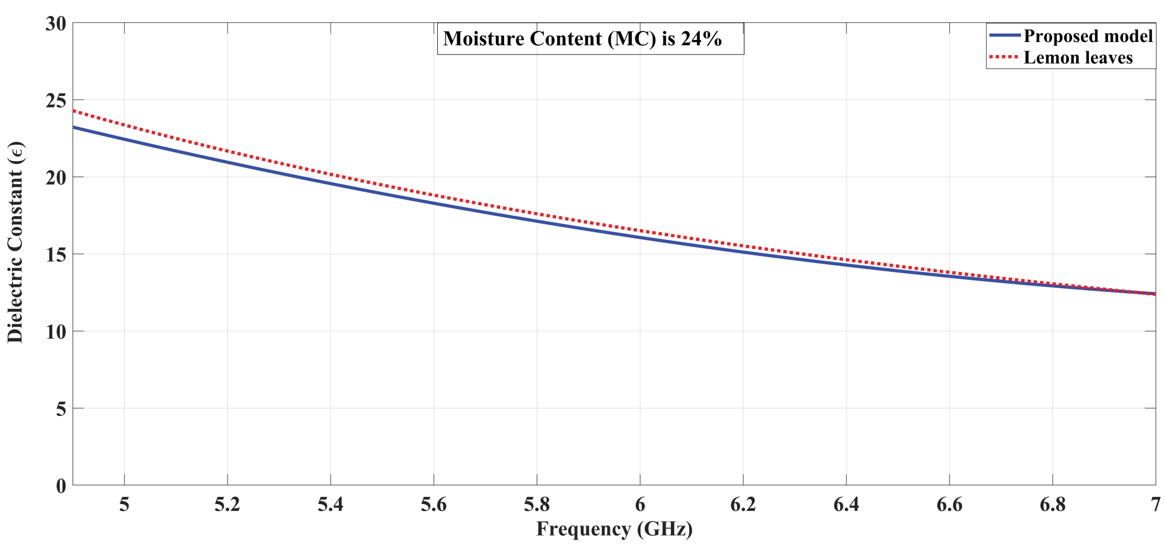

Figure 8. Testing the proposed model on lemon leaves.

4. Conclusion

In microwave remote sensing applications, the knowledge of the dielectric properties of the vegetative materials is used to detect planting areas for monitoring, to able to specify the growth stage of them in seasonal variations, also to determine the water requirement of the plant for controlling (water stress). For the dielectric measurements, there are some techniques such as microstrip transmission line (MTL), free-space transmission (FST), open-ended probe (OEP), coaxial transmission line (CTL), and WTL. MTL is suitable for applications other than agricultural and food products. FST method requires samples of very large dimensions for the S and C bands. The OEP method allows measuring only the reflection coefficient parameter. Since tiny sample sizes are used in the CTL method, it is not always possible to ensure sample homogeneity for accurate measurement. For these reasons, the WTL method is preferred in this study.

This study had two aims. Firstly, it obtained measurement results regarding the relative dielectric constant and dielectric loss of vegetation material, particularly for orange and lemon, as a function of MC of the material of the microwave frequency over the 4.90–7.05 GHz band. Secondly, as there are more than one species in some plant families, determining dielectric measurements of each species is not only costly, it also takes time. Thus, through this study, a new model derived from the dielectric parameters of a vegetable leaves can predict the dielectric characteristics of other vegetable species in the same family. In this way, only one model can be used for more than one vegetable species, providing time and cost advantages.

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References

[1] Mekonnen SA, Yenikaya S. Design optimization using dielectric slab for efficient microwave heating. Turkish Journal of Electrical Engineering & Computer Sciences 2019; 27 (4): 3055-3064. doi: 10.3906/elk-1802-164

[2] Chuah H, Kam S, Chye Y. Microwave dielectric properties of rubber and oil palm leaf samples: measurement and modelling. International Journal of Remote Sensing 1997; 18 (12): 2623-2639. doi: 10.1080/014311697217503

[3] Kocakusak A, Colak B, Helhel S. Frequency dependent complex dielectric permittivity of rubber and magnolia leaves and leaf water content relation. Journal of Microwave Power and Electromagnetic Energy 2016; 50 (4): 294-307. doi: 10.1080/08327823.2016.1254135

[4] Romanov AN, Ulanov PN. Seasonal differences in dielectric properties of dwarf woody tundra vegetation in a microwave range. IEEE Transactions on Geoscience and Remote Sensing 2018; 57 (6): 3119-3125. doi: 10.1109/TGRS.2018.2881048

[5] Ulaby FT, El-Rayes MA. Microwave dielectric spectrum of vegetation-Part II: Dual-dispersion model. IEEE Transactions on Geoscience and Remote Sensing 1987; 25 (5): 550-557. doi: 10.1109/TGRS.1987.289833

[6] Afzal A, Mousavi SF. Estimation of moisture in maize leaf by measuring leaf dielectric constant. International Journal of Agriculture & Biology 2008; 10 (1): 66-68.

[7] Itolikar AB, Kurtadikar ML. Microwave measurements of dielectric properties of corn vegetation at C-band and comparison with Debye-Cole dual dispersion model. Journal of Microwaves, Optoelectronics and Electromagnetic Applications 2017; 16 (4): 954-965. doi: 10.1590/2179-10742017v16i41087

[8] Krraoui H, Mejri F, Aguili T. Dielectric constant measurement of materials by a microwave technique: application to the characterization of vegetation leaves. Journal of Electromagnetic Waves and Applications 2016; 30 (12): 1643-1660. doi: 10.1080/09205071.2016.1208592

[9] Colak B. Moisture content effect of banana leaves to radio frequency absorbing. Microwave and Optical Technology Letters 2019; 61 (11): 2591-2595. doi: 10.1002/mop.31932

[10] Kaur R, Aul GD, Chawla V. Improved reflection loss performance of dried banana leaves pyramidal microwave absorbers by coal for application in anechoic chambers. Progress in Electromagnetics Research 2015; 43:157-164. doi: 10.2528/PIERM15072602

[11] Jayamani E, Hamdan S, Ezhumalai P, Bakri MK. Investigation on dielectric and sound absorption properties of banana fibers reinforced epoxy composites. Jurnal Teknologi 2016; 78: 6-10.

[12] Khaled D, Novas N, Gazquez J, Garcia R, Manzano-Agugliaro F. Fruit and vegetable quality assessment via dielectric sensing. Sensors 2015; 15 (7): 15363-15397. doi: 10.3390/s150715363

[13] Navarrete A, Mato RB, Dimitrakis G, Lester E, Robinson JR et al. Measurement and estimation of aromatic plant dielectric properties. Application to low moisture rosemary. Industrial Crops and Products 2011; 33 (3): 697-703. doi: 10.1016/j.indcrop.2011.01.012

[14] Kamaruddin MJ, Yusof MS, Ngadi N, Zakaria ZY, Arsad A et al. Dielectric properties for extraction of orthosiphon stamineus (java tea) leaves. Chemical Engineering Transactions 2017; 56: 1771-1776. doi: 10.3303/CET1756296

[15] Kraszewski AW, Nelson SO. Microwave permittivity determination in agricultural products. Journal of Microwave Power and Electromagnetic Energy 2004; 39 (1): 41-52. doi: 10.1080/08327823.2004.11688507

[16] Venkatesh M, Raghavan G. An overview of dielectric properties measuring techniques. Canadian Biosystems Engineering 2005; 47 (7): 15-30.

[17] Nelson SO. Fundamentals of dielectric properties measurements and agricultural applications. Journal of Microwave Power and Electromagnetic Energy 2010; 44 (2): 98-113. doi: 10.1080/08327823.2010.11689778

[18] Van Emmerik TH, Steele-Dunne S, Judge J, Van de Giesen N. A comparison between leaf dielectric properties of stressed and unstressed tomato plants. In: 2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS); Milan, Italy; 2015. pp. 275-278. doi: 10.1109/IGARSS.2015.7325753

[19] Van Emmerik TH. Diurnal differences in vegetation dielectric constant as a measure of water stress. MSc, Delft University of Technology, Delft, Netherlands, 2013.

[20] Durmus M, Salman AO, Yıldırım S. Finding electromagnetic parameters of materials by NRW method. Kocaeli Üniversitesi Fen Bilimleri Dergisi 2017; 1 (1): 13-19.

[21] Yaw KC. Measurement of Dielectric Material Properties: Application Note. USA: Rhode & Schwarz, 2012.

[22] Agilent De-embedding and Embedding S-parameter Networks Using a Vector Network Analyzer. Colorado, USA: Application Note 1364-1, 2004.

[23] Ye L, Li C, Sun X, Jin S, Chen B et al. Thru-Reflect-line calibration technique: error analysis for characteristic impedance variations in the line standards. IEEE Transactions on Electromagnetic Compatibility 2016; 59 (3): 779-788. doi: 10.1109/TEMC.2016.2623813

[24] Chung BK. Dielectric constant measurement for thin material at microwave frequencies. Progress in Electromagnetics Research 2007; 75: 239-252. doi: 10.2528/PIER07052801