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AUSTRALIA

# **Terahertz Spectroscopy and Imaging in Quantitative Assessment of Plant Hydration towards Implementing Optimized Irrigation Management in Australia and India**

*by*

**Mayuri Kashyap**

B.Tech. in Electronics and Communications Engineering

0000-0001-9510-5371

*A thesis submitted*

*in fulfilment of the requirements for the joint degree of*

**DOCTOR OF PHILOSOPHY**

to

**THE INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**&**

**THE UNIVERSITY OF QUEENSLAND**

April, 2024

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***I dedicate this thesis to my family:***

*To my mother, Monakshi Devi, for sharing with me her dream and for making me capable of achieving it;*

*To my father, Aswini Kumar Sarmah, for the life lessons that I cherish and for instilling in me the confidence to overcome any challenges;*

*To my sister, Kasturi Kashyap, for her love and comfort, for being my pillar of support whenever I struggled, and for inspiring me to aim higher;*

*To my brother, Suraj Pratim Kashyap, for being a friend and support, for his love and for keeping me updated with the recent trends in all spheres;*

*And, to my niece, Koirabhi, and nephew, Krisanu, for being the rainbow of happiness throughout my journey.*

## *Supervisor Certification*

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This is to certify that the thesis entitled “**Terahertz Spectroscopy and Imaging in Quantitative Assessment of Plant Hydration towards Implementing Optimized Irrigation Management in Australia and India**” is being submitted by **Ms. Mayuri Kashyap** to the Indian Institute of Technology Delhi and The University of Queensland for the award of the degree of **Doctor of Philosophy** is a record of *bonafide* research work carried out by her. **Ms. Mayuri Kashyap** has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The results contained in this thesis are original and have not been submitted, in part or full, to any other University or Institute for the award of any other degree or diploma.

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# Abstract

Precision agriculture and smart irrigation techniques have gained prominence in recent years to address the challenge of maximizing agricultural productivity with limited resources. Efficient water management is crucial for ensuring crop health and yield, as water plays a vital role in the photosynthetic process. Water-stressed plants are more susceptible to diseases, infestations, and reduced yield. Therefore, this research focuses on developing fast, accurate, and non-invasive methodologies assisted by machine learning (ML) for quantitatively assessing plant hydration levels, a key parameter for plant health.

Terahertz (THz) radiation, which is highly sensitive to water content, and considered non-invasive for biological materials, is explored here as a suitable tool here for monitoring plant hydration. The study investigates spectroscopic and imaging techniques in the THz region to understand the dynamics of plant hydration. The research is carried out in phases: the initial phases establish the viability of theoretical and inductive models for hydration monitoring, followed by the design of standardized methodologies and calibration curves of transpiration rates through *in-vivo* and *in-situ* analysis of plants. The plants are observed under unstressed and drought-stressed conditions using photoconductive-antenna-based frequency domain continuous-wave THz spectroscopy and time-domain THz imaging. In the next phase, complementary analysis is performed, utilizing high-resolution phase and amplitude information obtained from images captured at high frame-rates using a quantum-cascade-based laser-feedback interferometry system to map water dynamics in plants.

Supervised ML regression is employed to predict moisture content in plants by analysing time-lapsed THz images and spectroscopic information from the leaves. Decision trees, random forests, support vector regression, and partial least squares regression models are utilized based on the extracted predictors for the analysis. The research also explores signal-processing and image-processing algorithms for each system to integrate ML techniques with THz sensing data, contributing to the emerging field of data-driven algorithms for agriculture. The findings demonstrate the effectiveness of the THz technologies combined with appropriate ML models in estimating the moisture content in plants. The results indicate substantial potential for these techniques in agricultural applications, particularly in non-invasive monitoring of plant water status for the regulation of irrigation systems.

## Abstract in Hindi

पिछले कुछ वर्षों में सटीक कृषि और स्मार्ट सिंचाई तकनीकों ने काफ़ी महत्त्व प्राप्त किया है ताकि सीमित संसाधनों के साथ कृषि उत्पादकता को अधिकतम करने की चुनौती का सामना किया जा सके। फसल की स्वस्थता और उत्पादकता सुनिश्चित करने के लिए कुशल जल प्रबंधन महत्वपूर्ण है, क्योंकि पानी प्रकाश संश्लेषण प्रक्रिया में महत्वपूर्ण भूमिका निभाता है। पानी की कमी से पौधों को रोगों, कीटों और कम उत्पादकता का सामना करना पड़ता है। इसलिए, यह अनुसंधान पौधों के हाइड्रेशन स्तर का मापन करने के लिए मशीन लर्निंग (एमएल) द्वारा सहायित तेज़, सटीक और अग्रहणशील तकनीकों का विकास पर ध्यान केंद्रित करता है, जो पौधों के स्वास्थ्य के लिए महत्वपूर्ण पैरामीटर है।

टेराहर्ट्ज़ विकिरण, जो पानी की मात्रा के प्रति अत्यधिक संवेदनशील है, और जैविक सामग्री के लिए गैर-आक्रामक माना जाता है, यहाँ संयंत्र जलयोजन की निगरानी के लिए एक उपयुक्त उपकरण के रूप में अन्वेषण किया गया है। इस अध्ययन में, टेराहर्ट्ज़ स्पेक्ट्रोस्कोपिक और इमेजिंग तकनीकों का अध्ययन किया गया है ताकि पौधों की पानीपूर्ति की गतिविधियों को समझा जा सके। शोध को चरणों में आयोजित किया है: प्रारंभिक चरण जलयोजन निगरानी के लिए सैद्धांतिक और आगमनात्मक मॉडल की व्यवहार्यता स्थापित करते हैं, इसके बाद मानकीकृत पद्धतियों के डिजाइन और पौधों के *इन-विवो* और *इन-सीटू* विश्लेषण के माध्यम से वाष्पोत्सर्जन दर के अंशांकन घटता है। फोटोकॉन्डक्टिव-एंटीना-आधारित आवृत्ति-डोमेन कंटीन्यूअस-वेव टेराहर्ट्ज़ स्पेक्ट्रोस्कोपी और समय-डोमेन टेराहर्ट्ज़ इमेजिंग का उपयोग करके पौधों को अनस्ट्रेस्ड और सूखे-तनाव वाली स्थितियों में देखा जाता है। अगले चरण में, पूरक विश्लेषण किया जाता है। पौधों में पानी की गतिशीलता को मैप करने के लिए क्वांटम-कैस्केड-लेजर-आधारित लेजर-फीडबैक इंटरफेरोमेट्री प्रणाली का उपयोग करके उच्च-रिज़ॉल्यूशन और उच्च फ्रेम-दर पर अधिग्रहण की गई छवियों से प्राप्त चरण और आयाम जानकारी का उपयोग किया जाता है।

पौधों में नमी की पूर्वानुमान करने के लिए पर्यवेक्षित एमएल रिग्रेशन का उपयोग किया जाता है, जिसमें समय-बदलती टेराहर्ट्ज़ छवियों और पत्तियों से स्पेक्ट्रोस्कोपिक जानकारी का विश्लेषण किया जाता है। विश्लेषण के लिए निकाले गए पूर्वानुमानकों पर निर्भर करते हुए डिसीजन ट्री, रैंडम फॉरेस्ट, सपोर्ट वेक्टर रिग्रेशन, पारशियल लीस्ट स्क्वायरस रिग्रेशन मॉडल्स का उपयोग किया जाता है। अनुसंधान इसके साथ हर सिस्टम के लिए सिग्नल-प्रोसेसिंग और छवि-प्रोसेसिंग एल्गोरिथ्म का अन्वेषण भी करता है ताकि टेराहर्ट्ज़ संवेदन डेटा के साथ एमएल तकनीकों को एकीकृत किया जा सके, जो कृषि के डेटा-संचालित एल्गोरिदम्स के उभरते क्षेत्र में योगदान देता है। परिणाम स्पष्ट करते हैं कि उचित एमएल मॉडलों के साथ टेराहर्ट्ज़ तकनीकों का पौधों में नमी की मात्रा का अनुमान लगाने में प्रभावशाली होता है।

## **Declaration by author**

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, financial support and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my higher degree by research candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

I acknowledge that an electronic copy of my thesis must be lodged with the University Library and, subject to the policy and procedures of The University of Queensland, the thesis be made available for research and study in accordance with the Copyright Act 1968 unless a period of embargo has been approved by the Dean of the Graduate School.

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## Publications included in this thesis

1. [1] Khushboo Singh, Naini Bajaj, **Mayuri Kashyap**, Aparajita Bandyopadhyay, and Amartya Sengupta, Applications of multi-parameter sensing pharmaceutical, agriculture and mineral industry using THz spectroscopy and low-wavenumber Raman spectroscopy, *Manuscript accepted for publication in Optics and Laser Technology*, April, 2024.
2. [2] Urbi Kundu, Jari Torniainen, Karl Bertling, **Mayuri Kashyap**, Khushboo Singh, Bogdan C. Donose, Tim Gillespie, Dragan Indjin, Lianhe Li, Edmund H. Linfield, A. Giles Davies, Paul Dean, Aparajita Bandyopadhyay, Amartya Sengupta, and Aleksandar D. Rakić, Variability in plant cell water dynamics as a genetic discriminatory method using terahertz quantum cascade laser-based laser feedback interferometry, *Photonic Technologies in Plant and Agricultural Science*, Vol. 12879, pp. 129–138, SPIE, 2024.
3. [3] **Mayuri Kashyap**, Jari Torniainen, Karl Bertling, Urbi Kundu, Khushboo Singh, Bogdan C. Donose, Tim Gillespie, Yah Leng Lim, Dragan Indjin, Lianhe Li, Edmund H. Linfield, A. Giles Davies, Paul Dean, Millicent Smith, Scott Chapman, Aparajita Bandyopadhyay, Amartya Sengupta, and Aleksandar D. Rakić, Coherent terahertz laser feedback interferometry for hydration sensing in leaves, *Optics Express*, Vol. 31(15), pp.23877-23888, 2023.
4. [4] **Mayuri Kashyap**, Aparajita Bandyopadhyay, Karl Bertling, Aleksandar D. Rakić, and Amartya Sengupta, Study of moisture content in leaves through regression analysis of terahertz images, *Optical Sensing and Detection VII*, Vol. 12139, pp. 157-164, SPIE, 2022.
5. [5] **Mayuri Kashyap**, Aparajita Bandyopadhyay, Karl Bertling, Amartya Sengupta, and Aleksandar D. Rakić, Quantifying relative moisture content in dielectric models using CW-THz spectroscopy and supervised machine learning regression, *Terahertz Emitters, Receivers, and Applications XII*, Vol. 11827, p. 1182704, SPIE, 2021

## Submitted manuscripts included in this thesis

1. [6] Urbi Kundu, Jari Torniainen, Karl Bertling, **Mayuri Kashyap**, Bogdan C. Donose, Tim Gillespie, Dragan Indjin, Lianhe Li, Edmund H. Linfield, A. Giles Davies, Paul Dean, Aparajita Bandyopadhyay, Amartya Sengupta, and Aleksandar D. Rakić, Detecting Genetic Variation in Plants by Mapping Cell Water Dynamics with Terahertz Laser Feedback Interferometry, *Manuscript under review in IEEE Transactions on Terahertz Science and Technology*, 2024.

## Other publications during candidature

### Conference abstracts

1. [7] **M. Kashyap**, A. Bandyopadhyay, and A. Sengupta, Studying the Scattering of Electromagnetic Wave by a Composite 3D Model at Terahertz Frequencies, *Proceedings of COMSOL Conference, Bangalore, 2019*, COMSOL Multiphysics®, 2019.
2. [8] A. Dalal, K. Singh, U. Aalam, **M. Kashyap**, A. Bandyopadhyay, and A. Sengupta, Environment Dependent Propagation Response of High Frequency THz Band Antenna in Short Range, *2021 International Conference on Electrical, Computer and Energy Technologies (ICECET)*, pp. 1-4, IEEE, 2021
3. [9] K. Bertling, **M. Kashyap**, J. Torniainen, U. Kundu, K. Singh, T. Gillespie, Y. L. Lim, P. Dean, D. Indjin, Y. Han, L. Li, A. Sengupta, A. Bandyopadhyay, A.G. Davies, E. H. Linfield, A. D. Rakić, Hydration imaging with THz Quantum Cascade Lasers: Towards Precision Agriculture, *Conference on Optoelectronic and Microelectronic Materials and Devices (COMMAD)*, 2022

## Contributions by others to the thesis

### All chapters

Editorial suggestions were provided by the candidate's supervisors, Amartya Sengupta, and Aleksandar D. Rakić, and Aparajita Bandyopadhyay, Karl Bertling and Jari Torniainen.

## Statement of parts of the thesis submitted to qualify for the award of another degree

No works submitted towards another degree have been included in this thesis.

## Research involving human or animal subjects

No animal or human subjects were involved in this research.

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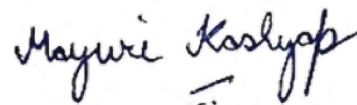
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A handwritten signature in black ink, reading 'Mayuri Kashyap' in a cursive script.

(Mayuri Kashyap)

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## **Keywords**

terahertz (THz), imaging, spectroscopy, plant hydration, quantitative assessment, optimized irrigation management, machine learning (ml), non-invasive methodologies, laser-feedback interferometry (LFI), precision agriculture

## **Australian and New Zealand Standard Research Classifications (ANZSRC)**

ANZSRC code: 400909 Photonic and electro-optical devices, sensors and systems (excl. communications), 60%

ANZSRC code: 510205, Terahertz physics, 20%

ANZSRC code: 460306 Image processing, 20%

## **Fields of Research (FoR) Classification**

FoR code: 4009 Electronics, sensors and digital hardware, 60%

FoR code: 5102 Atomic, molecular and optical physics, 20%

FoR code: 4603 Computer vision and multimedia computation , 20%

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