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

Indian Institute of Technology Delhi

THE UNIVERSITY OF QUEENSLAND 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

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

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.

Digitally signed by Amartya Sengupta
Date: 2024.04.26 13:12:41 +05'30'

Professor Amartya Sengupta
Department of Physics

Indian Institute of Technology Delhi
Hauz Khas, New Delhi - 110016, India

Professor Aleksandar D. Rakić
Faculty of Engineering, Architecture and Information Technology
The University of Queensland
St. Lucia, Australia - 4072

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 स्क्ुअरेस 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.

I acknowledge that copyright of all material contained in my thesis resides with the copyright holder(s) of that material. Where appropriate I have obtained copyright permission from the copyright holder to reproduce material in this thesis and have sought permission from co-authors for any jointly authored works included in the thesis.

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.

Acknowledgments

The completion of this doctoral dissertation has been an incredible and transformative journey, and I am profoundly grateful to all the remarkable individuals who have provided their unwavering support, guidance, inspiration, and care throughout my academic endeavours, particularly amidst the challenges posed by the Covid-19 pandemic.

First and foremost, I extend my sincere gratitude to my supervisors, Prof. Amartya Sengupta and Prof. Aleksandar D. Rakić, for their invaluable scholarly guidance, unwavering patience, and insightful contributions that have shaped my entire research journey. Their expertise and mentorship in the fields of research and scientific writing have played a pivotal role in fostering my growth as a research scholar.

I would also like to express my heartfelt appreciation to Dr. Aparajita Bandyopadhyay for generously dedicating her valuable time to engage in extensive technical discussions, share her profound expertise, and instil in me the confidence and academic rigour required to undertake research in the field of science and terahertz technology. My sincere gratitude goes to Dr. Karl Bertling for his support, patience, words of encouragement, and practical advice, which have made even the most challenging circumstances bearable. I am also grateful to the chairperson of my dissertation committee, Prof. Pramit Chowdhury, for providing valuable comments, constructive feedback, and thoughtful insights that have been instrumental in refining and elevating the quality of this research.

I would like to express my special appreciation to the UQIDAR program for granting me the opportunity to be part of this joint collaboration between both universities and for creating a warm and welcoming environment throughout my academic journey. I extend my sincere thanks to Dr. Naveen Garg, Rameswari Radhakrishnan, Georgia Mitchell, Belinda Bern, Assoc. Prof. Neetu Singh, Dr. Rajeev Shorey, the administrative staff of the Department of Physics at IITD, UQ Graduate School, UQ student services, School of Information Technology and Electrical Engineering (ITEE), and the support staff for their exceptional assistance and cooperation. Their contributions have made my stay not only enjoyable but also feasible.

I would like to acknowledge and thank Dr. Jari Torniainen for his guidance, insights, and expert views on information processing. His willingness to explain intricate concepts and details that are often overlooked has been greatly appreciated. My heartfelt gratitude also goes to my colleagues from IIT Delhi and UQ - Dr. Khushboo Singh, Dr. Diksha Garg, Urbi Kundu, Uzair Aalam, Xiao Guo (Peter), Jorge Silva, Xiaoqiong Qi, and Bogdan Donose. I consider myself extremely fortunate to have met these remarkable individuals who have shared their knowledge, support, encouragement, and above all, their comradeship during both good times and challenging moments.

I would like to extend my sincere thanks to my friend, Suruj, for his constant support, patience, understanding, encouragement, and valuable suggestions throughout this journey. I would also like to express my gratitude to my friends - Aneesha and Ben, Vallari, Alok, Simran, Achintha, Nitesh, Satakshi, Gopika, Samiha, Irfaan, Wali, Madhumumita, and Sudeep for their support, help and encouragement.

I am immensely thankful to the most important individuals in my life, my family, who have been my constant support throughout this journey and beyond. First and foremost, I am deeply grateful to my father, Dr. Aswini Kumar Sarmah, whose unwavering support and constant motivation have been instrumental in my pursuit of this doctoral thesis. His own attainment of MVSc and doctoral degree has always been a driving force and a source of inspiration for me. I am also indebted to my mother, Mrs. Monakshi Devi, who has consistently prioritized our well-being and has emphasized the significance of laying a strong foundation and pursuing higher education. Her advocacy for education, especially in a society where girls are often denied equal opportunities, has been invaluable to my academic journey.

A big thank you goes to my sister, Kasturi Kashyap, for always being there for me emotionally and financially. She has been my pillar of support and my comfort zone. I want to give a special shout-out to my brother, Dr. Suraj Pratim Kashyap, for his unwavering presence and for sharing with me valuable tips and tricks to stay focused and motivated. His playlists and artistic skills have been a source of solace during moments of loneliness. I am also thankful to my brother-in-law, Kaushik Sharma, and his mother, for the engaging discussions on food, careers and entertainment, and to my beloved niece, Koirabhi (Kuhu), and my nephew, Krisanu (Jiyon), for bringing boundless love and joy into my life. Their stories and adorable antics have always brought a smile to my face, even in the most challenging times.

Lastly, I want to express my gratitude to all my friends, extended family, and well-wishers who have supported me and offered their wishes and prayers. Your presence in my life has been a constant source of encouragement and motivation.

Mayuri Kashyap

(Mayuri Kashyap)

Financial support

This research was supported by an Indian Institute of Technology Delhi Research Scholarship, and a Research grant from the UQ-IITD Academy of Research (UQIDAR).

This research was supported by an Australian Government Research Training Program Scholarship.

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%

Contents

List of Figures

List of Tables