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CHARACTERISATION OF THE ELECTROMAGNETIC PROPERTIES OF FLOWER LEAVES FOR 2.45 GHZ ISM BAND BIODEGRADABLE ELECTRONICS APPLICATIONS

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Abstract: *The digital transformation of healthcare, education, industry, and agriculture has generated new opportunities but also led to an increased use of digital devices that will lead to an increase in electronic waste (e-waste) at the end of the life cycle of these devices. In this paper, we report the electromagnetic properties of plant leaves from ten of the most used flowers that can be used to produce environmentally friendly microstrip antennas or fully biodegradable sensors for application in smart agriculture. The analysis of the results for the electromagnetic properties of the leaves of selected plants showed that the real part of the relative permittivity varied widely from 22.962 to 67.43387 for the leaves of garden plants and from 27.82699 to 55.80639 for the potted plants. The variation of the loss tangent of leaves is quite similar in potted (from 0.22718 to 0.35972) and garden (from 0.22812 to 0.33277) flowers.*

Keywords: biodegradable substrate, electromagnetic properties, 2.45 GHz ISM band, biological dielectrics, biodegradable antenna

1. Introduction

The digital transformation of healthcare, education, industry, and agriculture has generated new opportunities, which include new approaches for learning, working, producing, and harvesting, as well as new economic and social models [1-4]. The digital transformation also leads to a significant increase in digital device use. According to Eurostat [5], almost 30% of employed people in the European Union used electronic devices during all working time in 2022. The increased usage of digital devices will lead to an increase in electronic waste (e-waste) at the end of the life cycle of such devices. One way to reduce e-waste is by using biodegradable and organic materials in the manufacturing process of electronic devices [6]. Natural materials, such as plant leaves, rice ashes, cellulose or rice papers, are some of the potential biodegradable candidates for the production process of new "green electronics" because they are low-cost (or even at no cost) and easy to obtain [7]. In [7, 8], the application possibilities of tea leaves and Mytilaria laosensis Lec. leafs, in the triboelectric nanogenerator, have been demonstrated. Also, biodegradable paper-based nanogenerators [9] and flexible sensors based on natural wheat flour polymer [10] have been presented. Concerning reducing environmental footprint, antennas on natural rubber-based bio-composite substrates [11] and botanic eco-friendly textiles have been designed

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[12]. Moreover, plant leaves also can be used as biodegradable antenna substrates. Electromagnetic properties of natural materials are of utmost importance during the design process of antennas, microwave filters or applicators [13]. Measurements show that permittivity and loss tangents of certain agricultural products, such as grain and corn, vary with frequency and moisture [14].

This paper presents results from measuring the electromagnetic properties of some naturally degradable materials (flower leaves) for 2.45 GHz ISM band biodegradable electronics applications.

2. Materials and Method

2.1. Materials

Leaves from ten of the most used (five potted and five garden) flowers were collected.

The potted flowers are: Pelargonium 'Calliope Dark Red', Pelargonium 'Géranium Maverick Pink', Red Miniature Rose 'Rosa spp.', White Rose 'Chardonnay rose', and Ficus Benjamina.

The garden flowers are: French Hydrangea, Geranium Dreamland ‘Bremdream’, Red English Rose 'Lady Emma Hamilton', White Rosa 'Yvonne Rabier' and Petunia x hybrida 'Purple Wave'

Plant leaves were harvested at soil moisture between 96.5% and 100%. Rectangular samples with small sizes were prepared by cutting off harvested plant leaves. The samples were prepared immediately before measuring the electromagnetic parameters.

2.2. Methods

The cavity perturbation method was used to determine the electromagnetic properties of the leaves. A short-circuited rectangular waveguide was connected to a vector network analyser (Tektronix TTR503A) via coaxial cable and coaxial waveguide transmission, as shown in Figure 1. TTR503A was connected to a laptop with a USB cable. Before measurements, an Open-Short-Load calibration was performed.

Figure 1: Setup used for measuring the relative complex permittivity and loss tangent of flower leaves

According to the cavity perturbation method, the real (ε_r') and imaginary (ε_r'') parts of the relative complex permittivity were estimated from the change in the resonant frequency and quality factor of the cavity [15] with and without a small plant sample. More details about the size and mode of cavity used for the measurements and equations used to calculate ε_r' and ε_r'' can be found in our previous work [16]. The resonant frequency of the empty cavity was 2.56 GHz. We used this frequency to obtain electromagnetic parameters of the flower leaves at 2.45 GHz ISM band because in this band work many wireless devices: IEEE protocols 802.11 b/g/n [17], IEEE protocol 802.15, etc.

To validate the measurement system ten consecutive measurements of the electromagnetic parameters of a Teflon sample were carried out. The results were compared with literature data and the accuracy of the measurements was determined. We observed a standard deviation of the set of measurements of 0.011203 for ε_r' that shows high repeatability confirming the conclusion in [18] that “resonant methods have the lowest uncertainties, usually less than 1% for the real part of the permittivity”.

Also, we used a transmitted light microscope (OBE114 KERN&SOHN GmbH) with a digital colour camera to provide information about the leaf surface.

We used testo 440 dP (Testo Ltd, UK) with a robust humidity/temperature probe (High-precision temperature/humidity probe 0636 9775, Testo Ltd, UK) to measure soil relative humidity.

3. Results and Discussions

The obtained values for relative complex permittivity and loss tangent of leaves from potted and garden flowers are presented in Tables 1 and 2, respectively. Tables also provided plant leaf surface images captured using the transmitted light microscope.

The analysis of the results for the electromagnetic properties of the leaves of selected plants showed that the real part of the relative permittivity varied widely from 22.962 to 67.43387 for the leaves of garden plants and from 27.82699 to 55.80639 for the potted plants.

The change in values of the imaginary part of the relative permittivity also varied widely: for leaves of garden flowers from 6.457184 to 22.4404, while for potted plants, the change is within the range of 8.63074 to 13.58718.

The variation of the loss tangent of leaves is quite similar in potted (from 0.22718 to 0.35972) and garden (from 0.22812 to 0.33277) flowers. As known from theory [15], the loss tangent is the ratio of the imaginary to the real part of the relative permittivity. In almost all the measured leaves of flowers, when the value of the real part of the relative dielectric permittivity is high, the imaginary part is also high, which explains the variation in a narrower interval of the loss tangent.

Table 1 Electromagnetic parameters and leaf epidermis images of potted flower

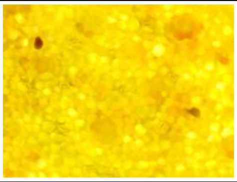
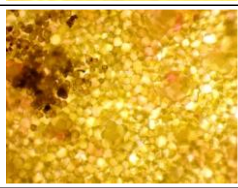
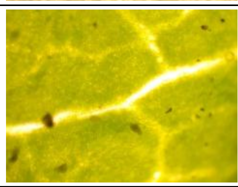
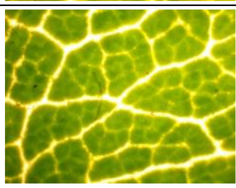
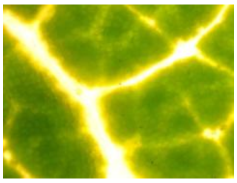
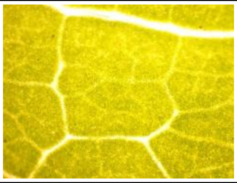
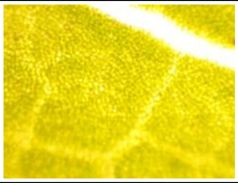
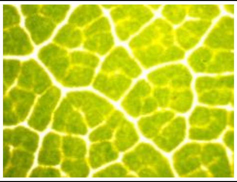
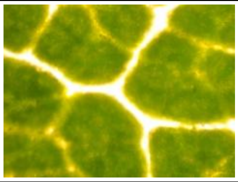
Plant	Electromagnetic parameters (ε_r', $\tan\delta$)	Leaf surface images		Soil relative humidity, %rH
		Magnification x4	Magnification x10	
Pelargonium 'Calliope Dark Red'	ε_r' = 37.99018 $\tan\delta$ = 0.22718			96.5
Pelargonium 'Géranium Maverick Pink'	ε_r' = 55.80639 $\tan\delta$ = 0.23308			99.0
Red Miniature Rose 'Rosa spp.'	ε_r' = 31.12037 $\tan\delta$ = 0.35972			98.3
White Rose 'Chardonnay rose'	ε_r' = 27.82699 $\tan\delta$ = 0.33447			100.0
Ficus Benjamina	ε_r' = 41.18402 $\tan\delta$ = 0.32991			96.5

Table 2 Electromagnetic parameters and leaf epidermis images of garden flower

Plant	Electromagnetic parameters	Leaf surface images		Soil relative humidity, %rH
		Magnification x4	Magnification x10	
French Hydrangea	ε_r' = 44.44021 tanδ = 0.244423			100.0
Geranium Dreamland 'Bremdream'	ε_r' = 41.21573 tanδ = 0.22812			100.0
Red English Rose 'Lady Emma Hamilton'	ε_r' = 33.02146 tanδ = 0.260781			100.0
White Rosa 'Yvonne Rabier'	ε_r' = 22.9620 tanδ = 0.281212			100.0
Petunia x hybrida 'Purple Wave'	ε_r' = 67.43387 tanδ = 0.33277			100.0

Also, the values of the complex permittivity and loss tangent of potted roses presented in Table 1 are similar to those of garden roses in Table 2. When comparing the electromagnetic parameters of the Pelargonium 'Calliope Dark Red' and Pelargonium 'Géranium Maverick Pink', no close values are observed, although, both plants are potted and of the same family.

One reason for the observed difference in the complex relative permittivity of flower leaves is their varying water content. It is well-known that increasing moisture content raises relative dielectric permittivity [14-15]. Differences in leaf density and structure may also account for the observed relative permeability values. Also, the water content changes throughout the plant lifecycle – it is lowest in summer and tends to increase between autumn and winter [19]. That may affect the electromagnetic parameters.

Usually, for the substrate of microstrip antennas during the design process, materials with ε_r' between 1.5 and 10 are preferred, but using materials with higher ε_r' has both advantages and disadvantages [20]. As known from theory, the substrates from material with a higher ε_r can significantly reduce the antenna's radiation efficiency, and consequently, such types of materials should be used carefully. Moreover, the higher ε_r' of the substrate material can also be used to reduce antenna size [20].

Hence, low-cost or even no-cost biodegradable materials, such as plant leaves, can be used to produce environmentally friendly microstrip antennas for application in smart agriculture.

4. Conclusions

In summary, we present the electromagnetic properties of plant leaves from ten of the most used flowers to produce environmentally friendly microstrip antennas or fully biodegradable sensors for application in smart agriculture. The analysis of the results for the electromagnetic properties of the leaves of selected plants showed that the ε_r' varied widely from 22.962 to 67.43387 for the leaves of garden plants and from 27.82699 to 55.80639 for the potted plants. Also, the values of the complex permittivity and loss tangent of leaves of flowers from the same family as potted roses are similar to those of garden roses. Moreover, when comparing the electromagnetic parameters of the other plants, no close values are observed, although both plants are potted and of the same family. Differences in leaf water content, density and structure may account for the observed relative permeability values. Consequently, when designing an antenna on a plant leaf substrate, it is necessary to determine the electromagnetic parameters at the frequencies of interest.

In our future work, we plan to measure the electromagnetic parameters of leaves during the plant life cycle to find the time-dependence of parameters of bio-dielectrics. Also, a guideline will be created to ensure high reproducibility of results for plant electromagnetic parameter measurements.

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