Article

Characterization and Water Content Estimation Method of Living Plant Leaves Using Terahertz Waves

Adnan Zahid [1,*], Hasan T. Abbas [1,2,*], Muhammad Ali Imran [1], Khalid A. Qaraqe [2] Akram Alomainy [3], and Qammer H. Abbasi [1]

[1] School of Electronics and Nanoscale Engineering, University of Glasgow, Glasgow, UK; Muhammad.Imran@glasgow.ac.uk, Qammer.Abbasi@glasgow.ac.uk

[2] Department of Electrical and Computer Engineering, Texas A&M University, Doha, Qatar; khalid.qaraqe@qatar.tamu.edu

[3] School of Electronic Engineering and Computer Science, Queen Mary University of London, London, UK; a.alomainy@qmul.ac.uk

* Correspondence: a.zahid.1@research.gla.ac.uk (A.Z.); hasan.abbas@qatar.tamu.edu (H.T.A.)

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Abstract: An increasing global aridification due to climate change has made the health monitoring of vegetation indispensable to maintaining the food supply chain. Cost-effective and smart irrigation systems are required not only to ensure the efficient distribution of water, but also to track the moisture of plant leaves, which is an important marker of the overall health of the plant. This paper presents a novel electromagnetic method to monitor the water content (WC) and characterization in plant leaves utilizing the absorption spectra of water molecules in the terahertz (THz) frequency for four consecutive days. We extracted the material properties of leaves of eight types of pot herbs from the scattering parameters, measured using a material characterization kit in the frequency range of 0.75 to 1.1 THz. From the computed permittivity, it is deduced that the leaf specimens increasingly become transparent to the THz waves as they dry out with the passage of days. Moreover, the loss in weight and thickness of leaves were observed due to the natural evaporation of leaf moisture cells and change occurred in the morphology of fresh and water-stressed leaves. It is also illustrated that loss observed in WC on day 1 was in the range of 5% to 22%, and increased from 83.12% to 99.33% on day 4. Furthermore, we observed an exponential decaying trend in the peaks of the real part of the permittivity from day 1 to 4, which was reminiscent of the trend observed in the weight of all leaves. Thus, results in paper demonstrated that timely detection of water stress in leaves can help to take proactive action in relation to plants health monitoring, and for precision agriculture applications, which is of high importance to improve the overall productivity.

Keywords: Vegetation health monitoring, leaf water content, terahertz, sensing, plants health.

1. Introduction

Over the past decade, the terahertz (THz) technology has seen an increased amount of interest in the scientific community chiefly due to its non-ionizing and less pervasive radiation properties [1]. There has been significant progress in tapping the so-called terahertz gap 0.3 THz to 3 THz of the electromagnetic spectrum. The THz technology has found extensive use in applications such as the imaging of concealed items [2], material characterization [1], diagnostic applications including treatment of skin and dental care [3,4], effective and quality control of food [5], and telecommunication [1,6,7]. Furthermore, a distinguishing feature of the THz waves is that the water molecules exhibit a strong absorption spectrum in the pertinent frequency range, leading to novel bio-sensing applications.

Despite these substantial contributions, the utility of the THz technology in the environmental control/monitoring systems has not been explored in depth, especially for the purpose of the vegetation monitoring [8,9]. Unlike the microwave-based remote sensing techniques, the THz technology can provide

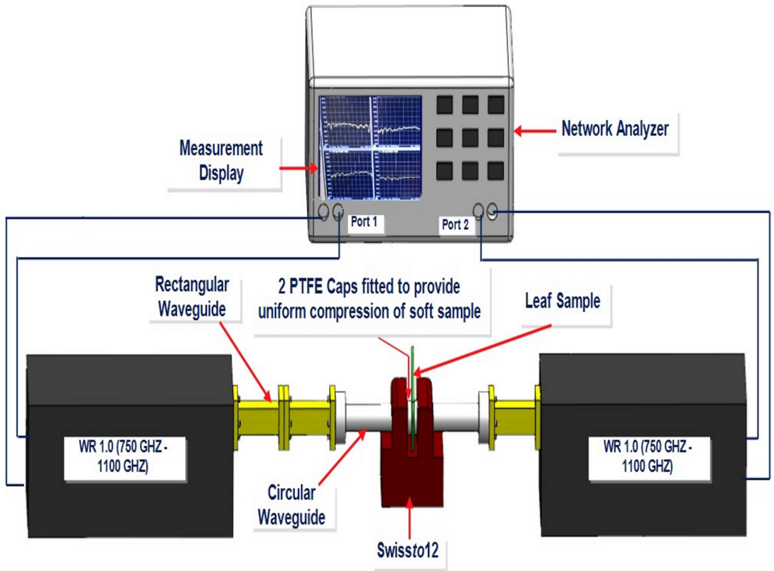
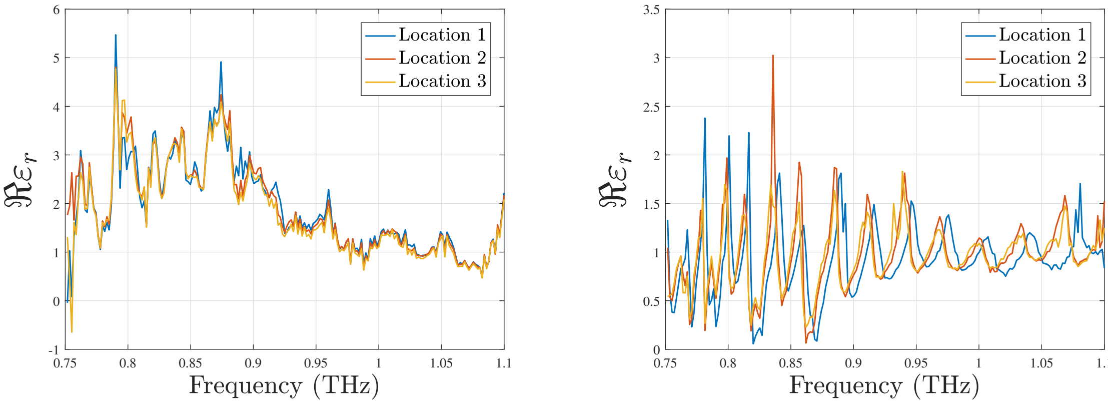


Figure 1. Schematic representation of experimental setup used for measurement of leaf sample. The leaf sample is placed between the two PTFE caps fitted to Waveguide

detailed insight into the health of a plant specimen in terms of the water content (WC) in the leaves [10]. Water is essential to the process of photosynthesis, transpiration and nutritional transport in the plants [11]. Designing a smart and plant-specific irrigation system that monitors the leaf WC in a non-invasive manner is, therefore, critical in the current circumstances governed by global climate change that demand water conservation. Over the years, significant amount of contributions have been made [9–13], that address estimating the leaf's WC. There are techniques that offer high reliability yet they are inappropriate for long-term studies of the same plant leaves [13–17] due to their destructive nature.

Non-destructive methods have previously been used to determine the water status in plant leaves, which include thermal, infrared and hyper-spectral imaging and magnetic resonance imaging (MRI) [18]. However, these techniques are limited by the resolution and thus, cannot provide any cellular-scale information about the plants. Other evolving methods based on THz electromagnetic radiation have revealed improvements in monitoring microscopic changes of WC due to high sensitivity[14,18]. However, these technique do not consider any environmental influence due to its low photon energy [14,18]. Lately, there has been a growing trend in the field of plant physiology and characterization of liquid to use THz spectroscopy [19], as a non-invasive technique to measure the leaf water status under certain conditions, such as drought stress[12,13,15,20,21] and dehydration kinetics [18]. However, the experimental setup of THz spectroscopy is not portable hence limits the on-site use of the technique.

In this paper, we present a novel, non-invasive approach to monitoring the WC of plant leaves using the scattering parameters of a THz pulse. Using a well-known material extraction algorithm, we computed permittivity from the scattering parameters for eight types of leaves, which we observed for four consecutive days. The WC was then gauged from the decrease in the permittivity as days passed. This paper is an expansion and presents a detailed analysis of our earlier work [8]. The significance of this paper lies in the simple, cost-effective technique and other advantages such as: a) This paper proposes a unique technique to characterize and estimate WC of eight various leaves in terms of electromagnetic parameters at THz frequency range from 0.75 to 1.1 THz. b) The electromagnetic parameters are measured in simple, fast, and non-invasive manner using a terahertz material characterization kit. Moreover, The structural integrity and configuration of leaves were also considered by employing two Polytetrafluoroethylene (PTFE) caps which were fitted internally to the waveguide. c) This paper establishes a notable correlation between electromagnetic parameters with WC in leaves i.e. an increment or decrement in WC status of leaves is evidently reflected in electromagnetic parameters at certain frequencies. The rest of the paper is structured as follows: Section 2 describes the experimental setup followed by the material characterization methods of plants leaves. Section 3 presents the measurement results and different parameters



(a) Day 1 **(b)** Day 4

Figure 2. Real part of permittivity of coffee leaves at three different locations taken on day 1 and 4.

are discussed such as permittivity, the effect of weight and thickness, and the refractive index of leaves, followed by a comparison of transmission response of all eight leaves between day 1 and 4. Finally, conclusion is discussed in Section 4.

2. Methods

2.1. Experimental Setup

We used a THz Swissto12 Material Characterization (MCK) to obtain the scattering parameters of the plant leaves. The MCK was attached to a Virginia Diodes (VNA) extender WM-250 (WR1.0) operating in the frequency range of 0.75 to 1.1 THz. The VNA was powered by a Keysight Technologies PNA microwave network analyzer N5224A. In order to avoid any structural damage while the leaf specimen was clamped in the MCK for observation, we used two PTFE caps that enabled a uniform compression of the samples as shown in Figure 1 . Prior to the measurement, the setup was configured using the two-port short-open-load-thru (SOLT) calibration technique.

2.2. Sample Details

Eight different kinds of pot herbs were used, namely coffee arabica, aromatic coriander, basil, baby-leaf, pea-shoot, parsley, lamb lettuce, and baby spinach. The fresh leaves were detached from the plants and placed in the laboratory for four consecutive days. The environment temperature for the measurements of leaves was 18.0 °C ± 0.1 °C, and the humidity was between 30 % ± 2 %. The leaves' thickness and weight were measured every 2 h during the natural evaporation of leaf moisture. We used a Vernier scale to measure the leaf thickness and this process was repeated to determine thicknesses at three different locations to ensure having similar all over the surface of a leaf, and found them in the threshold range of 40 µm to 4 mm. The weight of leaf was measured using a digital kitchen scale with a least count of 0.1 mg. All leaves were measured at three different locations and on every location, four various orientations were considered to investigate the behaviour of leaves. As an example, Figure 2 showed the response of a coffee leaf at three various locations.

2.3. Material Characterization of Plant Leaves

The Nicholson-Ross-Weir (NRW) method [22] is the most common technique in which the dielectric parameters ε_r and μ_r of a planar material are extracted from a two-port VNA measurement in which the transmission and reflection coefficients are obtained through the S-parameters. This method belongs to the category of frequency-by-frequency material extraction in which every point from the frequency sweep is used. In general, the NRW method generates both the complex permittivity $\varepsilon_r = \varepsilon_r'' - j\varepsilon_r'$ and permeability,

$\mu_r = \mu_r' - j\mu_r''$ of the specimen under test. Here, we assume that the leaves are non-magnetic and compute only the permittivity.One of the intrinsic problems of the NRW method is the periodicity of the phase of the electromagnetic wave that leads to ambiguous results. This problem has been discussed at length in other works [23–25]. In order to rectify this, we follow the step-wise approach in which the phase ambiguity is removed by using the phase delay information from the previous frequency point [26]. In this paper, we consider a plant leaf as a planar slab of thickness d which is positioned between two air-filled circular waveguides. With the help of an equivalent transmission line model, the reflection (Γ) and transmission (T) coefficients of a semi-infinite slab are expressed in terms of the measured s-parameters, S_{11} and S_{21} as [27],

$$\Gamma = \chi \pm \sqrt{\chi^2 - 1}, \qquad T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma}, \tag{1}$$

where the intermediate variable χ is defined as $\left(S_{11}^2 - S_{21}^2 + 1\right)/2S_{11}$. In the case of the slab having a finite thickness d, the transmission coefficient T can described in terms of the propagation constant, γ as, $T = \exp(-\gamma d)$, which can subsequently be written in the Euler form as $|T|\exp(-j\phi)$ where ϕ denotes the phase term. The propagation constant is then determined using [25],

$$\gamma = \frac{1}{d}\{-\log(|T|) - j\phi + j2\pi n\} \text{ where } n \in \mathbb{Z} \tag{2}$$

which results in an infinite number of branches of the complex valued root due to the logarithmic function, demonstrated by the presence of the $2\pi n$ term. The problem of selecting the proper branch is solved by the technique proposed in [26] in which at each frequency point, the phase delay information is recovered from the previous frequency point. If the phase difference, $\phi_i - \phi_{i-1} < \pi$, the method ensures the current branch is selected. The permittivity is then calculated by,

$$\varepsilon_r = \frac{\gamma}{\gamma_0}\left[\frac{1-\Gamma}{1+\Gamma}\right] \tag{3}$$

3. Measurement Results

The aim of this paper was to determine the electromagnetic properties of leaves including permittivity, refractive index and physiological features such as weight and thickness that can affect the WC of leaves. In addition, a strong correlation between the determined properties and WC of leaves was observed. Furthermore, the transmission response of all eight leaves were investigated for four consecutive days.

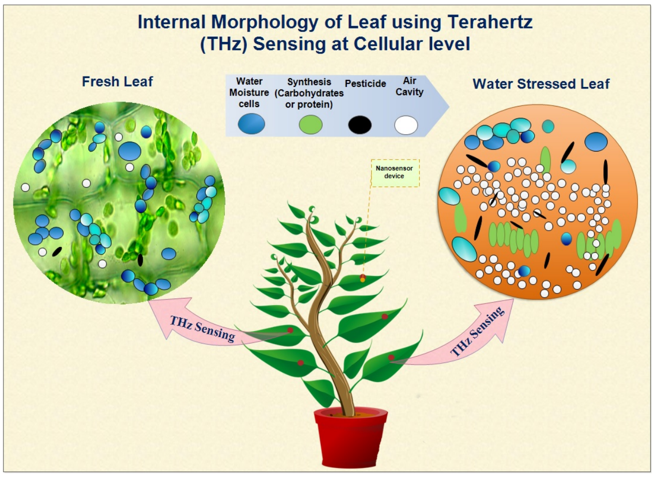
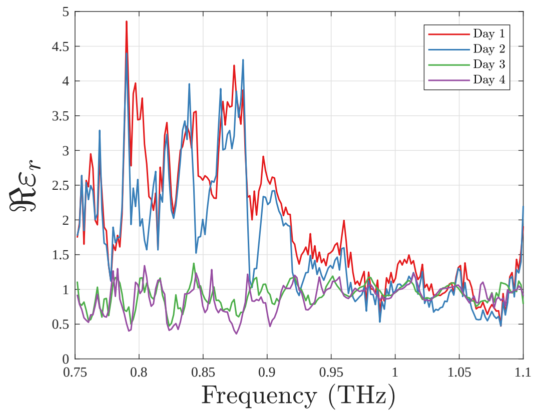


Figure 3. Internal morphology of fresh and water stressed leaf using terahertz sensing.

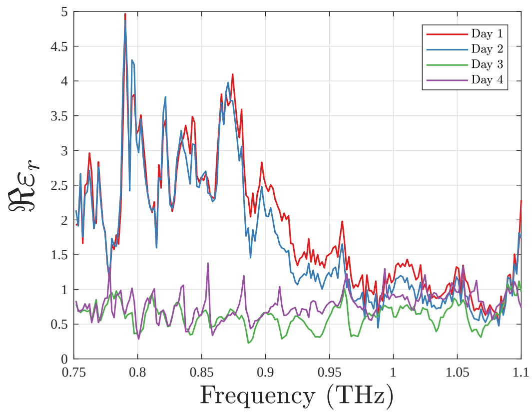
3.1. *Permittivity of Leaves*

A leaf essentially comprises of a composite biological structure of tissues and distinctive biomolecules like cellulose and synthesis compounds including proteins, carbohydrates and many other molecular weight compounds with different permittivity values [13] as depicted in Figure 3. It is significant to highlight the frequency dependence of the permittivity of leaves. In this study, the permittivity of eight different leaves were measured on three various locations with different percentage of water content in them. Furthermore, on every location, measurements were recorded using four different orientations of the leaves to observe any anisotropic behaviour. Figure 2 showed that the differences in permittivity were negligible regardless of the location and orientation.

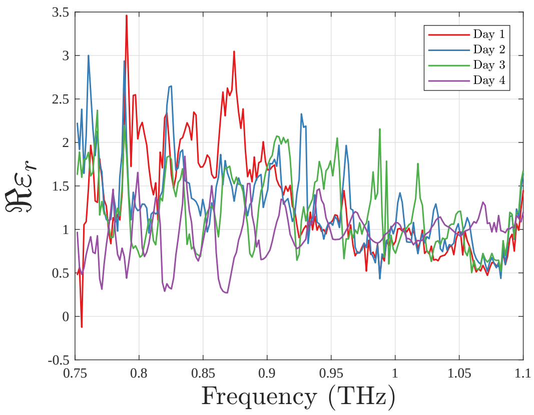
It was observed that a coffee leaf, in particular, showed a similar pattern across all the three locations and the leaf surface irregularities deemed to be very negligible. Likewise, the rest of other leaves displayed a similar trend. The purpose of these findings was mainly to investigate any variations in the permittivity which could occur due to different locations on the leaves. Figure 4 showed the real part of the permittivity for all the leaves measured on four consecutive days. It was significant to observe that all the leaves revealed the highest permittivity on day 1 when the WC in fresh leaves were considerably high, and as the days passed, permittivity showed a decrement when leaves became water stressed. Hence, dielectric parameter measurements differed significantly on day 1 and 4 for fresh, and water-stressed leaves. From these observations, it also showed a clear correlation between the permittivity and WC of leaves, i.e. fresh leaves with a higher amount of WC would have a high permittivity and vice versa. From Figure 5, it was evidently observed that permittivity showed a strong decaying correlation with



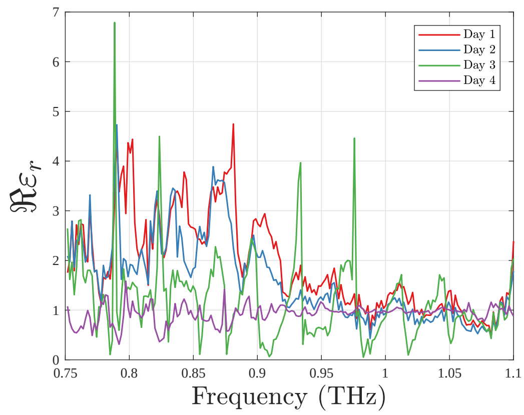
(a) Baby leaf



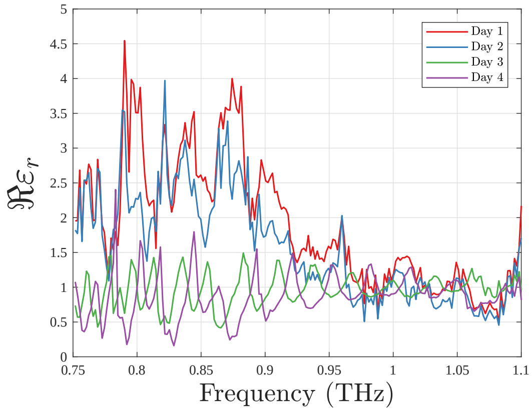
(b) Basil leaf



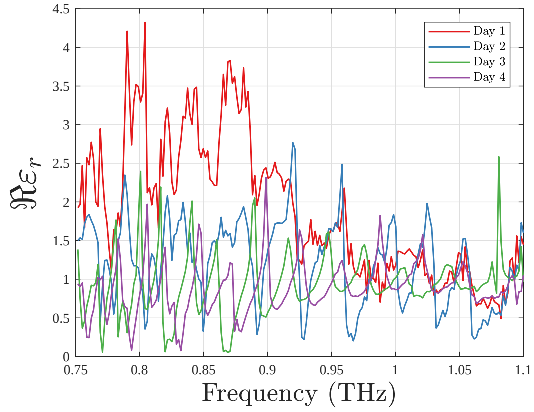
(c) Coffee Arabica



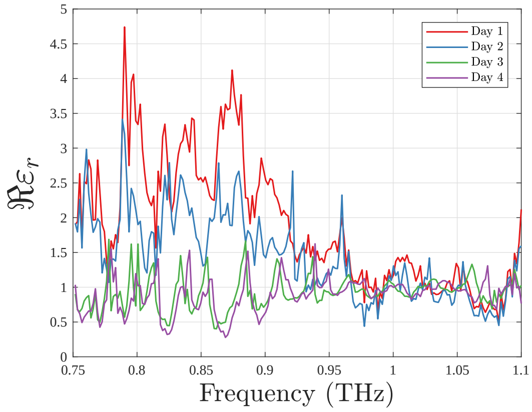
(d) Aromatic Coriander



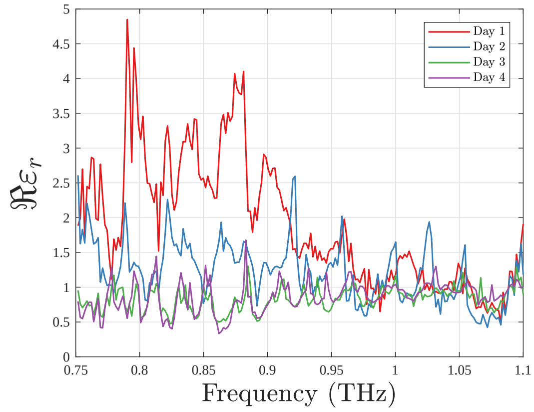
(e) Lamb Lettuce



(f) Parsley



(g) Peashoot



(h) Baby Spinach

Figure 4. Real part of permittivity of all eight leaves measured on four consecutive days. Leaves become transparent to electromagnetic waves with the passage of days as seen by the decrease in the permittivity.

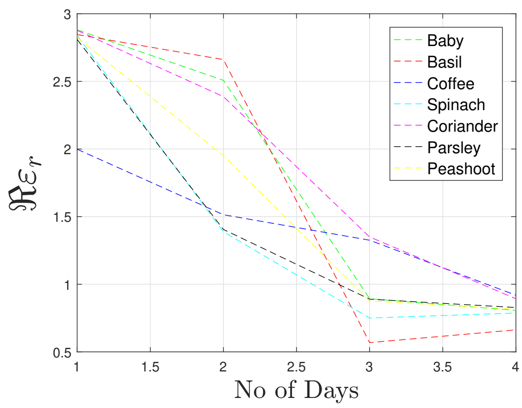
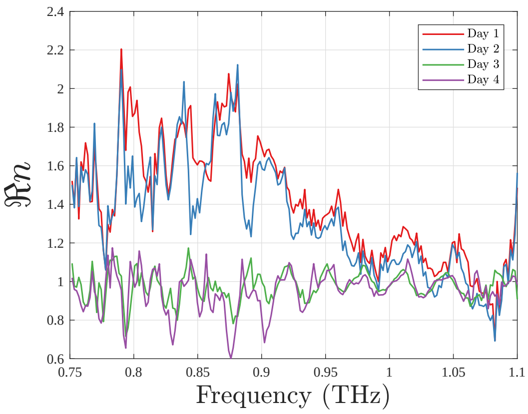


Figure 5. Correlation of permittivity with loss of WC in leaves.

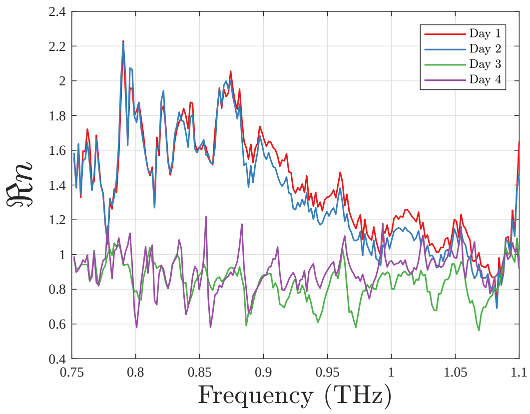
WC. With every passing day, water moisture had been kept evaporated and it eventually displayed an effect in electromagnetic properties of leaves. As observed in Figure 4, various leaves also showed distinctive decrement responses from each other, also attributing to have physiological and biological process growth. In this process, specific values of permittivity were investigated with a water loss of leaves from day 1 to 4.

3.2. Refractive Index of Leaves

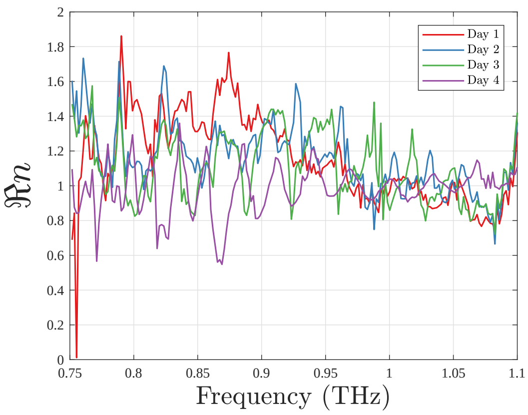
In this section, the refractive indices for all the leaves with variance level of WC were computed. It was examined that different leaves performed individually due to the internal characteristics of leaves and the amount of WC presence in the leaves at the time of measurement. Likewise, the same pattern was repeated to determine the refractive index of all leaves for four days. For some leaves as shown in Figure 6, a very robust and strong abnormal dispersion was perceived, which was clearly attributed to the presence of large WC. There is another significant optical parameter which can exploit the different characteristics of plant leaves and provide very meaningful and useful information about WC in leaves.



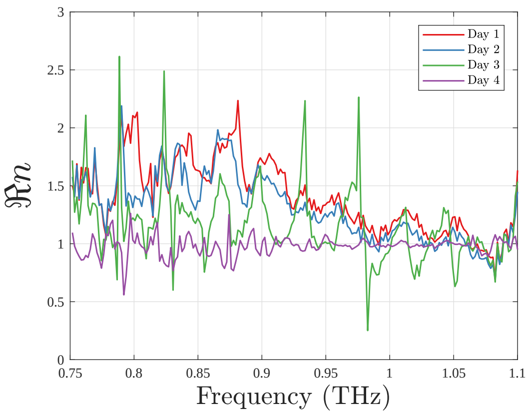
(a) Baby leaf



(b) Basil leaf



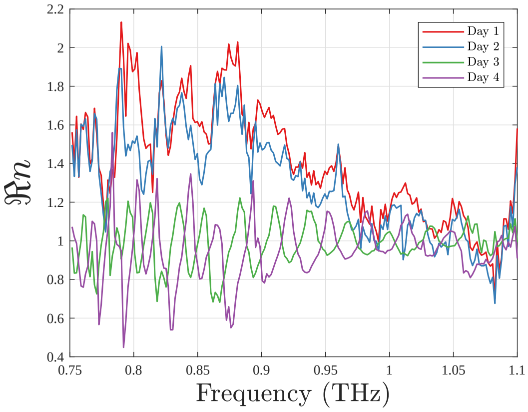
(c) Coffee Arabica



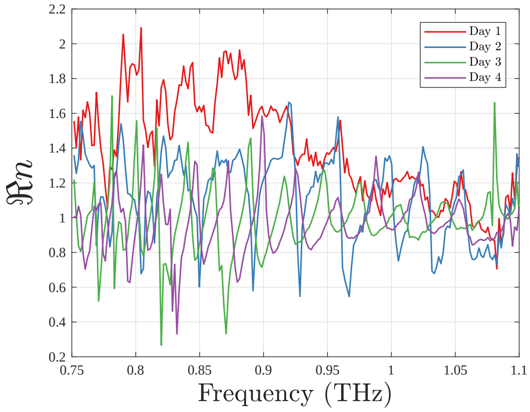
(d) Aromatic Coriander

3.3. Estimation of Water Content in Leaves

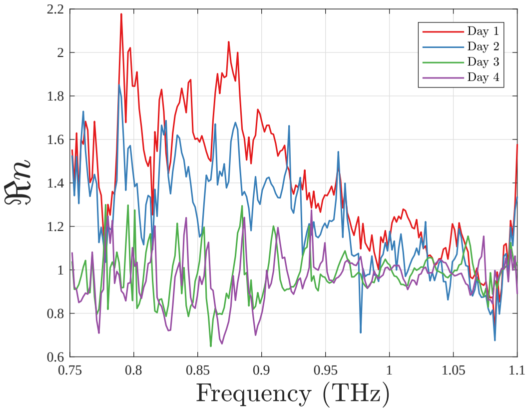
In this study, the weight and thickness of leaves were determined for four consecutive days using a precision electronic scale and Vernier calliper respectively. Referring to the weights of leaves, initially on the first day, the time duration between the two weight measurements were maintained from two to three hours. On the second day, this was extended to four hours and finally, on the third and fourth day, it was increased to 6 hours. It was noted that there was significant decrement in the weights of some leaves as shown in Figure 7 on day 1, i.e. basil, baby leaf and pea shoot, whereas, other leaves displayed a slow decrement in weight loss of leaves as days progressed. This clearly indicated that the moisture in leaves evaporated more rapidly on the day 1 and 2 compared to day 3



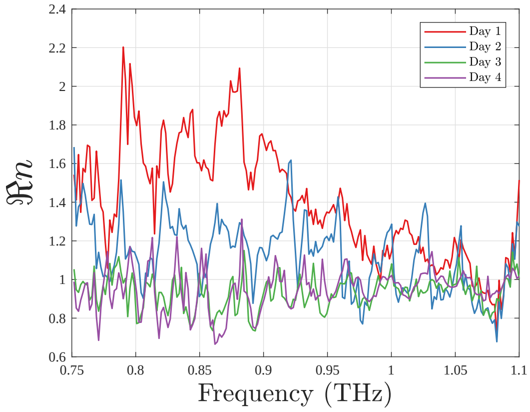
(e) Lamb Lettuce



(f) Parsley

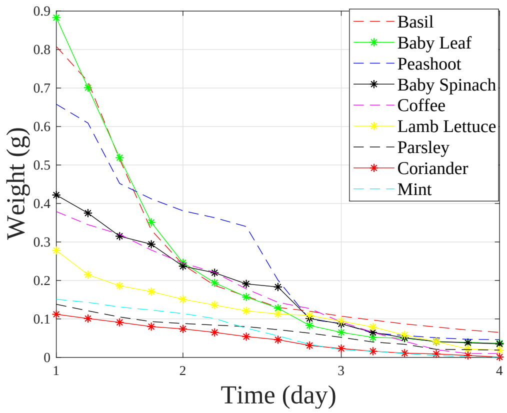


(g) Peashoot

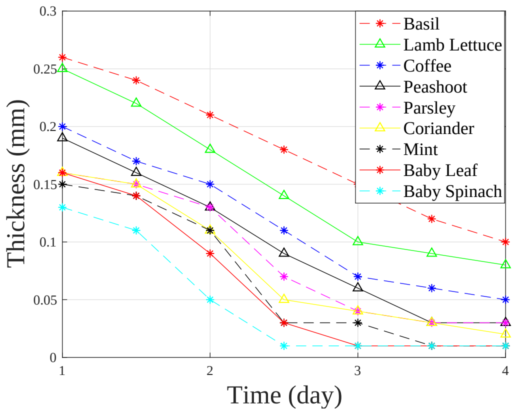


(h) Baby Spinach

Figure 6. Real part of refractive index of all the eight leaves measured on four consecutive days.



(a) Weight



(b) Thickness

Figure 7. Change in the physical properties of leaves with time.

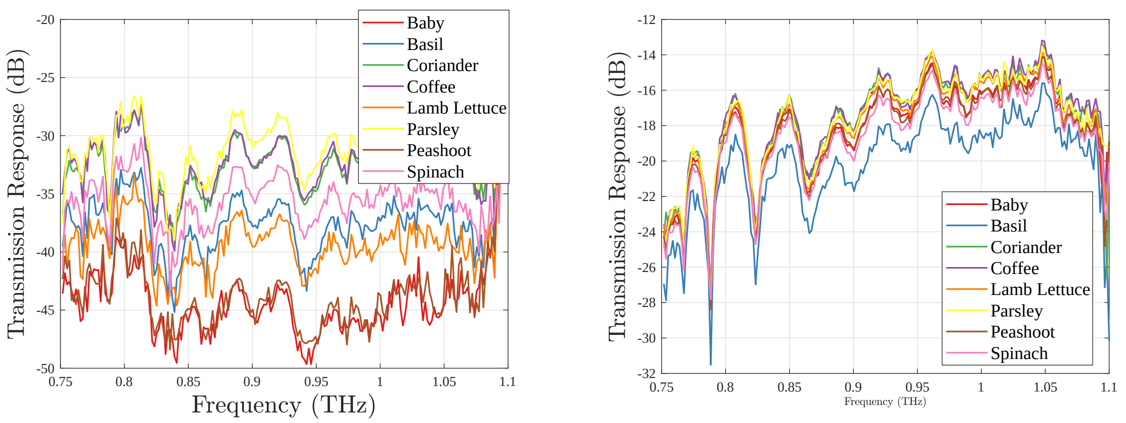
and 4, thereby creating more air cavities in the leaves. To assess the variation of leaf WC during the leaf's water evaporation process, the measurements were translated into WC using [17,28],

$$WC = \frac{W_{\text{time}} - W_{\text{dry}}}{W_{\text{fresh}}} \times 100 \tag{4}$$

where W_{fresh} is the weight of the fresh leaf, W_{time} is the weight of a leaf measured over time and W_{dry} is the weight of a dry leaf. In the beginning, the WC loss observed between the two hours on day 1 was found in the range of 5% to 22%. At the end of the investigation on day 4, this loss was increased during the natural evaporation of leaf moisture and was established in the range of 83.12% to 99.33%. The obtained percentages loss of WC can be validated with Figure 7a. Considering this discussion, it also showed a significant correlation with the real part of the permittivity which was the highest on the first day when the weight of leaves was considerably high compared with the fourth day as shown in Figure 4. The thickness of all the leaves was carefully determined to avoid any excess pressure to the samples, that would cause disturbances in the morphological structure of the leaves, changing the dielectric properties of the samples as a result. As seen in Figure 7b, the thickness of leaves was considerably higher on day 1, implying a greater WC in fresh leaves compared to day 4 when mostly, all leaves were dried out. From this significant and meaningful observation, it was concluded that dehydration of water contents in leaves with passing days affected the thicknesses to a substantial degree. On day 4, some leaves stayed invariant or slight changes occurred in the thickness of leaves i.e. coriander and spinach as shown in Figure 7a. These transformations in the thickness of leaves evidently showed that WC in coriander and spinach leaves had evaporated to the maximum on day 4 and no further variations could be observed in thickness of leaves.

3.4. Evaluation of Leaf Transmission Response

In this section, transmission responses of all leaves were observed on day 1 and 4 as shown in Figure 8. It was noticed that on day 1, attenuations of all leaves were substantially high due to the presence of higher WC in tissues of leaves, which resulted in a higher absorption and lower transmission response. Moreover, on day 4, a substantial degree of increment in transmission response was observed as WC in leaves had evaporated to large extent, which resulted in a decrement of weight and thickness of leaves and eventually, less absorption occurred at this time. Figure 8 exhibited a strong correlation of transmission response with WC, weight and thickness of leaves. Baby-leaf exhibited a lower transmission response on day 1 compared to others, reflecting a higher presence of WC in leaf, which resulted in higher absorption. Contrarily, parsley displayed an increment in transmission response due to the presence of less WC in the leaf and,hence, producing low absorption compared to other leaves.



(a) Day 1 **(b)** Day 4

Figure 8. Transmission response of leaves on first and fourth days.

4. Conclusions

In this paper, a novel, non-invasive technique of characterizing the water content, and in turn the health of plant leaves was proposed using terahertz waves. The electromagnetic properties of eight types of leaves were determined for four consecutive days through the measured scattering parameters. The weight and thickness of the leaves were also recorded at the same time. We observed that the leaves became increasingly transparent to the terahertz waves through the course of four days experiment, as seen by the peaks of permittivity as well as the refractive index of the leaves. Similar decaying trends were observed in the peak values of the real part of the extracted relative permittivity as the decreasing weight due to loss of water content. In the age of a climate change driven water conservation, the proposed scheme can be used to design efficient irrigation systems on-site without any need to remove the leaves from plants. The significance of this paper lies in employing this novel technique for the first time to obtain terahertz characterizations and the water content of eight leaves in the simple, fast and reliable way.

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Sample Availability: Samples of the compounds ...... are available from the authors.