Crop Water Status Monitoring by Terahertz Imaging

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Abstract: We demonstrate the reliability and applicability of THz imaging for destructive and non-destructive water status monitoring of winter wheat leaves. Based on the measured THz transmission amplitude, we find that the water loss in the distal region is less than that in the basal region during the nature dehydration process. A high correlation is shown between the transmitted THz signal and water content level measured by gravimetric weighing method during dehydration and after rehydration. The obtained results show that the water content in winter wheat leaves can be measured destructively and non-destructively with a high accuracy, using terahertz waves in a transmission geometry.

Keywords: THz imaging; water absorption; water status monitoring; winter wheat leaves;

1. Introduction

Leaf water content status of plants is usually regarded as an implication of their different exogenous and physiological conditions, which could affect productivity of crops [1]. So water content evaluation is regarded as an important indicator of crop health to farmers, agricultural scientists and plant physiologists. It provides valuable information in irrigation management, helps to avoid irreversible damage, and thus substantially reduces or prevents yields losses [2]. Owing to the importance of leaf water content monitoring in agriculture, it is definitely necessary to develop a method which can measure and assess water level of different types of crops.

The state-of-the-art techniques in determining leaf water content status can be divided into two groups, destructive (gravimetric [3], pressure chamber [4]) and nondestructive (chlorophyll fluorescence [5], visual estimate) techniques. Gravimetric measurement is usually considered as the most prominent destructive technique due to its high reliability and ease of handling. But it’s not preferred for long-term researches of the same plant. Contactless measurement, as a kind of non-destructive technique, is always required over a long duration. But its accuracy limitation always exists and imprisons its applications.

THz imaging, firstly demonstrated 40 years ago [6], was found to be a promising technique for water content assessment with numerous advantages [7-9]. It can provide complementary information to that obtained with microwaves, infrared, visible, ultraviolet, or x-ray images. Compared with images formed using lower frequencies, THz images have the advantage of superior spatial resolution due to their shorter wavelength. Compared with infrared and higher frequencies, many common materials are relatively transparent at THz range, including common packaging materials such as paper and cardboard, as well as many plastics and composites. Another advantage usually mentioned by researchers is that the THz radiation is non-ionizing [10], which makes it to be more harmless for biological tissues than other types of medical diagnostics.

THz imaging employs the correlation between water content status and attenuation of transmitted THz signal through the sample. It’s high sensitivity to water content [10] makes it to be a sensitive and precise tool in evaluating plants [11, 12] and biotissue [13, 14] dehydration. So the development of THz imaging for highly accurate sensing of water content within biological tissues would help enormously in such areas as cancer diagnosis [15-19], food and other products quality control [20, 21] and plants’ stress
responses monitoring [7, 8, 22]. However, on the other side, this approach operating in the transmission geometry is also limited significantly due to such strong water absorption of the plants. So the reflection geometry was usually applied to testticker biological samples [23, 24], which could help to reduce the effects of absorption due to water. But leaves are usually used for the testing in transmission geometry because of its thin thickness. There have been many researches concentrated on the water content assessment in leaves of plants, such as ginkgo [3], coffee [25], barley [8] and arabidopsis thaliana [26] by employing the transmission geometry as a general form. But more researches are still required for the water status monitoring for crops.

In this paper, we investigate the reliability and applicability of THz imaging in testing water status in winter wheat leaves. A THz time domain spectroscopy system is employed in transmission geometry as we used previously in [27], because of the large absorption coefficient of water [28] and the relatively small absorption coefficient of the dry-matter leaf [29]. Assessment on both the destructive and non-destructive methods is presented.

2. Materials and Methods

2.1. Experimental measurements

The THz imaging system used in this study is based on a standard commercial THz time-domain spectroscopy system (TERA K15 by Menlo Systems Company, Germany). Its spectral range is greater than 4 THz with frequency resolution less than 1.2 GHz. The schematic diagram of the whole system in transmission geometry is shown in Fig. 1(a). The THz-TDS pulse is excited with a Ti: Sapphire oscillator, which produces 1560 nm central wavelength pulses, 90 fs duration, and 100 MHz repetition rate, with a 33 mW average power. The transmitter and receiver are coupled with a collinear adapter to perform as a collinear transmission transceiver. A signal to noise ratio is better than 90 dB at the lower frequency beginning and about 20 dB at the high frequency end. A rapid scanning rate of 20 Hz, and a focal spot of 2 mm in diameter can be reached. The raster scan minimum step size is 2.5 mm and the imaging area of the XY-stage is up to 5×5 cm2. In the detection process, the substrate as placed at the focal point of the detector to test the reference signal in destruction method and air is tested as the reference in non-destruction method, followed by the sample signal detection. In order to remove the effects of background noise and improve the detection signal stability, we repeated twice for each measurement and averaged both to obtain reliable detection results.

![Figure 1](image)

By collecting, analyzing, and reconstituting the THz transmission spectrum data, the 2-D image of the sample containing all areas of the leaf can be obtained. For the time-domain imaging, each pixel in the image corresponds to the signal waveform of THz pulse in time-domain on one certain point of the leaf. It can reflect the obviously enhanced contrast difference [30]. While the frequency-domain pattern imaging based on the absorption coefficient, dispersive coefficient, refractive index, or other physical parameters
of each pixel can usually yield a relatively better imaging [31]. Imaging resolution increases with the frequency, but on the other hand, the penetration depth of the THz radiation decreases, leading to a decreased signal-to-noise ratio.

2.2. Sample preparation and configuration

Fresh leaves of winter wheat (Jingdong 24) cultivated in Beijing Research Center for Information Technology in Agriculture are shown in Fig. 1 (b). These fresh leaves were first used for THz imaging, and then weighed by an accurate electronic balance. Each of these leaves was tested individually and repeatedly every day at the same time and the same conditions during seven successive days. All the leaves were kept in self-sealing bags after they were taken from plants and then placed in an incubator (40°C) to decrease the water evaporation and tested immediately. Before the measurement, the leaves were wiped by sterile cotton, and then fixed onto the sample holder after the thickness was measured. To avoid scattering effect as much as possible, leaves with small surface roughness were chosen.

Simultaneously to the THz TDS measurements, the water content was tested gravimetrically for the reference. The sample was weighted using weight scales (0.1mg precision) at each stage of the experiment. In order to compensate for the sample’s drying independent on our dehydration procedures, the measurements were performed 2 times at each stage of the experiment (before and after THz measurements). The average value of weight was recorded. In the last stage of the experiment, the weight value of the sample was regarded as the weight of the dry component of the sample. The water content was calculated by the equation

$$C_{m} = \frac{(m - m_{dry})}{m} \times 100\%,$$

where \(m\) is the weight measured at the current measurement stage, \(m_{dry}\) is the weight of the dry component of the sample (weight of the sample at the last stage of the experiment).

3. Results and discussions

The first part of the measurements is the testing of the water content of the samples at several degrees of dryness by THz-TDS. During the experiments, the dryness of the samples can be created and controlled artificially. The sample was kept drying for several times with a time distance of 2 hours. Therefore, a number of different water content levels were obtained within each experiment in order to test the sensitivity of the method based on THz TDS. By the end, the sample was dried up as much as it was possible without using any other special equipment.

The THz time-domain waveforms were measured for each pixel during the imaging procedure. The peak-to-peak feature of the time-domain waveform imaging under different humidity is plotted. In this measurement, room temperature fluctuated regularly during the whole measurement period around 23°C. Relative humidity was kept at 15%. The photos of the samples at each stage of dryness are presented in Fig. 2. Though only one sample per dryness level was tested within a single experiment, each experiment was repeated approximately 2 times in order to increase statistical significance. With the decreasing of the water content, the blue color disappears and becomes red. Meanwhile, the size of the leaf decreases becomes of the water loss inside. This indicates that the THz imaging can be used to recognize the water content of wheat leaf qualitatively.
Furthermore, to quantitatively describe the temporal and spatial variability of the leaf water content, water content and peak-to-peak amplitude values at the same position on the leaf No.3 are plotted in Fig. 3. Here, the THz transmission in air is considered as a standard and the transmission without any samples is defined as 100%. During the entire drying process of the leaf, the water content decreases in a nonlinear form with the increase of the dehydration time. This is due to the intercellular spaces between the mesophyll cells, which do not differentiate palisade and spongy tissues [32, 33]. This spaces allow the passage of gases and makes the water loss rate to be slow in the later dehydration time [34]. In addition, the THz image signals decrease gradually along the distal, intermediate and basal regions at the same dehydration time, indicating the rate of water loss in the basal region is higher, which agrees well with the results in [35].

Here, we can also confirm that the THz transmission can be affected by both the water content and the measurement spot, which is investigated in [36]. Different spot corresponds to different leaf thickness/ composition. Repeated measurements of the wheat leaf at different spots could introduce a variation in transmission, even without a change in water content. So a successful monitor changes in plant water status should be done at the exact same spot with repeated measurements.

Non-destructive technique is preferred for long-term leaf water content assessment, and can also provide vital information about vegetation productivity [37]. To test the reliability and applicability of
this method, a piece of living wheat leaf was employed and the water content was measured at the same time (10:00am) on each day from May 16 to May 21, 2019 by the traditional gravimetric weighing method. Room temperature fluctuated regularly during the whole measurement period around 23°C, with maximum values up to 25°C during the day and minimum values down to 16°C at night. Relative humidity showed strong fluctuations from 17% to 47%, not following any recognized pattern. The evolution of the water level inside the leaf is shown in Fig. 4(a). Fig. 4(b) shows the effects of it on the testing results at different frequencies from 0.2 – 1.0 THz. Correlation analyses were performed to test the consistency of results obtained at different frequencies. From the Pearson analysis, the correlation coefficient between the water content status and THz signal transmission is calculated. The coefficient can be 0.9 at 0.6 THz, which indicates that the water content in the leaf can be monitored by the non-destructive THz imaging technique operating in transmission geometry.

The water content of soil and humidity of the lab should also affect the leaf water content. Here, we try to see whether we can predict the leaf water status by testing one of or both the parameters. The water content of soil was measured by the same gravimetric weighing method as above. The humidity was detected using a hygrometer. Fig. 4(c) and (d) shows the variation of water content in wheat leaf with respect to water content in soil and relative humidity in the lab. The non-linear relationships observed imply these two parameters cannot be used to assess the wheat leaf water content.

In above work, we did measurements during dehydration process to confirm that the THz imaging method can be used for water content assessment. A rehydration testing is also required to confirm our conclusion further. The plant was re-watered at 13:30 on May 21, 2019 and water content in the leaf was recorded at hourly intervals. Here, we measured the water content of the leaves at the same height in the plant by the gravimetric weighing method and hope the results should be as close as possible to the leaf we monitored. Several different water content levels were obtained as shown in Fig. 5(e). The water content does not increase quickly after rehydration. But a recovery from hydration is still observed. A 0.8 correlation coefficient between the water content and imaging amplitude is obtained at 0.2 THz. This confirms that the THz imaging method allows for the detection of the leaf water content over time.
Figure 4 (a) water content evolution in the wheat leaf; (b) Frequency-domain THz imaging signal variation; (c) Correlation between water content in the leaf and soil; (d) Correlation between water content in the leaf and humidity in the lab room; (e) Water content and (f) imaging signal after irrigation.

4. Conclusions

In this work, we demonstrate the application of THz imaging technique for the destructive and non-destructive water content sensing in winter wheat leaves. The relationship between the water content and the THz imaging is examined and a high correlation is observed during dehydration process and after rehydration. The water loss in distal, intermediate and basal regions is measured and higher water loss rate in the basal region is observed. This suggests that THz imaging has a good potential to measure the water content in different regions of wheat leaves in a simple and fast method. And we could confirm that repeated measurements at the same spot are highly accurate and reproducible. The leaf sample can be considered as a mixture of water and solid components [38] and a theoretical model considering surface roughness can be conducted to predict the signal transmission accurately, which will be our future directions.

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