Consiglio Nazionale delle Ricerche

CNR IRET Conference

Rome, February 18th-19th, 2025

CNR IRET
Istituto di Ricerca sugli Ecosistemi Terrestri

Terahertz Imaging for Agriculture and Non-Invasive Food Inspection

Mario Pagano
CNR-IRET (Florence, Italy)

GLOBAL CHALLENGES IN AGRICULTURE

→ Biodiversity preservation

→ Environmental sustainability

→ Expansion in cultivated areas

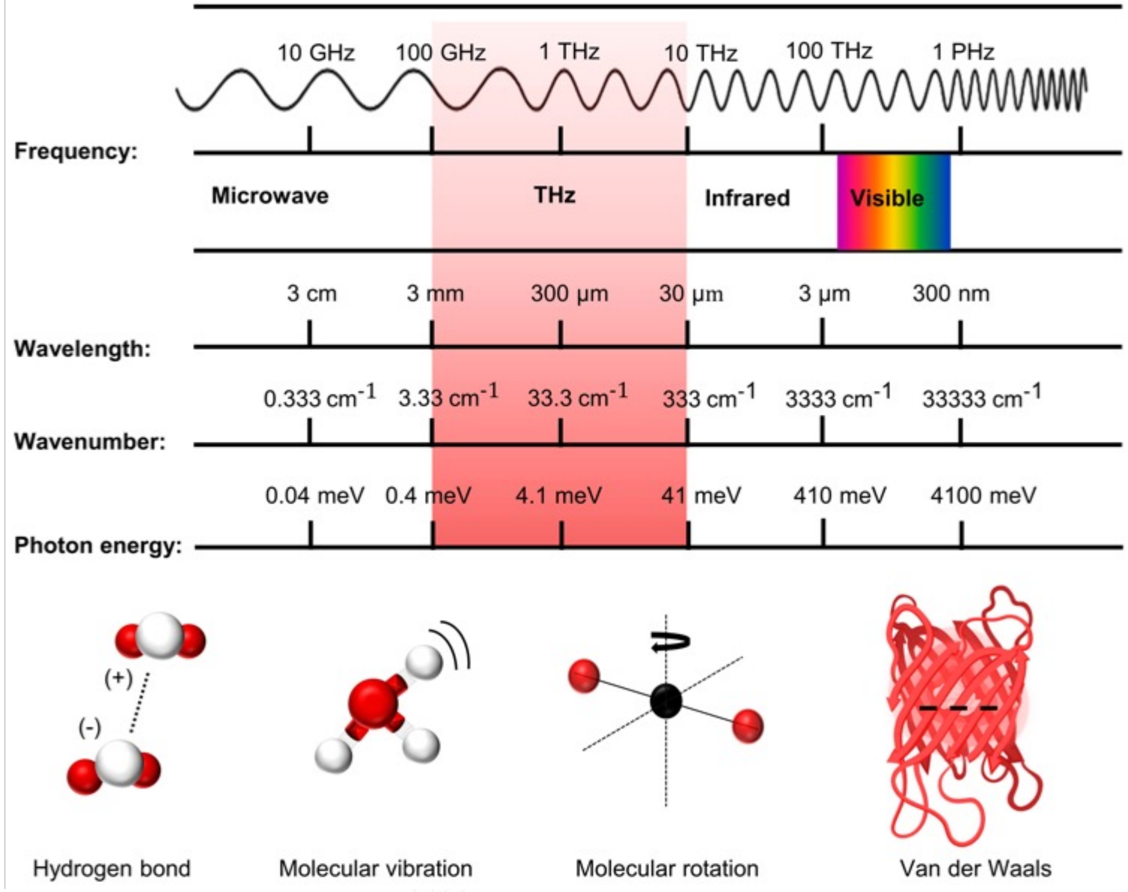
→ Efficient resource management

→ Food security

Terahertz (THz) radiation

THz radiation shows great potential as a tool to overcome at least the last two challenges mentioned earlier.

INTRODUCTION TO TERAHERTZ (THz) RADIATION



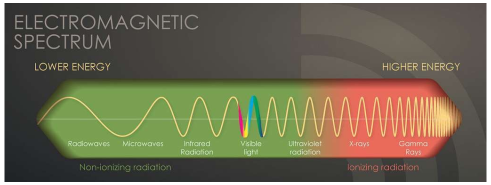
ADVANTAGES OF THz RADIATION:

→ Non-ionizing radiation

→ Evaluate packaging materials

→ Crop monitoring

→ Safe for biological analysis



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BEER–LAMBERT LAW

Oshina and Spigulis: Beer–Lambert law for optical tissue diagnostics: current state of the art...

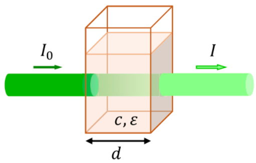

Fig. 1 Illustration of the Beer–Lambert–Bouguer law. I_0, intensity of the incident beam; I, intensity of the beam after transmission through a medium of thickness d; c, concentration; ε, extinction coefficient.

Oshina and Spigulis: Beer–Lambert law for optical tissue diagnostics: current state of the art...

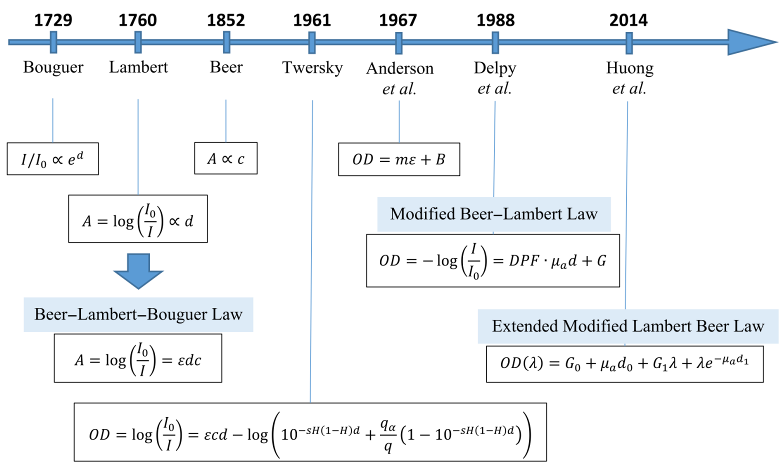

Fig. 2 Historical development of the BLL updates.

DOI: 10.1117/1.JBO.26.10.100901

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TERAHERTZ RADIATION IN AGRICULTURE AND IN PLANT SCIENCES

Baldacci *et al. Plant Methods* (2017) 13:51
DOI 10.1186/s13007-017-0197-z
Plant Methods
RESEARCH Open Access

Non-invasive absolute measurement of leaf water content using terahertz quantum cascade lasers

Lorenzo Baldacci[1†], Mario Pagano[2*†], Luca Masini[1], Alessandra Toncelli[4], Giorgio Carelli[3], Paolo Storchi[2] and Alessandro Tredicucci[4]

Abstract

Background: Plant water resource management is one of the main future challenges to fight recent climatic changes. The knowledge of the plant water content could be indispensable for water saving strategies. Terahertz spectroscopic techniques are particularly promising as a non-invasive tool for measuring leaf water content, thanks to the high predominance of the water contribution to the total leaf absorption. Terahertz quantum cascade lasers (THz QCL) are one of the most successful sources of THz radiation.

Results: Here we present a new method which improves the precision of THz techniques by combining a transmission measurement performed using a THz QCL source, with simple pictures of leaves taken by an optical camera. As a proof of principle, we performed transmission measurements on six plants of *Vitis vinifera* L. (cv "Colorino"). We found a linear law which relates the leaf water mass to the product between the leaf optical depth in the THz and the projected area. Results are in optimal agreement with the proposed law, which reproduces the experimental data with 95% accuracy.

Conclusions: This method may overcome the issues related to intra-variety heterogeneities and retrieve the leaf water mass in a fast, simple, and non-invasive way. In the future this technique could highlight different behaviours in preserving the water status during drought stress.

Keywords: Terahertz quantum cascade laser, Water content, Draught stress, *Vitis vinifera* L.

sensors
MDPI
Article

THz Water Transmittance and Leaf Surface Area: An Effective Nondestructive Method for Determining Leaf Water Content

Mario Pagano [1,2,*,†], Lorenzo Baldacci [3,†], Andrea Ottomaniello [3,4], Giovanbattista de Dato [5], Francesco Chianucci [5], Luca Masini [3], Giorgio Carelli [4], Alessandra Toncelli [4], Paolo Storchi [2], Alessandro Tredicucci [3,4] and Piermaria Corona [5]

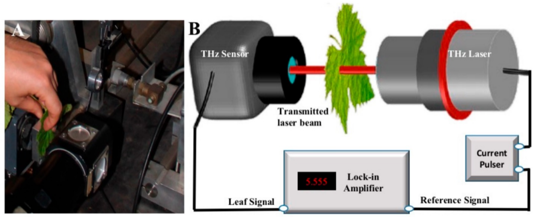

Figure 1. (**A**) THz leaf measurement method using a current pulser driving a THz cryo-cooled quantum cascade laser (QCL) to generate 2.55 THz laser radiation. (**B**) THz transmission measurement setup.

Gente and Koch *Plant Methods* (2015) 11:15
DOI 10.1186/s13007-015-0057-7
PLANT METHODS
REVIEW Open Access

Monitoring leaf water content with THz and sub-THz waves

Ralf Gente* and Martin Koch

Abstract

Terahertz technology is still an evolving research field that attracts scientists with very different backgrounds working on a wide range of subjects. In the past two decades, it has been demonstrated that terahertz technology can provide a non-invasive tool for measuring and monitoring the water content of leaves and plants. In this paper we intend to review the different possibilities to perform in-vivo water status measurements on plants with the help of THz and sub-THz waves. The common basis of the different methods is the strong absorption of THz and sub-THz waves by liquid water. In contrast to simpler, yet destructive, methods THz and sub-THz waves allow for the continuous monitoring of plant water status over several days on the same sample. The technologies, which we take into focus, are THz time domain spectroscopy, THz continuous wave setups, THz quasi time domain spectroscopy and sub-THz continuous wave setups. These methods differ with respect to the generation and detection schemes, the covered frequency range, the processing and evaluation of the experimental data, and the mechanical handling of the measurements. Consequently, we explain which method fits best in which situation. Finally, we discuss recent and future technological developments towards more compact and budget-priced measurement systems for use in the field.

Keywords: THz, Sub-THz, Water-status, Water-content, Drought-stress

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TERAHERTZ RADIATION IN AGRICULTURE AND IN PLANT SCIENCES

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

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

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(This article belongs to the Special Issue Terahertz Communications: Present and Future)

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 characterisation in plant leaves using 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 characterisation 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. View Full-Text

frontiers in Plant Science | Plant Physiology

Impact Factor 5.753 | CiteScore 8.2
More on impact ›

Terahertz time domain spectroscopy allows contactless monitoring of grapevine water status

Luis G. Santesteban [1*], Inés Palacios [2], Carlos Miranda [1], Juan C. Iriarte [2], José B. Royo [1] and Ramón Gonzalo [2]

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[2]Department of Electrical and Electronic Engineering, Universidad Pública de Navarra, Pamplona, Spain

Agriculture is the sector with the greatest water consumption, since food production is frequently based on crop irrigation. Proper irrigation management requires reliable information on plant water status, but all the plant-based methods to determine it suffer from several inconveniences, mainly caused by the necessity of destructive sampling or of alteration of the plant organ due to contact installation. The aim of this work is to test if terahertz (THz) time domain reflectance measurements made on the grapevine trunk allows contactless monitoring of plant status. The experiments were performed on a potted 14-years-old plant, using a general purpose THz emitter receiver head. Trunk THz time-domain reflection signal proved to be very sensitive to changes in plant water availability, as its pattern follows the trend of soil water content and trunk growth variations. Therefore, it could be used to contactless monitor plant water status. Apart from that, THz reflection signal was observed to respond to light conditions which, according to a specifically designed girdling experiment, was caused by changes in the phloem. This latter results opens a promising field of research for contactless monitoring of phloem activity.

Zahid *et al. Plant Methods* *(2019) 15:138*
https://doi.org/10.1186/s13007-019-0522-9

Plant Methods

RESEARCH | Open Access

Machine learning driven non-invasive approach of water content estimation in living plant leaves using terahertz waves

Adnan Zahid [1], Hasan T. Abbas [1], Aifeng Ren [1,2], Ahmed Zoha [1], Hadi Heidari [1], Syed A. Shah [1], Muhammad A. Imran [1], Akram Alomainy [3] and Qammer H. Abbasi [1*]

Abstract

Background: The demand for effective use of water resources has increased because of ongoing global climate transformations in the agriculture science sector. Cost-effective and timely distributions of the appropriate amount of water are vital not only to maintain a healthy status of plants leaves but to drive the productivity of the crops and achieve economic benefits. In this regard, employing a terahertz (THz) technology can be more reliable and progressive technique due to its distinctive features. This paper presents a novel, and non-invasive machine learning (ML) driven approach using terahertz waves with a swissto12 material characterization kit (MCK) in the frequency range of 0.75 to 1.1 THz in real-life digital agriculture interventions, aiming to develop a feasible and viable technique for the precise estimation of water content (WC) in plants leaves for 4 days. For this purpose, using measurements observations data, multi-domain features are extracted from frequency, time, time–frequency domains to incorporate three different machine learning algorithms such as support vector machine (SVM), K-nearest neighbour (KNN) and decision-tree (D-Tree).

Results: The results demonstrated SVM outperformed other classifiers using tenfold and leave-one-observations-out cross-validation for different days classification with an overall accuracy of 98.8%, 97.15%, and 96.82% for Coffee, pea shoot, and baby spinach leaves respectively. In addition, using SFS technique, coffee leaf showed a significant improvement of 15%, 11.9%, 6.5% in computational time for SVM, KNN and D-tree. For pea-shoot, 21.28%, 10.01%, and 8.53% of improvement was noticed in operating time for SVM, KNN and D-Tree classifiers, respectively. Lastly, baby spinach leaf exhibited a further improvement of 21.28% in SVM, 10.01% in KNN, and 8.53% in D-tree in overall operating time for classifiers. These improvements in classifiers produced significant advancements in classification accuracy, indicating a more precise quantification of WC in leaves.

Conclusion: Thus, the proposed method incorporating ML using terahertz waves can be beneficial for precise estimation of WC in leaves and can provide prolific recommendations and insights for growers to take proactive actions in relations to plants health monitoring.

Keywords: Water content, Plant leaves, Terahertz (THz), Sensing, Agriculture, Classification, Machine learning

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Science of the Total Environment 956 (2024) 177358

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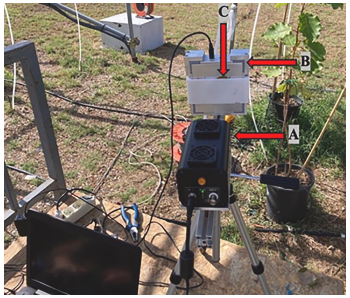
Science of the Total Environment

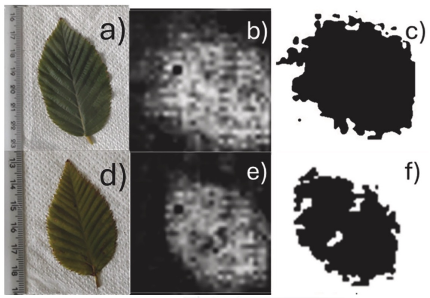
journal homepage: www.elsevier.com/locate/scitotenv

ELSEVIER

Probing ozone effects on European hornbeam (*Carpinus betulus* L. and *Ostrya carpinifolia* Scop.) leaf water content through THz imaging and dynamic stomatal response

Mario Pagano [a,1], Yasutomo Hoshika [a,b,1], Fulvia Gennari [d,*], Jacopo Manzini [a,c], Elena Marra [a], Andrea Viviano [a,c], Elena Paoletti [a,b], Sharmin Sultana [d], Alessandro Tredicucci [d,e,f], Alessandra Toncelli [d,e,f,g]





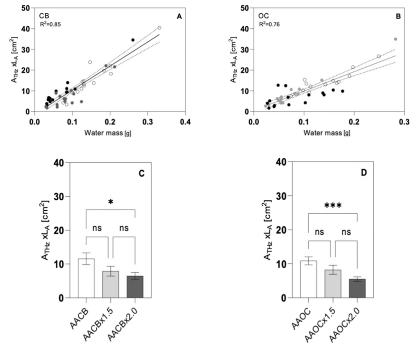


Fig. 2. The A and B graphs represent the calibration of THz acquisition versus absolute leaf water mass, with a sample size of 45 leaves and a 95 % confidence interval in *Carpinus betulus* (CB) and *Ostrya carpinifolia* (OC) grown under three levels of ozone. C and D display the results of the ANOVA analysis comparing measurements obtained through THz x L_A, based on a sample size of 25 leaves per treatment with standard errors indicated. Asterisks denote the significance of ANOVA: $^{***}p < 0.001$, $^{*}p < 0.05$, ns: not significant.

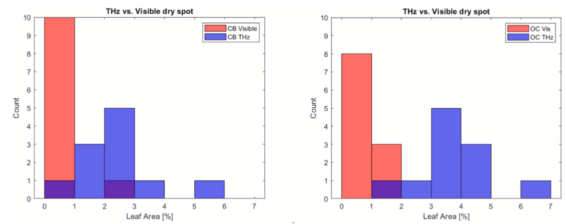


Fig. 3. Percentages of dry spot areas over the total area of the leaf in twice AA measured by visible images (Vis) and Terahertz images (THz) in *Carpinus betulus* (CB) and *Ostrya carpinifolia* (OC).

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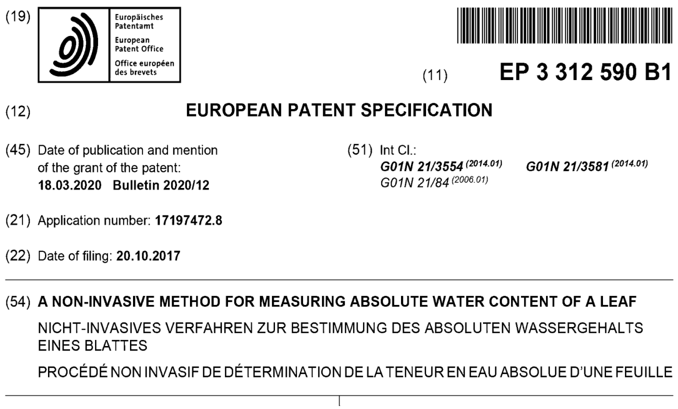

(19) Europäisches Patentamt / European Patent Office / Office européen des brevets

(11) **EP 3 312 590 B1**

(12) **EUROPEAN PATENT SPECIFICATION**

(45) Date of publication and mention of the grant of the patent: **18.03.2020 Bulletin 2020/12**

(51) Int Cl.: ***G01N 21/3554*** *(2014.01)* ***G01N 21/3581*** *(2014.01)* *G01N 21/84* *(2006.01)*

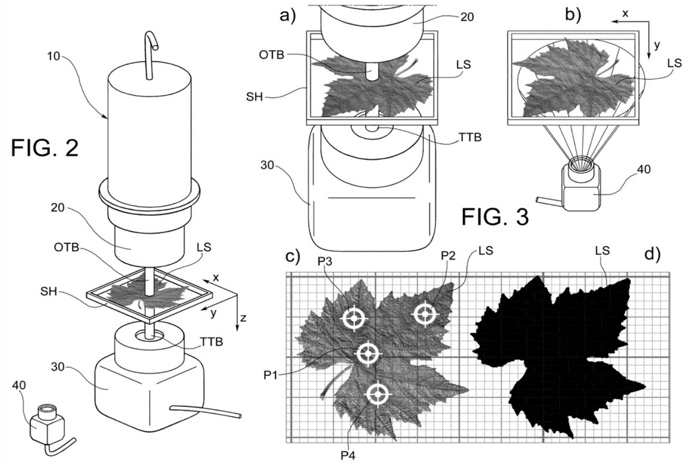
(21) Application number: **17197472.8**

(22) Date of filing: **20.10.2017**

(54) **A NON-INVASIVE METHOD FOR MEASURING ABSOLUTE WATER CONTENT OF A LEAF**

NICHT-INVASIVES VERFAHREN ZUR BESTIMMUNG DES ABSOLUTEN WASSERGEHALTS EINES BLATTES

PROCÉDÉ NON INVASIF DE DÉTERMINATION DE LA TENEUR EN EAU ABSOLUE D'UNE FEUILLE



A Pilot Study on Food Security:

Terahertz Imaging for Hazelnut Classification

Heliyon 9 (2023) e19891

CellPress

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Heliyon

journal homepage: www.cell.com/heliyon

Terahertz imaging for non-invasive classification of healthy and cimiciato-infected hazelnuts

Fulvia Gennari [a,1], Mario Pagano [b,1], Alessandra Toncelli [a,c,e,h,*], Maria Tiziana Lisanti [d], Riccardo Paoletti [e,f], Pio Federico Roversi [g], Alessandro Tredicucci [a,c,h], Matteo Giaccone [i]

CHALLENGES IN HAZELNUT QUALITY AND CROP

- **Increasing Importance of Hazelnut Cultivation**

Hazelnut (*Corylus avellana*) cultivation is expanding rapidly in terms of cultivated areas and expected crop yields.

- **Confectionery Industry Requirements**

Raw hazelnuts must be free from defects and alterations to ensure products with acceptable organoleptic quality throughout their shelf-life.

- **Halyomorpha halys (Brown Marmorated Stink Bug)**

A pest belonging to the family Pentatomidae, commonly referred to as the brown marmorated stink bug.

- **Impact of Infestation on Hazelnuts**

Damage during kernel expansion or ripening results in shriveled kernels or high incidences of off-flavor described as "cimiciato" or "corked."

- **Cimiciato Defect and Its Consequences**

Affected hazelnuts develop a bitter, astringent taste due to the presence of diarylheptanoids, including asadanin, giffonin P, and related compounds.

METHODOLOGY AND SAMPLE DESIGN

- **Plant species**
  - Trials were conducted on hazelnut kernels (*Corylus avellana L.*), cultivar *Tonda di Giffoni*.

- **Calibration Sample**
  - Trial comprised of **150 hazelnuts** used to develop the classification model.
  - Hazelnuts were manually shelled and visually inspected prior to THz analysis.
  - Two sub-samples:
    - **110 Healthy Hazelnuts (HH):** Free from defects.
    - **40 Cimiciato Hazelnuts (CH):** Damaged by stink bugs.

- **Validation Sample**
  - Trial Consisted of **50 hazelnuts** used for blind evaluation of the classification model.
  - Each hazelnut was:
    - Manually shelled.
    - Analyzed with a THz device for classification.
    - Visually inspected to confirm or reject the THz classification results.

Heliyon 9 (2023) e19891

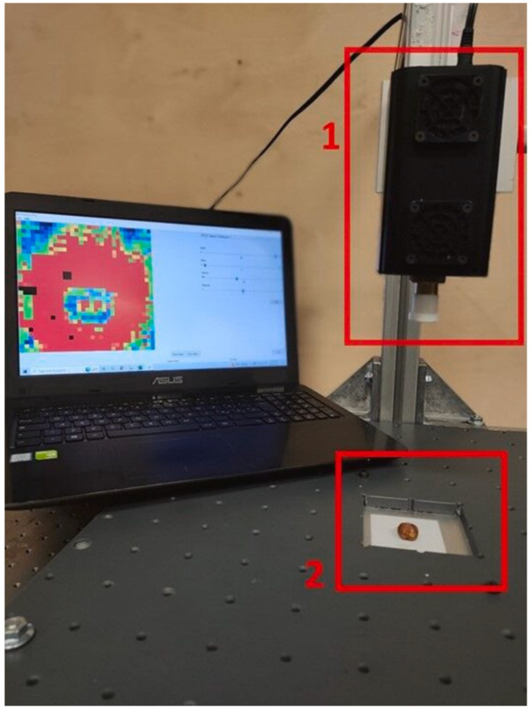


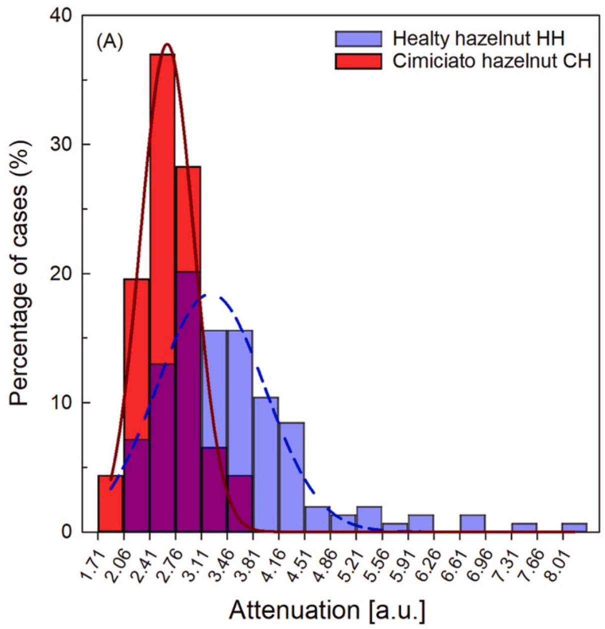
Fig. 1. Terahertz measurement setup for hazelnut imaging. 1: Terahertz source, 2: Terahertz camera.

THE THz IMAGING SYSTEM

Source:
Type: Impact Avalanche Transit Time Diode Source (IMPATT-100-H/F)
Manufacturer: TeraSense, San Jose, USA
Nominal Output Power: 30 mW
Output Frequency: 140 GHz

THz Camera:
Model: T15/32/32
Manufacturer: TeraSense, San Jose, USA
Sensor Matrix: Square matrix with 32 x 32 pixels

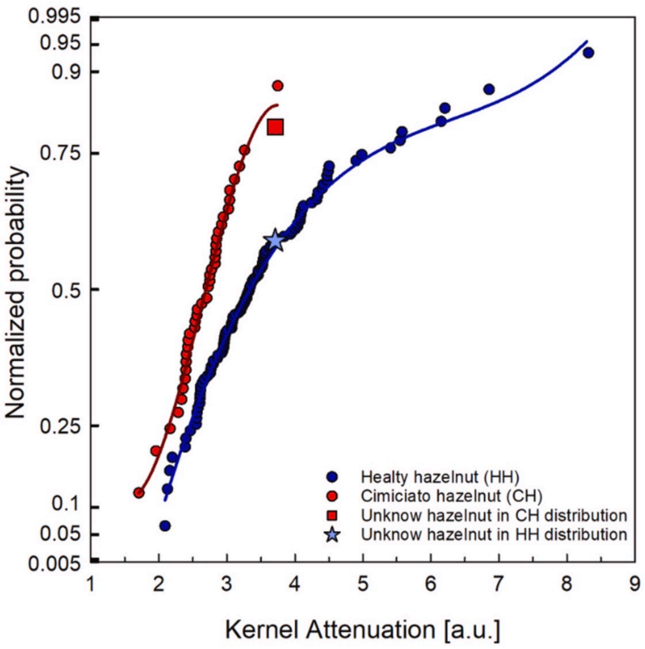
THE HISTOGRAMS OF THE DISTRIBUTION OF THE ATTENUATION VALUES



Lower Attenuation Levels in CH Sample:
The CH sample generally exhibits lower attenuation levels compared to the non-CH sample. However, a complete separation between the two histograms is not observed.

Potential Causes for Lower Absorption in Damaged Hazelnuts (CH):
Structural alterations in tissue due to stink bug stings may contribute to reduced absorption. Stink bug injuries are reported to cause dry, necrotic tissue in infected hazelnuts.

Role of Stink Bug Saliva:
Stink bugs inject watery saliva containing hydrolyzing enzymes (protease, amylase, esterase, lipase) into hazelnuts. These enzymes may trigger biochemical reactions that alter THz absorption properties of the nuts.



Classification Model Development

•Plotted distributions for healthy and damaged hazelnuts.

•Fitted both distributions with third-degree polynomial curves.

Model Evaluation Process

•Introduced data from an unknown hazelnut sample as a new data point in both distributions.

•Calculated the minimum distance between the new point and each fitted curve.

•Assigned the sample to the distribution with the smaller distance.

Model Performance Highlights

•True Negative Rate (TNR): **100%** (all unhealthy hazelnuts correctly identified).
•False Positive Rate (FPR): **0%**.

Sensitivity Results

•True Positive Rate (TPR): **75%**.
•False Negative Rate (FNR): **25%** (lower sensitivity for healthy hazelnuts).

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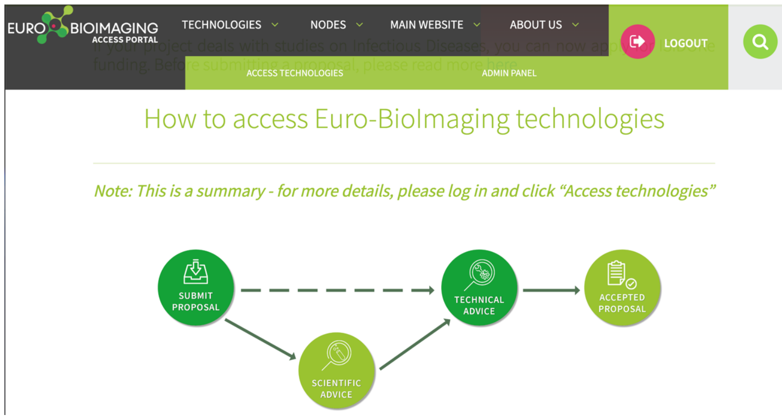
Fruit recognition using terahertz imaging for swift contamination assessment and non-invasive inspection

(FRUITSCAN)



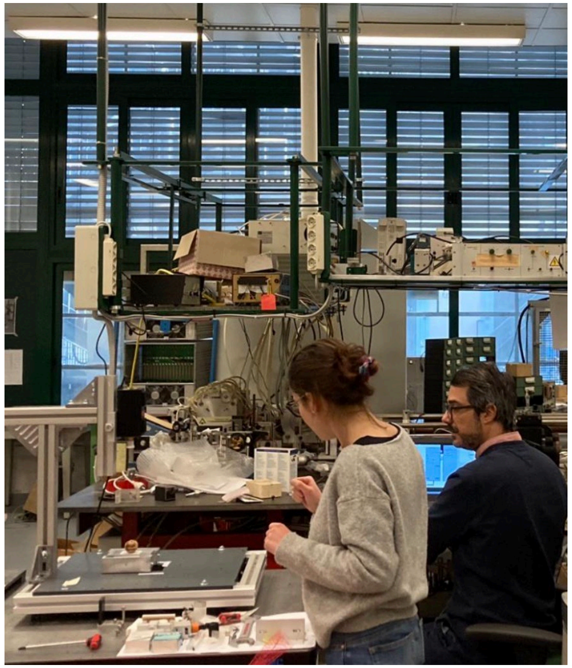
Eurobioimaging Node - Terahertz Plant Imaging, THzI @ Italy - Molecular Imaging Italian Node

- **Project Objective**

Leverages the synergy between **terahertz (THz) imaging** and **artificial intelligence** to classify hazelnuts and other fruits as healthy or unhealthy in a **non-invasive** manner.

- **Benefits of Terahertz Imaging**

✓ Facilitates **early pest detection**.
✓ Aims to **reduce chemical interventions**.
✓ Promotes a **positive environmental impact**.



CONCLUSIONS

Strong potential of continuous-wave terahertz (THz) transmission imaging as a reliable, non-invasive method for agricultural applications, particularly in identifying unhealthy samples.

The integration of THz imaging with artificial intelligence further expands its potential for agricultural quality control, driving innovation in food security and promoting resource-efficient practices.

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Fulvia Gennari, Riccardo Paoletti, Pio Federico Roversi,

Maria Tiziana Lisanti, Matteo Giaccone,

Alessandro Tredicucci and Alessandra Toncelli

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