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Review

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Studies of leaf water content in smart agriculture using THz technologies: a review

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Abstract

In recent years, the concept of smart agriculture has entered our collective daily routine by radically modifying the methods by which crop monitoring was previously carried out. More precisely, the term smart farming focuses its attention on the use technologies already present on the market like, sensors (multispectral, hyperspectral, thermal and terahertz sensors), WNS (wireless sensor network) and drones capable to reduce the human work in the fields, optimizing at the same time the quantity and quality of the products limiting the use of resources, as water, fertilizers, pesticides and herbicides. Recently, one of the most important problem in the field of precision farming is the availability of water; unfortunately, this factor becomes more critical from year to year. To resolve this problem, the first step is to reduce consumption and rationalize the use of water by adjusting the water supply to the needs of the systems in order to increase its yield while saving money. In this respect, the development of non-destructive techniques operating in the THz spectral region has allowed to monitor in real time the water content present in leaves and plants. In fact, due to the strong water absorption and reflection in this spectral region, this feature can be exploited to detect the water content of leaves and plants helping us to intervene promptly in cases where the plant needs water, avoiding so does water stress, but above all trying to use our primary resource adequately by reducing waste. About this, Imaging and Time-Domain Spectroscopy (THz-TDS) techniques have been applied to monitor soil conditions, drought stress and presence of pathogens on the plants. In this review, we focus our attention on the latest research carried out on monitoring the water content present in leaves through THz technologies. Moreover, we pose particular attention in the description of our system set composed by a 97 GHz transmitter-receiver able to analyze the spatial distribution of the water inside a leaf.

Keywords: Smart agriculture, Terahertz Time-Domain Spectroscopy (THz-TDS), imaging, herbicides, leaf water content, drought-stress

INTRODUCTION

In the last years, several definitions have been given for the phenomenon concerning digital transition in agriculture: agriculture 4.0, smart agriculture, precision agriculture *etc*,. The term agriculture 4.0 originally derives from the denomination of Industry 4.0 coined in Germany as early as 2011 to identify the deep digital transformation that has characterized the world of design, production and services due to the ubiquitous availability of highly interconnected and data intensive computational technologies[1,2].

The purpose of this new way of thinking about agriculture is linked to the use of digital technologies whose advantage is to project the farmer towards intelligent and sustainable agriculture. The most widely used technologies in this sector include Wireless Sensor Network (WSN), Internet of Things (IoT), sensors (multispectral, hyperspectral and thermal) and all those applications that exploit artificial intelligence.

In this regard, smart farming uses precision agriculture to monitor the main parameters of crops, increasing their productivity and minimizing the environmental impact, reducing the adoption of pesticides, fertilizers, fungicides but, above all, saving costs and water. In the latter period, sensitivity in using water appropriately has increased significantly, however, in the world still many farmers waste impressive quantities of water to irrigate their fields. In agriculture, water stress, which is one of the major problems, indicates a lack of water in the soil and this can cause significant damage to plants. Therefore, irrigation and water resources management are tools that the farmer can and must optimize if an increase in agricultural productivity is desired. To remedy this waste, the use of vegetative indices such as Crop Water Stress Index (CWSI), unmanned aerial vehicles (UAVs) and multispectral, hyperspectral, thermal and terahertz cameras for mapping, can improve the utilization of this primary resource that is water.

By equipping drones with specific sensors, it will be possible to monitor the plants temporarily during their cultivation. A large number of sensors are used on board the UAVs in order to collect spectral data useful for generating maps of specific areas aimed at indicating the evolution of the health status of plants. These data are thus analysed and used to carry out more accurate and timely decision-making processes, through constant monitoring, accompanied by specific analyses of the so-called big data[3].

In recent years, the use of WSN in precision agriculture has made possible to resolve various agricultural problems, concerning in this case the optimization of resources, to monitor in real time the main constituents of the soil, such as nitrogen, phosphorus and potassium, therefore, helping farmers to apply the most appropriate decisions.

In addition to WSN, thanks to the development of non-destructive and non-invasive techniques, such as those based on radiation in the terahertz band, it was possible to monitor the water content in leaves and plants.

The first studies conducted by Hu *et al.* and Mittleman *et al.* demonstrated how THz techniques are able to measure the amount of water present in plants[4,5]. In particular, in order to monitor the quantity of water Hu *et al*. and Mittleman *et al.* have applied Terahertrz Time Domain Spectroscopy technique to a fresh leaf[4,5]. From the measurements, it was observed how the veins of the leaf were visible thanks to the quantity of water present. An appreciable increase in transmission was observed when the THz measurements were carried out two days after the interruption of the irrigation of the plant, resulting in a decrease of water content in the leaves.

Regarding environmental monitoring, THz technologies can bring improvements, particularly in vegetation monitoring[6,7]. Exploiting the sensitivity of THz radiation to water, they are able to provide information on the health of the plant[8].

In the past, thermogravimetric analyses were performed to quantify the water content in plant leaves[9], but due to their destructive nature, they have been gradually abandoned, and now better methods are available for estimating water content in plant leaves. In addition to thermogravimetric analysis, non-destructive techniques such as thermal and hyper-spectral imaging[10,11], infrared[12] and magnetic resonance imaging (MRI)[13] have been used to estimate the water content in plant leaves. Nevertheless, all these methods have limitation related to the resolution, to the selectivity or to the time needed for a reliable measurement and sometimes, they are unable to provide information about the plants[11].

In this last period, THz techniques, like THz-Time-Domain Spectroscopy, have been employed more frequently in the field of plant physiology[14,15], demonstrating how these methods are able to measure the amount of water in specific circumstances, like drought stress[12-14,16,17] and dehydration kinetics[11].

In this work, we present some case studies where THz technologies have been applied to monitor the amount of water present in the leaves. It must be pointed out that THz radiation penetrates deep into dry dielectric materials, but it is strongly reflected by samples containing water. This feature could also be exploited to investigate the spatial distribution of water into a sample, thus allowing to monitor the structure of the leaf veins and the health status of a leaf, or the internal structure on thick samples, like nuts, with a dry outer shell.

CASES DISSCUSION

THz-TDS and imaging

Currently the most used imaging techniques operating in THz band are based on Frequency Domain and Time Domain Spectroscopy. Both techniques can be modified to operate in transmission and reflection mode. However, as reported above, the water present in the plant strongly absorbs and reflects the THz radiation at the same time, so this feature severely limits the THz technique in transmission mode. Therefore, performing THz measurements using a reflection setup has advantages, when applied to biological specimen that have a greater thickness[18]. Nevertheless, leaves, due to their limited thickness, can also be analyzed using a transmission geometry[19]. THz spectroscopy can operate in either time-domain (THz-TDS) or frequency domain (FDS), but in this latter case a frequency tunable source or broadband source is required. In the framework of the THz-Arte project, whose purpose was to employ THz spectroscopy and THz imaging techniques as non-destructive tools to investigate artistic artifacts, the laboratories of the ENEA research center of Frascati (Rome-Italy), have developed an innovative THz imaging technique, able to produce real time the images of the sub-surfaces layers of the samples, and, at the same time, to provide information about the optical properties of the sample, making use of a fixed frequency source [Figure 1][20].

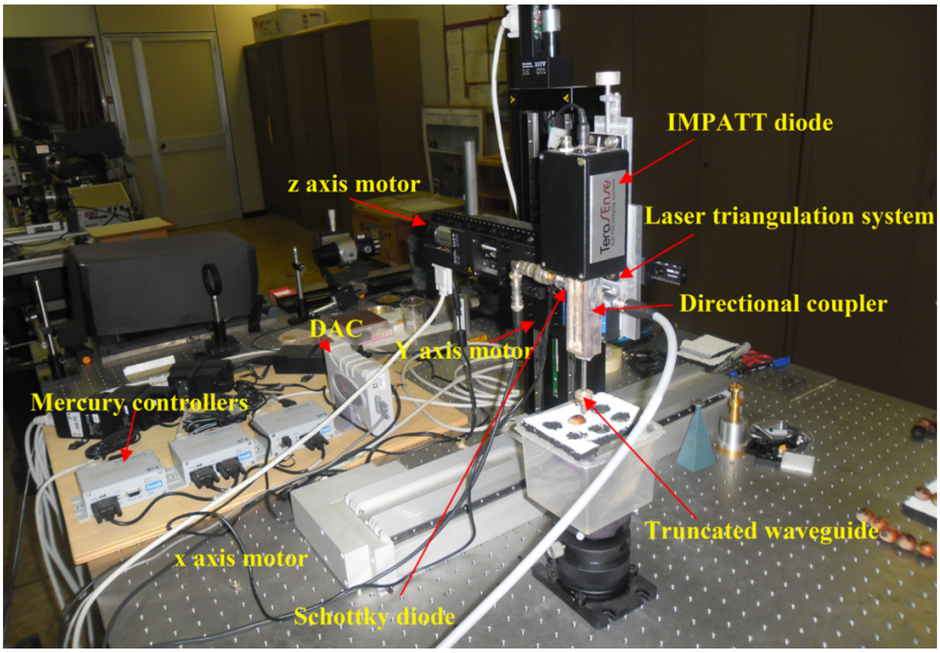

Figure 1. 3D imaging THz scanner in horizontal configuration with the most important components. (1) PI mercury controllers PI; (2) motors; (3) 97 GHz impatt source; (4) directional coupler; (5) waveguide; (6) schottky diode; (7) DAC; (8) sample.

This THz imaging system, shown above, composed by three high-speed motorized translational stages, is able to perform measurements on vertical and horizontal surfaces. The scan time of an area of 500 × 300 mm^2 is about 40 min, while the typical scan of a basil leaf requires less than a minute.

An IMPATT diode oscillator, operating at a frequency of 97 GHz with an output power of about 70 mW, has been used as radiation source. A WR10 truncated waveguide and a directional coupler was used to detect the signal reflected by the sample. A key element of this device is the ability to measure both the phase and the amplitude of the reflected signal. This system has also been equipped with a laser triangulation system, which has the function to correct the sample surface non-planarity that affects phase measurements.

This THz scanner can work both in reflection and in transmission mode, and, when operating in reflection mode, it can measure the phase shift induced during by the reflection process, which depends on the optical properties of the sample. This system has already been used in the field of cultural heritage for detecting water infiltrations under mosaics and fresco samples[20].

On the other hand, time-domain THz Spectroscopy is a powerful technique for materials characterization and control[21-24]. A THz-TD spectrometer, shown in Figure 2, consists of a THz source (emitter) and a THz detector, both excited by a femtosecond laser system (Ti: sapphire). To generate THz pulses, a zinc telluride crystal or a photoconductive antenna are usually used. The detector is also based on the same physical principle of the emitter, and detects the THz radiation when it is activated by an IR pulse. The time domain setup present in the laboratories of the ENEA center in Frascati is shown below [Figure 2]. In this device a photoconductive antenna is used to generate THz pulses, while a zinc telluride crystal is used as a detector.

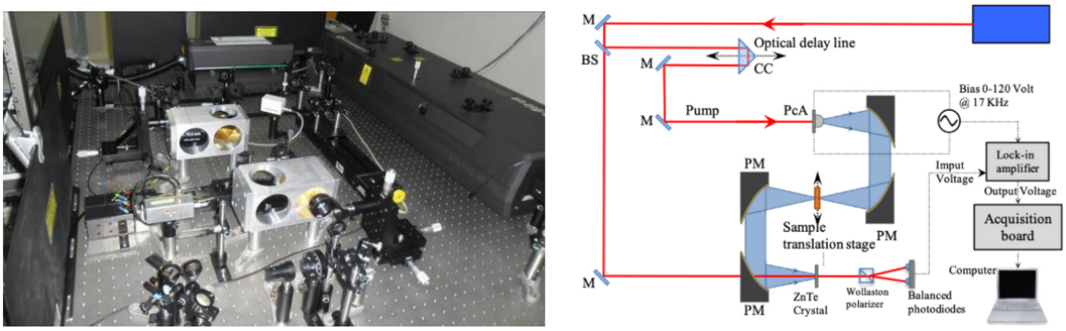

Figure 2. THz-TDS setup present at the ENEA center in Frascati. This setup uses a photoconductive antenna to generate THz pulses and a zinc telluride (ZnTe) crystal as a detector.

Once the THz pulse reaches the detector, it is transformed into a single cycle electrical pulse with a duration of 1 picosecond or less, containing a frequency spectrum that is extended over the THz region. The same laser beam is therefore used to activate both the emitter and the detector, dividing it in two through a system of mirrors and an appropriate optical delay line. Using this line to change the delay with which the THz detector is activated by the laser pulse, is therefore possible to scan the THz pulse point by point, obtaining the profile as a function of time on the fs scale. It is also possible to switch from the time profile to the frequency spectrum by simply applying the Fourier transform [Figure 3].

Monitoring leaves water content: case studies of THz technologies

As already pointed out, the propagation of THz radiation is sensitive to the presence of water. By exploiting this characteristic, Greco *et al.* have used the experimental setup, shown in Figure 4, to follow the dehydration of a basil leaf[25]. In order to speed up the dehydration process, the leaf was detached directly from the plant. In Figure 4 is shown the experimental setup, modified to perform measurement on vertical surfaces.

The THz measurements were performed on a basil leaf belonging to the species Ocimum Basilicum [Figure 5A]. The leaf was placed under a THz transparent Petri dish container and pressed directly on a TeraSense THz imaging matrix, with pixel size of about 1.5 mm, in order to operate on a planar surface [Figure 5B].

To follow the dehydration process, a first scan was carried out on the fresh basil leaf detached from the plant, while the others were performed after predefined time intervals, allowing evaporation of the water. In Figure 6A-D the THz images of the basil leaf are shown for different time intervals.

Figure 6A was acquired at time zero. The central vein is clearly visible from the image. After 2 h from the detachment of the leaf from the plant, the basil leaf begins to dehydrate highlighting how the topology of the surface is changing due to evaporation of water [Figure 6B]. After 4 h from the first scan [Figure 6C] the dehydration process becomes more accentuated, while after 2 days the leaf is completely dehydrated becoming transparent in the THz frequency [Figure 6D].

The high sensitivity of THz radiation to the presence of water, lead Gente *et al.* to attempt to use such a feature, using THz time domain spectroscopy, for long-term measurements on several of plants, in order to monitor the drought stress[26]. In Figure 7 we report their results from one of these plants.

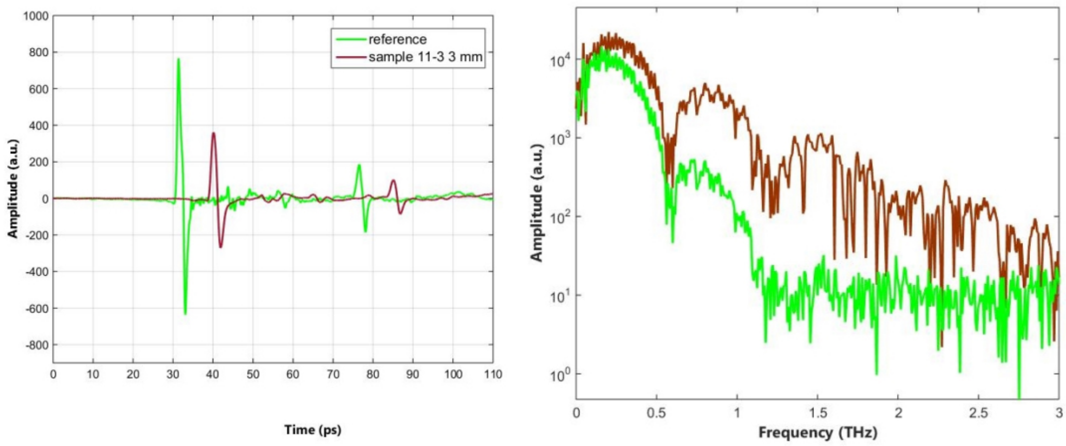

Figure 3. Terahertz signal with its frequency spectrum. The time profile of the THz pulse detected after passing through the sample gives us information on the internal structure of the sample itself. Furthermore, thanks to the Fourier transform it is possible to switch from the time profile to the frequency spectrum.

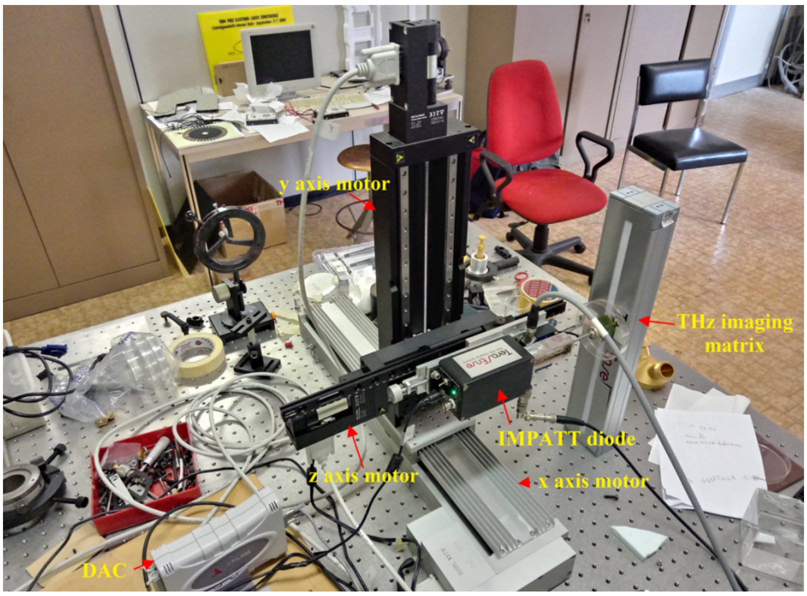

Figure 4. 3D scanner modified to carry out measurements on vertical surfaces.

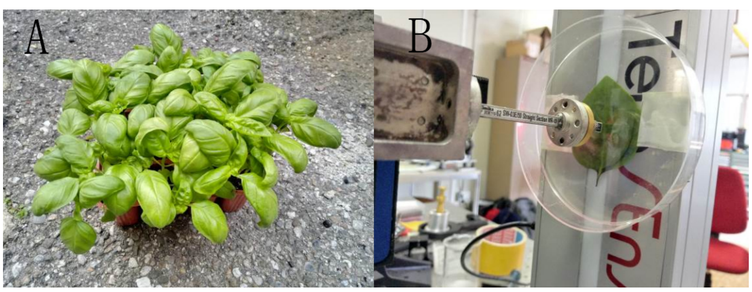

Figure 5. (A) basil plant; (B) basil leaf mounted on the detection system.

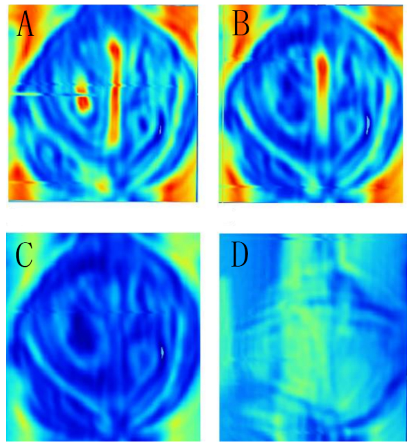

Figure 6. THz images of basil leaf ad different time intervals after detachment from the plant (A) Δt = 0; (B) Δt = 2h; (C) Δt = 4h; (D) Δt = 2 days.

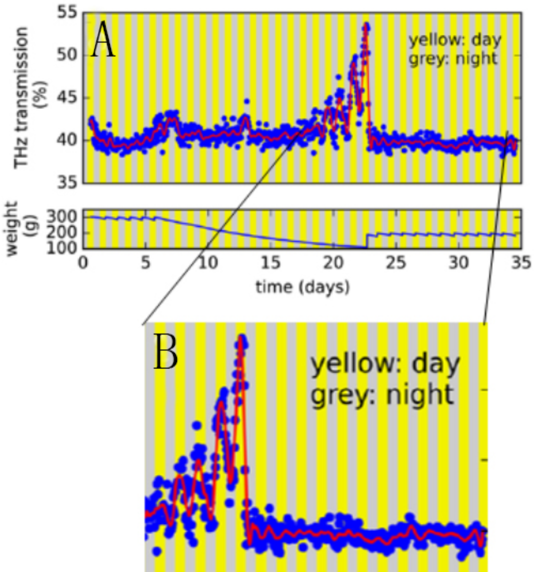

Figure 7. (A) Results obtained by Gente *et al.* after performing THz measurements on a leaf with a THz time domain setup[26]. In this figure THz transmission through the leaf of a rye plant is plotted together with the weight of the plant, proportional to the water content. (B) Magnification of the period after day 19. An increase of the transmittivity during daytime and a decrease during nighttime is evident, and it is correlated to the water exchange processes in the plant.

In the example reported in Figure 7, a rye plant (Secale cereale), was first subjected to drought stress, and subsequently rehydrated. Initially the plant was watered with the same amount of water, while after 6 days it was decided to stop irrigating the plant. As shown in Figure 7A the water stress becomes important starting from day 19. Looking at Figure 7B, it is possible to notice that the transmission is higher during daytime, this happens because during the first hours of the day the stomata present on the leaf surface open and a percentage of water, about 90 percent, is lost in transpiration. Therefore, to compensate for the loss of water that occurs during the day, the plant absorbs water and mineral salts during the night. As shown in Figure 7, the end of water stress is clearly visible on day 23. An important information can be deduced from the graph: the transmission returns to the initial values when water is made available again to the plant.

Using the absorption spectra of water molecules, Zahid *et al*. have determined several electromagnetic properties of leaves, like permittivity, transmission and refractive index[9]. In particular, a non-invasive approach has been used to detect the water content in plant leaves using the scattering of a THz pulse. Measurements were carried out on eight different kinds of potherbs such as coffea arabica, aromatic coriander, basil, baby-leaf, pea-shoot, parsley, lamb's lettuce and baby spinach.

Figures 8-10 show some experiments performed on leaves samples. The procedure foresees that each leaf sample has been separated by the plant at the first day and leaved naturally drying during the next three days. It is clear that at the beginning of the experiment, after the separation of the leaf from the plant, the water content inside the leaf was at the maximum level, decreasing day by day with the time progress. Every day we performed again the experiments recording the changes happened in the leaves and memorizing the results.

Figure 8 shows the real part of the permittivity for baby-leaf and basil leaf measured during the 4 days. It is possible to observe that the baby-leaf and basil leaf have the highest permittivity in day 1, because the water content in fresh leaves is higher, and, when the time passes permittivity shows a decrease because leaves lose water. There is a strong variation occurring between day 2 and day 3: this is the time interval when the dehydration is completed, and the permittivity goes to the final value (dry leaf).

From this consideration it is clear that there is a correlation between the permittivity and the water content in the leaves. Hence, decreasing the water content in the leaves at the same time decreases the permittivity.

In Figure 9 the transmission of all leaves, measured on the first and fourth days, is shown. Observing the spectra, it can be seen that there is a greater absorption and, therefore, a lower transmission in the first day, while an increase in the response of the transmission during day four is evident. Figure 9 clearly shows as baby-leaf has a lower transmission on the first day, if compared to other species, reflecting at the same time a greater quantity of water, thus causing greater absorption. Otherwise, parsley has a greater transmission due to a smaller amount of water contained in the leaf and, therefore, produces less absorption.

Finally, in another paper, Zahid *et al.* measured refractive index n for baby-leaf, basil, pea-shoot and spinach[27]. The results show how the real part of the refractive index decreases over the time. This study was conducted by comparing the value of the real part of the refractive index recorded on the first day with those of the fourth and last day. From this, it was possible to deduce that there is a strong correlation between the amount of water present in the leaf and the refractive index. From the results obtained, it was seen that this variation is more appreciable in the frequency range between 0.75 GHz and 1 THz.

Li *et al.* applied THz imaging to monitor the amount of water on a leaf belonging to the species of winter wheat[28]. In Figure 10A-B, the setup and the samples of winter wheat leaves are shown. As shown in Figure 10B, to perform the measurements, three samples of healthy leaf were obtained, which were cut into 3 parts.

The images were obtained through the reconstruction of the transmitted THz spectral components. During the experiment, the dryness of the samples was controlled using an electronic balance for the determination of the water contained in the three leaf samples. During the imaging process, THz time-domain waveforms were acquired for each pixel.

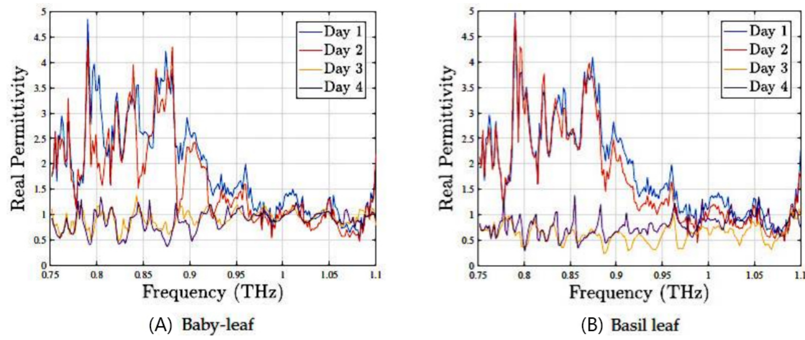

Figure 8. Real part of permittivity of baby-leaf (A) and basil leaf (B) measured by Zahid *et al.* on four consecutive days[9]. Permittivity decreases while time progress, with the consequence that at these frequencies the leaves are transparent. A careful analysis shows how the leaves have a high permittivity on day 1, this is due to a greater quantity of water present in the fresh leaves. Otherwise, with the passing of the days and with the gradual loss of water in the leaves, there is a decrease in the permittivity values.

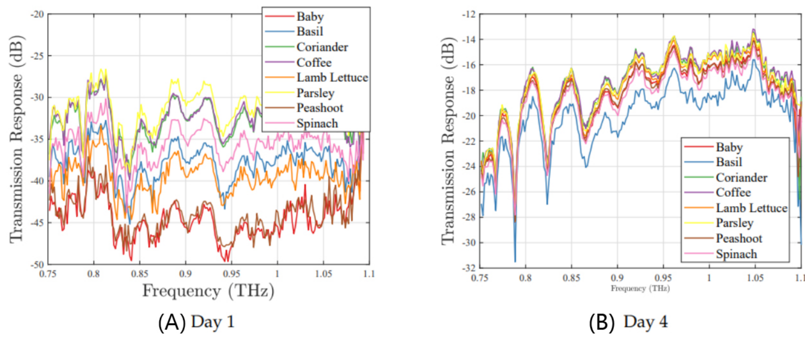

Figure 9. Transmission values of different leaves on days 1 (A) and 4 (B)[9]. Observing the graphs it is evident that on the first day, the absorption of the leaves was high due to a greater quantity of water present in the leaves showing how at these frequencies the water heavily absorbs this type of radiation; On the contrary, after four days, however, there is a gradual increase in the transmission values, a phenomenon explained by the evaporation of the water inside the leaves.

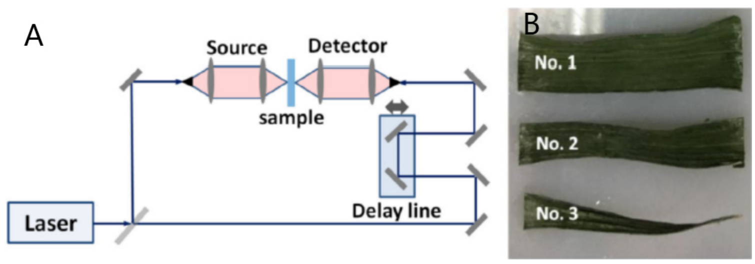

Figure 10. (A) THz-TSD setup; (B) leaf specimen belonging to the species of winter wheat[28].

Figure 11 shows the decrease of the water content, which is highlighted from the color changes from blue to red. Furthermore, it is possible to see how the dimension of the leaf samples decreases due to a gradual evaporation of the water present inside the leaves. This means that terahertz-imaging techniques are capable to detect at a qualitative level the amount of water present in the leaves.

CONCLUSION

With the aim of helping the sector to face new challenges, especially those related to environmental impact, technology has forcefully entered smart farming in the past few years. Surely drones are among the most

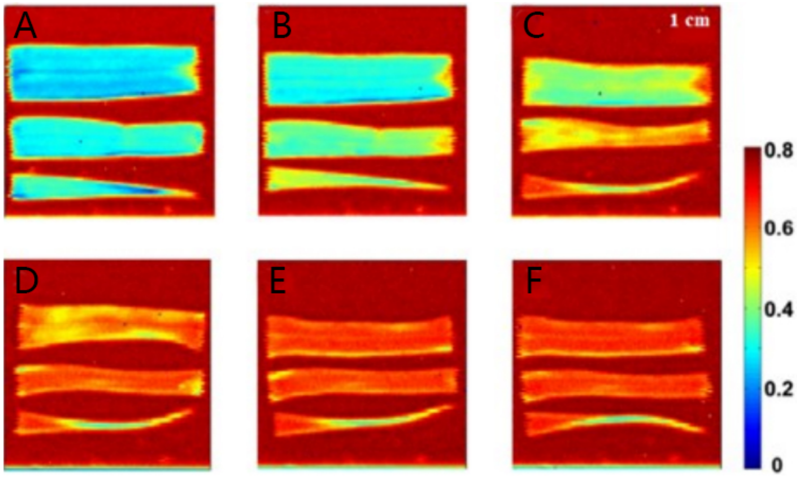

Figure 11. Imaging of wheat leaf with an interval of 2 h[28]: (A) 13.00, (B) 15:00, (C) 17:00, (D) 19.00, (E) 21:00 and (F) 1:00.

interesting and promising technologies in this field. Drones could represent the future of so-called precision farming, a strategy aimed at optimizing resources through monitoring and analysis systems.

Devices that can be installed on an aircraft, such as multi-spectral, hyperspectral, thermal and terahertz systems, can collect data and information with the aim of making agricultural work more efficient.

The advantages that can be obtained by using these technologies are manifold, in particular on the sustainability front. The ability to monitor the physiological state of crops can allow optimization of water consumption and the use of fertilizer treatments. Thanks to a variety of new sensors, drones can detect different details, from irrigation levels to possible changes in the state of the soil up to identify the presence of pests or molds. The infrared or hyper-spectral sensors are able to capture aspects otherwise invisible to the human eye, including plant stress levels or minimal changes in the crop.

Through a targeted study, the next challenge will concern the possibility of equipping drones with terahertz cameras, thus extending the spectral range, from the visible wavelengths to the terahertz ones, acquiring further data and information.

This study shows as imaging and THz spectroscopy could become a useful tool to monitor water content in leaves and, therefore, in precision agriculture. The experimental work has proved how a THz imaging scanner at 97 GHz is able to detect changes in the leaf topology, showing at the same time the contribution coming from water reflection. Currently, in order to test its potentiality and its practical limits the system has only been used in laboratory tests.

In recent years, several researchers have tested the terahertz technologies in the world of precision agriculture: in the study of Gente *et al.* is shown that the rye plant had a higher transmission during the daytime and a lower transmission signal during the night, because the plant tends to loss water during the day and to absorb it during the night[26]. Zahid *et al.*, instead, has analysed the permittivity, refractive index and transmission of some plants[9]. From the measurements emerged that on day 1, permittivity was very high due the highest water content in the leaves, and it decreases on day 4, when water was lost. Similar results are reported for the refractive index. Finally, the research conducted by Li *et al.,* demonstrated that using THz imaging in transmission mode is possible to monitor qualitatively the water content in leaves[28].

In order to apply new technologies to optimize results, more studies are desirable in this field: the possible application of THz cameras, and the use of drones to monitor the water content in leaves in real time, can give good results, leading to a monitoring system able to manage thus periods of drought that can compromise the harvest.

As future trends, it is imaginable that using the latest generation solid-state THz sources, which have reduced dimensions, it will be possible to set up portable systems and, therefore, move from a laboratory device to one that is easily transportable and applicable in the field. In this address, already exist some pioneer studies, e.g. those proposed by Mittleman *et al.* in which some portable hand-carried prototypes to perform measurements on leaves have been proposed, even if the still far from a robust and reliable system[5]. Extending the use of such devices using automated drones, that could operate without human intervention, would allow a great number of possible applications. A test of a prototype of this kind, if proved effective in monitoring the amount of water present in plants, could help the farmer to make strategic decisions to improve irrigation systems. The experiments conducted in laboratory demonstrated that capabilities of the THz devices represent an interesting challenge and give new complementary results with respect to other investigation techniques. The costs of such an implementation are not fully definable yet because this technology is not fully developed yet. Obviously, the costs should be considered in order to verify the practical applicability of such a system in function of the specific practical application. Nevertheless, we are confident that the recent advances in drone technology, solid-state THz sources and detectors, together with the reduction of the costs of such components. In the next future, this cost reduction could make such a technology even commercially convenient and so more spread and applicable in different contexts with respect to those typically of our interest as the Precision Agriculture and the Cultural Heritage measurements and conservation are.

DECLARATIONS

Authors' contributions

Made substantial contributions to conception and design of the study, made implementation, performed data analysis, and interpretation: Greco M, Leccese F, Doria A, Taschin A, De Francesco E, Giovenale E, Senni L, Gallerano, GP

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Not applicable.

Financial support and sponsorship

None.

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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