TRANSFORMING FOOD ANALYSIS AND CONTROL:

NON-DESTRUCTIVE TECHNOLOGIES AND INNOVATIONS

K. Prasad, S. Shekhar, M. K. Paswan and R. Ahuja



Advancing Food Quality, Safety and Sustainability with Smart, Innovative and Non-Destructive Technologies

Sant Longowal Institute of Engineering and Technology, Longowal

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SLIET LONGOWAL

Transforming Food Analysis and Control: Non-Destructive Technologies and Innovations

Transforming Food Analysis and Control: Non-Destructive Technologies and Innovations

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Transforming Food Analysis and Control: Non-Destructive Technologies and Innovations

About the Editor

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Prof. Kamlesh Prasad is a distinguished academician, researcher, and food technologist with extensive experience in teaching, research, academics, administration, and scholarly publishing. He is currently serving as Professor in the Department of Food Engineering and Technology at Sant Longowal Institute of Engineering and Technology (SLIET), Longowal, Punjab, India. In addition to his academic responsibilities, he serves as the Coordinator of the Internal Quality Assurance Cell (IQAC), Chairman of the Rajbhasha Hindi Cell, and Public Grievance Officer (PGO) of the institute. He is also the Chairman of the Conference on Future Innovations, Food Allergies, and Traditional Foods (FIFATF-2025 and FIFATF-2026).

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Prof. Prasad has authored and co-authored more than 200 research papers published in reputable national and international journals and conference proceedings. He has also authored several books, edited scholarly volumes, and contributed chapters to books published by leading national and international publishers. His publications have served as valuable references for researchers, students, and professionals working in the fields of food science, food engineering, and postharvest technology.

In addition to his research accomplishments, Prof. Prasad has actively contributed to academic leadership, curriculum development, student mentoring, and research capacity building. This edited book is being published as part of the conference proceedings, reflecting his commitment to advancing research and disseminating knowledge in these critical domains. Also associated with several prestigious professional societies and scientific organisations, including the ASABE, IFT, AFST(I), NSI, USI, IEEE, and other national and international professional bodies. Prof. Prasad continues to inspire students, researchers, and professionals while contributing significantly to the advancement of food engineering, food processing technologies, and sustainable food systems.

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Mr Shubhra Shekhar is a PhD candidate in the School of Chemical Engineering at the University of New South Wales (UNSW), Sydney, Australia. He is currently a member of the Faculty Board, holds higher-degree research student positions in engineering, has served as President of the Chemical Engineering Research Society (CERS), and is a member of the AGSE Industry PhD cohort, actively engaging with both industry and academic partners. His research focuses on non-destructive sensing and advanced characterisation methods to improve quality assurance and process understanding in modern food systems. His work brings together principles from chemical engineering, computer science, and data-driven modelling to develop innovative approaches for analysing complex food products and their behaviour.

He is a GATE achiever and has completed an M. Tech. (Food Process Engineering) from NIT, Rourkela. He received the Best Student Award from the Association of Food Scientists and Technologists, India (AFSTI), Mysuru, for the year 2021. Besides that, he was the All-India Topper (Elite) and received a Silver Medal for the NPTEL Course conducted by IIT Kharagpur. Got an appreciation letter from Nestle India Ltd, Moga, for his contributions in the form of recommendations. Won several prizes in academic, co-curricular and extracurricular activities. Received letters of appreciation for his contributions to several events and activities. He has successfully delegated his responsibilities as the in-charge of the Society of Food Technocrats (SOFT), the Photography Club (SVIESA), and numerous other professional committees and events. Undergone industrial training and internship from renowned industries and organisations such as Mondelez India Foods Private Limited, Baddi, HP; Mrs Bector's Food Specialities Limited, Greater Noida, UP; Nestle India Limited, Moga, Punjab; and ICAR-National Dairy Research Institute, Karnal, Haryana. His work is published as articles in books, journals, and conference proceedings.

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Prof. Mani Kant Paswan, Director, SLIET, Longowal, is an accomplished academician, researcher, and administrator. He has more than twenty-five years of experience in teaching, research, academic leadership, and institutional development. Throughout his distinguished career, he has made significant contributions to engineering education, research, and capacity building in Mechanical Engineering.

Prof. Paswan completed his B.Tech. in Mechanical Engineering from NIT Patna, M. Tech. in Machine Design from NIT Jamshedpur, and PhD in Mechanical Engineering from Ranchi University through NIT Jamshedpur. Before assuming the position of Director at SLIET, he served as Professor in the Department of Mechanical Engineering at the National Institute of Technology (NIT), Jamshedpur. During his tenure, he held several key administrative responsibilities, including Dean (Faculty Welfare), and played an important role in academic planning, faculty development, student welfare, and institutional governance.

His research interests span manufacturing engineering, materials processing, material characterisation, mechanical behaviour of materials, heat transfer, energy systems, and sustainable engineering technologies. He has published extensively in reputed national and international journals, conference proceedings, and edited volumes, contributing valuable insights to the advancement of mechanical and manufacturing sciences. He has successfully guided and supervised doctoral scholars, postgraduate students, and research projects, fostering innovation and developing highly skilled engineers and researchers.

Prof. Paswan has actively participated in numerous academic, research, and professional activities, including curriculum development, accreditation processes, research collaborations, faculty mentoring, and industry engagement initiatives. His contributions have strengthened the linkage between academia and industry while promoting outcome-based education and research-driven learning.

Prof. Paswan is committed to fostering academic excellence, interdisciplinary research, innovation, entrepreneurship, and global engagement. Under his leadership, the institute continues to strengthen its research ecosystem, enhance its national and international visibility, and create opportunities for collaborative learning and technological advancement.

Rajeev Ahuja, PhD

Prof. Rajeev Ahuja, Director of the Indian Institute of Technology (IIT) Ropar, is a Professor of Computational Materials Science at Uppsala University, Sweden. He is internationally recognised for his pioneering contributions to computational materials science, condensed matter physics, and energy-related materials research. He obtained his PhD from IIT Roorkee and a Postdoctoral Fellowship from Uppsala University, Sweden. His research spans a broad spectrum of interdisciplinary areas, including batteries and energy storage systems, hydrogen production and storage, nanomaterials, sensors, advanced functional materials, high-pressure physics, and computational modelling of materials. By combining theoretical approaches with advanced computational techniques, he has helped address critical scientific challenges related to energy security, environmental sustainability, and materials design.

Prof. Ahuja has published more than 1,200 research papers in leading international journals and conference proceedings. His publications have garnered over 50,000 citations, reflecting the global impact and relevance of his research contributions. He is widely regarded as one of the most highly cited researchers in materials science. In addition to his scholarly achievements, he has played a pivotal role in nurturing future generations of scientists and engineers by supervising more than 30 doctoral scholars and over 35 postdoctoral researchers, many of whom now hold prominent academic and research positions worldwide.

He is a Fellow of the Royal Society of Chemistry (FRSC), UK and the American Physical Society (APS), US. His exceptional contributions to science and engineering have been acknowledged through numerous prestigious awards and honours.

As an academic leader, Prof. Ahuja has consistently promoted excellence in research, innovation, and international collaboration. Through his leadership at IIT Ropar and his continued engagement with global scientific communities, he has strengthened interdisciplinary research initiatives and fostered partnerships between academia, industry, and research institutions. His vision for advancing science and technology continues to inspire researchers, students, and educators worldwide.

Through his groundbreaking research, distinguished academic career, and unwavering commitment to scientific advancement, Prof. Ahuja continues to make significant contributions to materials science, engineering, and sustainable technology, shaping the future of research and innovation worldwide.

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List of Abbreviations

PBF	Pregelatinized banana flour
CF	Chickpea flour
BKCM	Banana kofta composite mix
CCRD	Central composite randomized design
RTU	Ready-to-use
ADFF	Atmospheric deep-fat frying
FEM	Finite element method
HMT	Heat and mass transfer
CHTC	Convective heat transfer coefficient
DBMC	Dry basis moisture content
DBOC	Dry basis oil content
SMC	Surface moisture content
SOC	Surface oil content
MAE	Mean absolute error
MSE	Mean square error
RMSE	Root mean square error
χ^2	Chi-square
R^2	Coefficient of multiple determination
N	Number of observations
T	Temperature (°C/K)
t	Frying time (s)
2D	Two-dimensional
w.b.	Wet basis

d.b.	Dry basis
c	Concentration (mol/m^3)
D	Diffusivity (m^2/s)
ρ	Density (kg/m^3)
k	Thermal conductivity (W/(m.K))
C_p	Specific heat (J/(kg.K))
n	Outward unit normal vector
λ	Latent heat of vaporization (J/kg)
R	Universal gas constant (J/(mol.K))
M	Molecular weight (kg/mol)
k_m	Mass transfer coefficient (m/s)
h	Heat transfer coefficient (W/(m^2.K))
ϕ	Porosity
A	Surface area (m^2)
m	mass (kg)
$M_{w,db}$	Dry basis moisture content (g/g)
$M_{o,db}$	Dry basis oil content (g/g)
Le	Lewis number
P	Pressure (Pa)

Subscript

w	Water
o	Oil
g	Gas
v	Vapour
0 or i	Initial
avg	Average
eff	Effective

Preface

It gives me great pleasure to present "*Food Analysis and Control: Non-Destructive Technologies and Innovations"*, a book volume that emerged from the organised National Conference on Food Innovations, Food Allergies and Traditional Foods (FIFATF-2025).

The food sector is evolving rapidly, with increasing emphasis on quality, safety, authenticity, and sustainability. At the same time, advances in sensing technologies, artificial intelligence, machine learning, and digital tools are transforming the way food products are evaluated and monitored. This book brings together recent developments in these areas and highlights innovative approaches that can support the future of food quality assessment. The chapters included in this volume cover a diverse range of topics, including bacteriophage applications in food safety and health, microwave technologies for food analysis and processing, smart sensing systems, machine learning-based quality assessment, advanced sensor development, computational modelling of food processes, predictive shelf-life evaluation, quality characterisation of traditional food products, hyperspectral imaging, and Internet of Things (IoT) enabled monitoring systems. Together, these contributions demonstrate how emerging technologies are helping to address real-world challenges across the food supply chain.

One of the strengths is its multidisciplinary nature, as the chapters bring together expertise from food engineering, agricultural sciences, physics, electronics, sensing technologies, and data analytics, reflecting the efforts needed to develop innovative solutions for modern food systems. I hope this book serves as a valuable resource for researchers, academicians, students, and industry professionals and encourages further innovation in the fields of food quality characterisation and non-destructive evaluation.

I sincerely thank all the advisory members, committee members, faculty and staff members, sponsors, participants, administrators of participating institutions, research scholars, and supporters for their valuable contributions to the successful organisation of the PAN-India conference, FIFATF-2025. Special thanks to all the reviewers for the blind review of the submitted manuscripts and to the sponsors for their valuable financial contributions toward publishing the submitted full-length manuscripts as an edited book.

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Acknowledgement

This volume would not have been possible without the support and contributions of many enthusiastic researchers from various well-recognised institutions involved in teaching and research on food technology, and we extend our sincere gratitude to all of them.

We would first like to congratulate all the authors for sharing their valuable research and expertise. Their contributions form the foundation of this book and showcase recent advances in food quality characterisation, authentication, innovations, and non-destructive technologies.

Our sincere appreciation goes to the reviewers for their time and constructive feedback, which helped to improve the quality of the chapters included in the present book. We are also grateful to the organising committee, advisory committee members, keynote speakers, invited experts, and participants of the organised PAN-India National Conference on Food Innovations, Food Allergies and Traditional Foods (FIFATF 2025), which has paved the way for organising the upcoming International Conference, FIFATF-2026.

We would especially like to acknowledge Sant Longowal Institute of Engineering and Technology (SLIET), Longowal, the organising institute of FIFATF 2025, for providing the platform and support for this initiative. We also thank our collaborating institutions and partners, including ICAR–Central Institute of Post-Harvest Engineering and Technology (CIPHET), Ludhiana; Punjab Agricultural University (PAU), Ludhiana; Bidhan Chandra Krishi Viswavidyalaya (BCKV), West Bengal; Indian Institute of Technology Ropar; Indian Institute of Technology Delhi; ICAR–Central Institute of Temperate Horticulture; and the University of New South Wales, Australia, for the present outcome.

Finally, we thank our colleagues, collaborators, students, and well-wishers for their encouragement and support throughout this journey.

K. Prasad, S. Shekhar, M. K. Paswan and R. Ahuja (Editors)

Bacteriophage: Against Bacterial Infections and Improving Overall Gut Health

Sunil Kumar, Praveen Saini, Gunjan Thakur, Shubhra Shekhar, Kaushal Kishor Prasad, Amit Rai and Kamlesh Prasad

Abstract. Bacterial infections, mainly caused by enterobacteria in livestock, poultry, and humans, are the leading cause of illness and mortality worldwide. Bacteriophages are bacterial-infecting viruses that interact dynamically with bacteria and mammalian cells, thereby greatly influencing human health. Despite the vast reservoirs of bacteriophages in the human body, their potential to treat bacterial diseases has been undermined by the widespread use of antibiotics for many years. Despite the rise in antibiotic-resistant bacteria and our growing understanding of the gut microbiota's significance for health, the exploitation of bacteriophages is making a comeback. Considering the recent trend, the article comprehensively summarizes bacteriophages, their classification, mechanisms of action, comparisons with antibiotics, and some important studies related to phage therapy. Their applications against bacterial infections (e.g., Tuberculosis) and for improving gut health (e.g., Inflammatory Bowel Disease) are also discussed. Also, some novel applications of bacteriophages, such as gene and vaccine delivery, bacterial detection (phage typing), immunomodulation, and use in the food industry, are covered. With the expanding scope of phage therapy, the present review underscores the need to exploit it further and overcome its limitations, thereby improving human health.

Keywords: Antibiotic resistance; Gene regulation; Immunomodulation; Opsonization; Phage typing; Tuberculosis.

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1. Introduction

The vast diversity of microorganisms, including viruses, archaea, eukaryotes, and bacteria, present in the gastrointestinal (GI) tract is commonly referred to as the "gut microbiota". This microbiota plays an essential role in maintaining digestion, enabling the absorption of various important nutrients, and supporting the immune response. Any alteration in the gut microbiota, also called dysbiosis, leads to various GI disorders, metabolic diseases, and other diseases such as Alzheimer's disease (Morais et al., 2021), diabetes (Komaroff, 2017), and various types of tumours (Guglielmi, 2018). Bacterial infections, which pose major public health concerns, also result from dysbiosis and lead to sexually transmitted diseases, food poisoning, skin infections, and most urinary tract infections. Human organs or cells are susceptible to various bacterial infections; for example, *Mycobacterium tuberculosis* causes tuberculosis (TB), which primarily infects the lungs, and *Neisseria meningitidis* infects the central nervous system. These bacterial infections can also spread easily through the air, water, and other vectors to healthy individuals. Antibiotics are drugs used to treat bacterial infections either by destroying bacterial cells or preventing their growth, ultimately aiding the body's immune system in fighting off the infection (Galarza et al., 2021). In recent years, the high death rate from bacterial infections and the limited effectiveness of even strong antibiotics prescribed for bacterial diseases due to multidrug resistance (MDR) have drawn increased attention to alternative, effective treatment methods (Pang et al., 2019). The rising crisis of MDR has revitalized the scope of bacteriophages (phages) against MDR bacterial strains (Azam et al., 2021). The therapeutic application of bacteriophages to treat bacterial infections and improve gut microbiota is also reemerging (Gordillo Altamirano and Barr, 2019; Kaur et al., 2024; Qv et al., 2021). The potential of bacteriophages is not being fully utilized. It needs to be accelerated, as more and more bacteria are becoming resistant to most antibiotics, resulting in infections that are difficult to cure.

2. Bacteriophages (bacteria-eating viruses)

Viruses are acellular, intracellular parasites that act as a connecting link between living and non-living and require specific host cells for their growth.

and further explore the scope of phage therapy. Considering their potential, bacteriophages are natural antibiotics that can be used as powerful weapons not only against bacterial diseases but also to treat non-bacterial disorders, including metabolic, genetic, and autoimmune disorders. There are various reports on the successful use of phage therapy for TB and GI disorders. The use of phages to precisely modify the gut microbiota and their therapeutic potential for many GI disorders is astonishing. Thus, there is an urgent need to further explore the potential of phage therapy for other diseases and to enable its widespread use. In the future, phages as immunomodulators, phage-based vaccines, and phage-mediated gene editing could be key areas for discovery and research. The potential of artificial phages to target specific cells and enzymes to control metabolic diseases is also a great area of interest.

Conflict of Interest

The authors have disclosed that there are no conflicts of interest to declare

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Insights of Microwave: Analytical and Food Processing Applications

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Abstract. Dielectric properties form a bridge between material and material characterisation. Low-power microwaves are non-destructive, and dielectric measurements have made this an emerging method in material characterisation. Compilation of various aspects of microwave, their categorisation, and the generation of microwaves are covered. Open-ended coaxial probe method, waveguide-as-transmission-line method, cavity perturbation method, time-domain spectroscopy method, impulse time-domain transmission method, free-space transmission method, and parallel-plate method as measurement techniques are reviewed, along with instrumentation, including Vector Network Analyser and Impedance Analyser. The applications of high-power microwaves in various thermal processing unit operations, such as blanching, pasteurisation, sterilisation, thawing and tempering, drying, and baking, may be revolutionised by integrating microwaves with conventional thermal approaches to enable efficient food processing. A thorough effort to consolidate all aspects of dielectric measurements and encompassing diverse applications in food engineering under the canopy of microwaves may thus prove to be the future tool for researchers and industrialists to fulfil the need.

Keywords: Microwave, Dielectric constant; Dielectric loss; Analytical tool; Processing methods; Frequency; Microwave heating.

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1. Introduction

Gamma rays to radio waves in the electromagnetic spectrum surround the universe in various forms and play a crucial role in research. The electromagnetic spectrum includes radio waves, microwaves, infrared rays, visible light, ultraviolet rays, X-rays, and gamma rays (Fig. 1). A varied range of spectrum over frequencies, electromagnetic radiations can be used to study a system of different sizes from a size much smaller than nanoscale to a size in kilometres. Electromagnetic radiation has both electric and magnetic fields oscillating in perpendicular directions, travelling at a speed of 3×10^8 m/s through space (Fig. 2). The behaviour of electromagnetic radiation is mainly governed by Maxwell's equations (Griffiths, 2023; Jackson, 2021).

Both low and high power microwaves have been widely used for research purposes, such as in astrophysics, where radio- telescopes use microwaves for the study of cosmic background; for drying materials in textile and paper industries; for medical purposes in the treatment of cancer, etc.; in microwave spectroscopy to analyse molecular structure; as well as in daily life, microwave ovens for food processing applications, wireless communication such as WiFi, radar systems for military defence, and air traffic (Pozar, 2021). Further, the applications of microwaves can be extended to the knowledge of dielectric properties. Several other properties of a material can be determined using dielectric properties, which describe the material's response to electromagnetic radiation. A Vector Network Analyser (VNA) is employed for this purpose. Depending on factors affecting the dielectric and the state of the dielectric (solid, semi-solid, or liquid), there are various approaches to finding the dielectric constant, such as Transmission / Reflection Line Method, the Cavity Perturbation Method, the Coaxial Probe Method, Time-Domain Spectroscopy, the Impulse Time Domain Transmission technique, the Free Space Transmission technique, and the Parallel Plate technique. Further details, along with advantages and disadvantages, are summarised in the upcoming sections.

The device described to heat food utilising electromagnetic waves with a wavelength of 10 cm, a microwave, is a major revolution in food heating and cooking, and was patented in 1945 (Tang, 2015). As the name suggests, microwave ovens utilise microwaves for heating purposes (Ohlsson and Bengtsson, 2001). Heat generation throughout the entire volume of food material occurs due to the interaction of microwaves with polar molecules, mainly water and charged ions. Therefore, discussing the mechanisms of

10. Conclusion

A comprehensive progression from the fundamentals of microwaves, including the electromagnetic spectrum, to their impact on a material's dielectric properties, covering both physics and food engineering standpoints. The methods for generating microwave, its transmission, and its applications, along with its classification and importance in the food industry, are discussed. The Physics angle includes understanding electromagnetic theory and knowledge of polarisation and its types, i.e., electronic, ionic, dipolar, and spatial polarisation. Microwaves, due to their ability to interact with dipolar polarisation, are an exceptional tool to investigate the dielectric properties of a material. All the formulations of dielectric properties, that is, dielectric constant, dielectric loss and loss tangent, discussed before, are based on the fact that the dielectric property has a complex nature. The various approaches to dielectric constant, such as Debye Model, Parallel Plate Capacitor Method, the Clausius-Mossotti relation, and the Optical Method have been outlined thoroughly in the previous sections under theoretical approaches. Experimentally, both the impedance analyser and the VNA have their grounds. Despite being sensitive to surrounding noise and expense, operating in the frequency domain is the only main drawback of the impedance analyser. VNA is in the spotlight because of its operation in both the time and frequency domains. The open-ended coaxial probe method, Waveguide method, and cavity perturbation method are widely used to determine the dielectric properties of a material. The direct application of microwave in the food industry is microwave heating in the 915 MHz and 2450 MHz bands, as specified by the FCC ISM bands.

The integration of microwaves in the food industry has led to a revolution in processing and preservation methods, with several benefits, including reduced processing time, nutrient retention, effective control of microbial growth, improved quality and texture, cost efficiency, and energy efficiency. Microwave technology is an emerging tool for developing new products and processes while ensuring compliance with product quality and safety regulations. The major concern with the use of microwaves in food is non-uniform heat distribution due to several factors, including shape, size, moisture content, and fat content. Thus, it has been observed that combined microwave heating methods, compared with separate ones, offer greater benefits.

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Smart Vibration Sensing and Machine Learning for Non-Destructive Estimation of Tender Coconut Water Volume

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Abstract. Tender coconut quality is primarily determined by internal attributes such as water volume and physiological maturity, which are difficult to assess using conventional destructive or subjective methods. Acoustic non-destructive techniques have emerged as effective tools for evaluating these attributes by exploiting the relationship between mechanical vibration response and internal mass stiffness characteristics. This chapter reviews the principles, instrumentation, and signal-processing approaches of acoustic resonance, mechanical vibration, ultrasonic, and acoustic emission methods specifically applied to tender coconut. Recent advances integrating machine learning models for water volume prediction are discussed, highlighting their relevance for large-scale grading and quality assurance in the coconut industry.

Keywords: Non-destructive evaluation, vibration, sensing, tender coconut

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1. Introduction

Tender coconut (*Cocos nucifera* L.) holds a unique position in the global horticultural and beverage markets due to its high nutritional value, refreshing taste, and rising consumer demand for natural, minimally processed drinks. Unlike mature coconuts, tender coconuts are harvested at an early physiological stage (typically 6–7 months after flowering), when the liquid endosperm (coconut water) is at its maximum volume and optimal sensory quality (Naik et al., 2022). At this stage, the kernel is soft and gelatinous, and the shell has not yet fully hardened. These attributes make tender coconut highly desirable but also extremely challenging to grade and standardise using conventional quality evaluation methods (Shi et al., 2025). Traditionally, tender coconut quality has been judged using empirical and experience-based practices such as tapping the shell and listening to the sound, visual inspection of husk colour, weight-based estimation, or flotation tests (Dubey et al., 2025). While these approaches are rapid and inexpensive, they are inherently subjective, inconsistent, and poorly correlated with internal attributes such as water volume, kernel thickness, and physiological maturity. Destructive methods, including cutting the nut to measure water volume or biochemical analysis, provide accurate information but result in complete product loss and are therefore unsuitable for commercial grading, especially when 100% inspection is desired (Wang et al., 2026).

In this context, non-destructive testing (NDT) techniques have gained increasing attention as tools capable of evaluating internal quality while preserving the integrity of the fruit. Among various NDT approaches, acoustic-based non-destructive methods have emerged as particularly promising for tender coconut due to their simplicity, low cost, rapid measurement capability, and a strong physical link between acoustic response and the mechanical–structural properties of biological tissues (Dubey et al., 2025). Acoustic methods are fundamentally rooted in the interaction between mechanical vibrations and the mass–stiffness characteristics of the coconut shell–water–kernel system. Even subtle changes in water volume or tissue firmness can significantly alter the acoustic signature generated when the fruit is excited (Nair U. K et al., 2024; Syahansyah et al., 2022).

This chapter presents a focused synthesis of acoustic-based non-destructive techniques for the quality assessment of tender coconut. It critically examines

Table 1. Overview of acoustic non-destructive techniques for tender coconut quality assessment.

Technique	Principle	Key Parameters	Advantages	Limitations
Acoustic Resonance	Natural vibration response to impact	Dominant frequency, damping	Simple, low-cost, fast	Sensitive to noise
Mechanical Vibration + ML	Frequency attenuation modelling	Spectral features	High accuracy	Requires training data
Ultrasonic Analysis	Wave propagation in liquid/tissue	Velocity, attenuation	Sensitive to composition	Limited penetration
Acoustic Emission	Stress-induced elastic waves	Event rate, amplitude	Structural insight	Complex setup

8. Conclusion

Acoustic non-destructive methods provide a scientifically grounded, practical, and scalable solution for assessing tender coconut quality. By exploiting the intrinsic relationship between acoustic response and internal physical properties, these techniques enable rapid estimation of water volume and maturity without damaging the fruit. The integration of advanced signal processing and machine learning has significantly enhanced prediction accuracy, moving acoustic methods beyond empirical tapping toward quantitative, automated grading systems. Continued advances in sensor design, embedded intelligence, and field validation are expected to accelerate commercial adoption, particularly in major coconut-producing countries such as India.

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Microfluidic Half-Mode Substrate Integrated Waveguide Sensor Development for Non-Destructive Real-time Qualitative and Quantitative Evaluation of Liquid Foods and Beverages

Swapnil Shekhar

Abstract. Quality evaluation involves the systematic assessment of product characteristics and is essential to ensuring compliance with predefined standards in meeting consumer expectations. The traditional approach to destructive quality evaluation destroys the sample and is thus unsuitable for future use. In contrast, non-destructive quality evaluation assesses attributes without compromising the sample's integrity, enabling real-time monitoring. Beverages are liquid consumables and may be alcoholic or non-alcoholic in nature. Determining the specific constituents of alcoholic and non-alcoholic beverages is of utmost importance for quality control, regulatory compliance, consumer safety, and consistency, all achieved through a low-cost approach to characterisation. Substrate-integrated waveguide (SIW) based sensors are precise and compact, with low loss and suitable for both contact and non-contact detection. SIW-based sensors offer a cost-effective and easily integrable solution for real-time quality evaluation. A novel half-mode SIW sensor, based on the material-perturbation cavity resonator approach, was designed for real-time assessment of its applicability in characterising liquid foods. Selection covers the range of most commercially available concentrations of water-soluble beverage components. The measured results show a significant shift in the resonant frequency, enabling quantitative estimation of the loaded sample under test. The findings suggest that the developed sensor can be successfully applied as a precision sensor in a real-time system.

Keywords: Cavity resonator, non-destructive evaluation, substrate-integrated waveguide, sensor, beverage, characterisation.

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1. Introduction

Concerns about food safety, authenticity, and quality assurance have created an increasing demand for non-destructive quality assessment techniques suitable for a varied range of food products. From pre-harvest to post-harvest processing, storage, transportation, and distribution need to be strengthened by developing an appropriate sensing system that provides alerts and guidance on the steps required to meet specific consumer needs. Liquid foods and beverages, alcoholic and non-alcoholic, are mainly susceptible to adulteration, microbial contamination, and spoilage. Since these quality changes directly impact consumer acceptance, food characteristics, and regulatory compliance, rapid assessment methods are becoming indispensable for food industries where subjective quality evaluation techniques are in force.

Traditional advanced analytical methods and conventional approaches, although they provide accurate compositional characteristics, require extensive sample preparation, sophisticated instrumentation, and skilled technicians, and are expensive and time-consuming. Also, most conventional techniques are destructive and unsuitable for real-time quality assessment. Subsequently, non-destructive testing (NDT) techniques have emerged as suitable alternatives, as they are rapid, reagent-free, repeatable, and enable in situ quality assessment without damaging the food products. In recent years, numerous non-destructive sensing approaches, including electronic nose systems, computer vision, machine vision, hyperspectral imaging, impedance spectroscopy, and microwave sensing, have been successfully investigated for agricultural commodities and processed food products. A comprehensive review further established the importance of non-destructive quality measurement for fruits and vegetables (Prasad, 2015a, b).

Recent advances in artificial intelligence, coupled with non-destructive assessment data, have significantly expanded the application of non-destructive food evaluation. Deep learning-based classification of ripening bananas (Kapri and Prasad, 2025) and quality assessment of mung beans using machine vision (Kaur et al., 2026) have been successfully applied, demonstrating that intelligent non-destructive sensing techniques are becoming reliable tools for rapid food quality evaluation. Nevertheless, optical techniques are primarily suitable for assessing food products based on their external features, thereby limiting their applicability to liquid foods and beverages, where quality is predominantly determined by internal physicochemical properties.

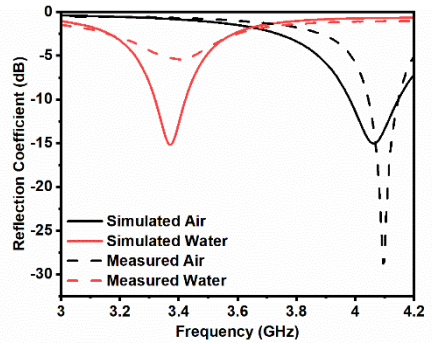

Fig. 12. Simulated and measured reflection coefficient for air and distilled water using the proposed sensor.

5. Conclusion

A dual-port microfluidic extended half-mode substrate integrated waveguide cavity resonator sensor is proposed for non-destructive complex permittivity measurement of liquid foods and beverages. The sensor incorporates a hole near the open edge of the modified cavity, where the electric field intensity reaches the maximum value. An open-ended PVC tube is inserted through this hole to facilitate the loading of liquid samples into the sensing region. To enhance the sensor sensitivity, a copper metal sheath is wrapped around the tube, resulting in stronger electromagnetic field confinement and improved interaction between the sample and the fields. A prototype of the optimised design was fabricated in the form of a sensor and experimentally validated for extreme sensing conditions for the sensing performance. The developed sensor thus can run in dual mode, namely single frequency mode and sweeping mode, for the complex permittivity characterisation of liquid foods in even real-time conditions.

Conflict of Interest

The authors have disclosed that there are no conflicts of interest to declare.

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Finite Element Modeling for Bi-Directional Transport Phenomena During Atmospheric Deep Fat Frying of Kofta: Simulation and Experimental Validations

Rahul Das and Kamlesh Prasad

Abstract. The growing demand for convenient, nutritionally improved, and lower-oil traditional foods has encouraged the development of optimized ready-to-use (RTU) mixes to deliver consistent quality. In this context, the present study focuses on optimizing banana and chickpea flour for the development of an RTU kofta dry composite mix using a statistical optimization technique. A 2D axisymmetric finite element method (FEM) was applied to model atmospheric deep-fat frying at 170°C for 180 s, with a 30 s time interval, for a kofta ball using COMSOL Multiphysics 6.0. Simulated results showed that the surface temperature quickly reached the bulk temperature of frying oil, while the center temperature gradually increased to 113°C after 180 s as expected. The dry-basis moisture content at the surface decreased by 52.60% during frying, while the oil content increased by 11.17%. However, the crumb portion exhibited minimal change in both moisture and oil content. The optimized kofta had a 42.68% reduction in surface oil compared to the control, with comparable texture and flavor. Experimental data were used to validate the FEM predictions using statistical parameters such as mean absolute error, mean square error, root mean square error, chi-square, and coefficient of multiple determination, highlighting the accuracy of the FEM in tracking HMT phenomena. Future research should focus on refining the HMT model for different-shaped and sized food products, improving oil absorption mechanisms, exploring alternative frying methods, such as air frying and vacuum frying, to further reduce oil content at the pilot plant or industrial scale to maintain the product quality.

Keywords: Atmospheric deep fat frying, Composite mix, COMSOL Multiphysics, Heat and mass transfer, Microstructure

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1. Introduction

Indian food differs from that of the rest of the world due to its unique taste. Local and homemade snacks have always been a part of Indian culture. In India, fried foods are in high demand at every festival and social gathering, as they are considered essential to a complete meal. This love for fried foods extends beyond India, as consumers worldwide are captivated by their distinctive golden color, crispy texture, and enticing aroma (Wang et al., 2023). Banana kofta is a delicious fried food made from a mixture of pre-boiled mashed banana, chickpea flour (CF), and other suitable ingredients. It is characterized by a golden-brown crust and a soft, flavorful interior, often enhanced with various spices and seasonings. However, in today's fast-paced society, busy lifestyles and the search for easier alternatives are driving consumers towards convenient, ready-to-use (RTU) composite food products, particularly those that offer low-fat fried options.

Considering these factors, the development of a popular Indian RTU kofta composite mix product with banana as the primary ingredient is of great concern to food technologists and researchers for the production of fried banana kofta. In this innovative approach, the pregelatinized banana flour is substituted with the required proportion of CF, and the careful selection and homogeneous dry mixing of other ingredients, such as bell peppers, including green, red, and yellow, $NaHCO_3$, salt, and spices, are equally important for the successful development of the composite flour blends. To prepare smooth, spherical dough balls before frying, a required quantity of mild warm water is added to the developed dry composite flour. This step ensures that the dough achieves the right consistency, facilitating the formation of uniform kofta that can be fried to perfection.

Furthermore, to enhance the quality of fried products and reduce oil absorption during frying, it is essential to optimize key process parameters and frying conditions (Dehghannya and Ngadi, 2021). The color of dried food items is an important parameter that directly affects the final quality of fried foods. It is influenced by pretreatments and the adaptation of appropriate dehydration methods. Besides, pretreatment methods also reduce the oil uptake of fried foods (Dehghannya and Ngadi, 2023). Various pretreatment methods, including coating potato strips with different concentrations of alginate (Naghavi et al., 2018a)and blanching (Moyano and Pedreschi, 2006), are used before deep-fat frying to reduce oil absorption. In addition, blanching can be used to inactivate enzymes, which subsequently cause the leaching of carbohydrates and starch gelatinization, and induce cell disintegration. It helps produce samples with reduced moisture content,

MSE: 7.68×10^{-6}-21.45; RMSE: 0.003-1.520; χ^2: 0.001-1.207; R^2: 0.937-0.999) confirmed the model accuracy, offering valuable insights for improving product quality and frying efficiency in food engineering.

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Integrating Sensor Fusion, Machine Learning, and Physics-Based Modelling for Predictive Shelf-Life Assessment of Apples in Cold Storage

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Abstract. Accurate prediction of shelf-life in cold-stored apples remains a complex challenge due to the interplay of physiological, biochemical, and environmental factors. This study develops an integrated computational framework combining dense sensor data acquisition, machine learning (ML) algorithms, and physics-based modeling to predict core temperature dynamics and shelf-life trajectories of Red Delicious apples over six months. The high-resolution dataset includes continuous measurements of temperature, humidity, and critical quality parameters such as total soluble solids (TSS), titratable acidity (TA), moisture, and weight loss. Core temperature prediction was achieved using extreme gradient boosting (XGBoost) and long short-term memory (LSTM) networks, with XGBoost outperforming LSTM by attaining an R^2 of 0.88. An entropy-based multi-criteria weighting methodology objectively ascertained the relative importance of multiple quality indices, emphasizing TSS and titratable acidity. Incorporation of a temperature and humidity modified Arrhenius equation provided an explicit mechanistic model for TSS degradation kinetics, capturing nonlinear decay trajectories under realistic storage conditions. Critically, hybrid modeling, integrating autoregressive lagged TSS features with ML-predicted core temperature and physics-modeled degradation rates yielded superior TSS prediction ($R^2 \approx 0.99$), underscoring the temporal autocorrelation and temperature dependencies essential for robust shelf-life estimation. However, inherent limitations include potential noise amplification in numerical differentiation of quality rates and assumptions of homogeneous storage conditions. Validation through time-series cross-validation protocols minimized information leakage and evaluated generalizability. This comprehensive approach demonstrates the feasibility of digital twin frameworks that fuse data-driven and mechanistic models for precision post-harvest management.

Keywords: apple cold storage, shelf-life prediction, core temperature, total soluble solids, machine learning, Arrhenius kinetics, digital twin, XGBoost, hybrid modeling

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1. Introduction

Post-harvest losses of fruits and vegetables represent a critical challenge to global food security, with estimates suggesting that approximately 20-30% of harvested produce is lost before reaching consumers (Singh et al., 2022). Apples, as one of the most economically important temperate fruits globally, require precise cold storage management to maintain quality and extend shelf-life. The complexity of predicting apple shelf-life stems from the intricate interactions among physiological processes, biochemical transformations, and environmental storage conditions (Farkas et al., 2024). Traditional quality assessment methods rely on periodic manual sampling and destructive testing, which are labor-intensive, time-consuming, and fail to capture the continuous dynamics of quality deterioration. Recent advances in digital twin technology have emerged as transformative tools for food storage systems, enabling real-time monitoring and predictive analytics throughout the supply chain (Verboven et al., 2020). Digital twins create virtual replicas of physical processes, integrating sensor data with computational models to simulate and predict system behavior. In postharvest agriculture, such systems promise to revolutionize quality management by providing continuous, non-invasive monitoring and early warning capabilities for quality degradation.

Machine learning applications in postharvest agriculture have gained substantial momentum, with researchers demonstrating the effectiveness of various algorithms for quality classification, defect detection, and shelf-life prediction (Chen et al., 2024; Kumari and Singh, 2025). Convolutional neural networks (CNNs) have shown remarkable success in image-based fruit quality assessment, achieving accuracies exceeding 99% in freshness classification tasks. However, most existing approaches focus on classification rather than continuous prediction of quality trajectories over extended storage periods. Recent studies on apple storage have emphasized the importance of precise environmental control, with research demonstrating that cultivar-specific storage protocols significantly impact quality retention (Allagui and Ben Amara, 2025; Watkins, 2018). For Golden Delicious apples, storage temperatures of 5-10°C with controlled humidity (85% RH) have been shown to influence physical and chemical properties over 10-week periods (Farkas et al., 2024). Red Delicious and other premium cultivars require even more stringent conditions, with temperatures maintained at 0-2°C and controlled atmosphere (CA) storage protocols involving specific oxygen and CO_2 concentrations (Watkins, 2018). While purely data-driven

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Electrical Properties of Jaggery as a Function of Moisture Content: Implications for Quality Control and Shelf-Life Augmentation

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Abstract. Jaggery, an uncentrifuged sugar product rich in essential minerals and bioactive compounds, represents a healthier alternative to refined sugar; however, its hygroscopic behaviour significantly compromises product quality and shelf life through moisture absorption and subsequent microbial degradation. The internal moisture content is the critical quality attribute governing its stability, yet the conventional hot air oven method for moisture determination is time-consuming and unsuitable for real-time industrial monitoring. This study addresses the need for a rapid, non-destructive quality assessment technique by examining the relationship between the physicochemical properties of solid jaggery and its electrical characteristics as a function of varying moisture levels. Plain jaggery samples were analysed using a custom-designed setup to measure electrical conductivity (σ), resistivity (ρ), resistance (R), and conductance (G) across a moisture range of 4.5%–7.58%. The results revealed a complex but consistent relationship between moisture and electrical properties, providing a basis for indirect moisture estimation. Electrical resistance and resistivity generally increased with higher moisture content, attributed to the insulating effect of entrapped air pores. In contrast, conductivity and conductance decreased until 6.67% moisture, beyond which conductivity exhibited an unexpected rise. Additionally, the study established a direct correlation between current flow and temperature elevation in the jaggery matrix, highlighting the influence of ionic resistance and moisture-filled pores on heat dissipation, an important aspect for ohmic heating applications. These findings lay a crucial foundation for developing an electrical resistivity based, real-time moisture measurement system, facilitating improved process control and enhanced shelf-life management of solid jaggery.

Keywords: Jaggery, Moisture content, Electrical conductivity, Resistivity, Non-destructive testing, Quality assessment, Ohmic heating.

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1. Introduction

With the increasing global demand for natural and minimally processed foods, traditional sweeteners such as jaggery have regained importance due to their nutritional richness and sustainability. Jaggery is an uncentrifuged sugar produced by concentrating sugarcane juice without separating molasses, thereby retaining minerals, vitamins, and antioxidants that contribute to its therapeutic value. Jaggery contains essential minerals such as calcium (40–100 mg), magnesium (70–90 mg), potassium (10–56 mg), phosphorus (20–90 mg), sodium (19–30 mg), manganese (0.2–0.5 mg), zinc (0.2–0.4 mg), copper (0.1–0.9 mg), chloride (5.3 mg), and iron (10–13 mg), along with vitamins A (3.8 mg), C (7 mg), and D_2 (6.5 mg). These nutrients make jaggery a healthier alternative to refined sugar and a key component of India's rural economy and export sector (Singh, 2013).

Despite its nutritional and economic value, jaggery exhibits limited storage stability due to its hygroscopic nature, which causes it to readily absorb atmospheric moisture. This results in microbial spoilage, stickiness, and quality deterioration, especially during humid conditions. The major problem in jaggery storage arises from the presence of invert sugars and mineral salts, which absorb moisture during the monsoon season, leading to spoilage losses exceeding 10% of the national production valued at approximately ₹40 crore annually (Mandal et al., 2006). The storage stability of jaggery is strongly influenced by environmental humidity. Their study demonstrated that applying edible coatings of carboxymethyl cellulose (CMC) and hydroxypropyl methylcellulose (HPMC) effectively minimized moisture absorption and microbial growth, thus extending shelf life. These findings underline the crucial role of moisture control in maintaining the quality and marketability of jaggery (Kumar et al., 2017).

Currently, conventional methods such as the hot air oven technique are widely used to measure moisture content; however, these methods are destructive, time-consuming, and unsuitable for real-time industrial monitoring. This limitation highlights the need for a non-destructive, rapid, and reliable method for moisture determination. The electrical measurement techniques can provide a low-cost and effective approach for estimating moisture in agricultural products. Their study found that electrical conductivity and dielectric constant increase with moisture content due to the high dielectric coefficient of water molecules, indicating the potential of electrical properties for indirect moisture assessment (Jafari et al., 2020). Similarly, it was observed that the moisture content of agricultural materials significantly influences their dielectric properties, and that these variations

moisture levels. Electrical conductivity initially decreased with increasing moisture content but showed a sharp rise beyond 6.67% moisture due to the ionization of mineral salts and enhanced ionic mobility within the jaggery matrix. Resistivity and temperature also demonstrated a strong dependence on moisture content, indicating that moisture significantly influences the electrical and thermal behaviour of jaggery. These findings establish electrical conductivity and resistivity as effective indicators for indirect moisture assessment. The study thus provides a scientific foundation for developing an electrical resistivity–based, non-destructive device capable of rapid and accurate moisture determination, which can significantly improve quality control, process monitoring, and storage stability in jaggery production.

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Hyperspectral Imaging as an Intelligent Nondestructive Food Quality Assessment Tool

Komalpreet Kaur, Shubhra Shekhar, Dhritiman Saha, and Kamlesh Prasad

Abstract. Ensuring food safety and quality is a worldwide issue that demands swift, dependable, and non-invasive assessment techniques. Traditional analytical methods like chromatography and mass spectrometry, while precise, are destructive, labour-intensive, and not ideal for real-time industrial use. Hyperspectral Imaging (HSI), which combines imaging and spectroscopy, has emerged as a promising optical sensing method that captures both spatial and spectral data across numerous adjacent wavelength bands. This dual capability enables in-depth analysis of the chemical composition, physical structure, and contaminant identification in food matrices. This paper presents the core principles, components, and data-acquisition techniques of HSI, highlighting its benefits over conventional RGB, NIR, and multispectral imaging systems. Additionally, it delves into recent uses of HSI in assessing food quality, such as detecting adulteration, estimating moisture and protein levels, and analysing microbial contamination. HSI, combined with machine learning and deep learning, has amplified its potential for automated, real-time quality inspection and classification. Despite its benefits, industrial adoption is hindered by high system costs, data redundancy, and limited algorithmic generalisation. Future developments should aim at compact hardware design, effective spectral data reduction, and interpretable AI models for scalable implementation. In summary, HSI is a revolutionary, non-destructive approach to intelligent monitoring systems, promoting improved safety, authenticity, and sustainability in contemporary food production.

Keywords: Hyperspectral Imaging, Non-Destructive Testing, Food Quality, Machine Vision System, Deep Learning, Artificial Intelligence

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1. Introduction

Food safety and quality have become global concerns due to the growth of food supply chains, increased consumer awareness, and rising incidents of adulteration. The foodborne risks and adulterants pose significant public health threats; consumers are increasingly seeking food products that are not only safe but also nutritious, fresh, and authentic (Ahmed, Monjur, et al., 2025). Therefore, fulfilling these demands requires implementing a rapid, reliable, and precise quality-control strategy by both industry and regulatory bodies. Traditional food testing methods, such as chromatography, HPLC, GC, mass spectrometry, and classical wet chemistry, are well known for their accuracy and sensitivity (Saha et al., 2023). However, these techniques are destructive, labour-intensive, and not suitable for large-scale or real-time monitoring systems. These drawbacks have prompted the exploration of nondestructive, rapid, less labour-intensive, time-efficient technologies capable of continuous monitoring throughout the food supply chain. Various non-invasive techniques have been explored, including near-infrared spectroscopy (NIRS), X-ray imaging, E-nose, and machine vision. Among these**,** Hyperspectral Imaging (HSI) has garnered particular attention. HSI stands out as a nondestructive technique that combines imaging and spectroscopy to capture hundreds of spectral bands across the visible, near-infrared, and short-wave infrared regions (Cheng et al., 2025; Manea & Calin, 2015). This unique capability to deliver both spatial and spectral information enables a thorough assessment of food quality characteristics, including chemical composition, physical properties, and contaminant detection, all without damaging the samples. Over the past decade, the versatility of HSI has been demonstrated in a variety of food applications (Anderssen et al., 2020; Cao et al., 2021; Çetin et al., 2022; Chen et al., 2023; Choi et al., 2024). These applications include evaluating the ripeness and freshness of produce, estimating protein and moisture content, assessing meat quality, detecting adulteration in products such as milk, oils, cereals, and spices and identifying foreign objects like stones, plastics, and insects, thus improving food safety (Gul et al., 2024; Kabir et al., 2025). As chemometric tools, machine learning, and deep learning become more integrated, HSI is evolving from a laboratory-based method to a practical solution for continuous, real-time monitoring during food processing. Furthermore, HSIs with artificial intelligence have garnered increasing interest, expanding their capabilities beyond traditional spectral analysis to become more sophisticated sensing tools for spatial structures and molecular compositions. These advancements are paving the way for the development of intelligent, automated inspection systems within the food processing sector (Ang & Seng, 2021; Mavani et al.,

7. Conclusion

Hyperspectral imaging represents a major shift in spectroscopy and imaging. It captures valuable spatial and spectral information for evaluating food quality and safety. Its ability to assess various attributes, including identification and classification of constituents, nutritional profiling, and adulteration detection, makes it a quick, reagent-free, and non-destructive tool that fits present food production needs. However, significant challenges still hinder industrial use of HSI. Issues like measurement variability due to changing environmental conditions, high setup costs, operational complexity, and heavy computational load from large hyperspectral datasets. Therefore, advances in models and algorithms tailored to specific food types and imaging conditions are crucial for improving prediction accuracy and reducing processing time. The shift from large and costly lab instruments to smaller, compact, field-deployable systems is also urgent. Emerging advancements, including environmental compensation modules, are making meaningful progress. Hybrid approaches, such as targeted multispectral imaging and RGB-based hyperspectral systems, may offer a practical solution that reduces data requirements while maintaining the characteristic chemical sensitivity of the HSI. The lack of standardised protocols for data collection, preprocessing and model validation, along with a shortage of publicly available reference datasets, creates a major barrier to reproducibility and comprehensive transparency. Therefore, developing guidelines and making datasets available on public platforms will be essential to accelerating the regulatory acceptance and practical use of HSI-based quality assurance systems. In the future, improvements in deep learning models, combined with hyperspectral databases, are expected to improve model performance and prediction accuracy across various food categories. Hence, exploring the combined use of HSI with other sensor technologies, such as fluorescence imaging, Raman spectroscopy, or X-ray CT, shows great promise for next-generation non-destructive analysis throughout the food production chain.

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Real-Time Respiration Rate Measurement of Fresh Capsicum Using an IoT-Enabled Smart Chamber

Majahar Ali and Pradeepta Kumar Sahoo

Abstract. An Internet of Things (IoT)–based airtight smart respiration chamber was developed to enable real-time measurement of the respiratory characteristics of fresh capsicum under ambient storage conditions. The system integrates Arduino Nano 33 IoT and ESP32 microcontroller platforms with a DHT22 temperature–humidity sensor, an electrochemical oxygen sensor (SEN0322), and an NDIR-based carbon dioxide sensor (SEN0220) to continuously monitor headspace O_2 and CO_2 concentrations, temperature, and relative humidity. Sensor data were wirelessly transmitted at 15 s intervals to the ThingSpeak cloud platform for real-time visualisation, storage, and analysis. Respiration rates were determined using mass-balance equations based on measured rates of oxygen consumption and carbon dioxide evolution in the closed system. The results showed a decrease in O_2 concentration from 20.97% to 20.31% and a corresponding increase in CO_2 concentration from 0.0395% to 0.6732%, confirming active aerobic respiration. The calculated rates of O_2 consumption and CO_2 production were 19.575 mL kg^{-1} h^{-1} and 18.699 mL kg^{-1} h^{-1}, respectively. The respiratory quotient (RQ) was found to be 0.96, indicating predominantly carbohydrate-based metabolism. Proper sensor calibration ensured high measurement accuracy and system stability. The developed IoT-based smart chamber demonstrated reliable performance in quantifying respiration dynamics of fresh capsicum and offers a low-cost, scalable, and efficient alternative to conventional laboratory-based respiration measurement techniques. This system provides a scientific basis for optimizing postharvest handling strategies and designing suitable modified atmosphere packaging (MAP) systems to reduce postharvest losses.

Keywords: Internet of Things (IoT), respiration rate, respiratory quotient (RQ), capsicum, smart chamber, postharvest management.

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1. Introduction

Sweet pepper (*Capsicum annuum* L.), commonly known as bell pepper or paprika, is an economically important vegetable crop valued for its attractive appearance, pleasant flavour, and high nutritional quality. It is a rich source of vitamin C, carotenoids, phenolic compounds, and other antioxidant compounds that contribute significantly to human health and nutrition (Howard et al., 2000; Kader, 2024; Singh et al., 2014). The characteristic green, yellow, orange, and red colours of sweet pepper are primarily attributed to chlorophylls and carotenoids, particularly β-carotene, which possess strong antioxidant activity and enhance its nutritional value (Howard et al., 2000). Owing to its nutritional attributes and wide culinary applications in salads, curries, and processed foods, sweet pepper has seen substantial consumer demand worldwide.

Despite its commercial importance, sweet pepper is highly perishable after harvest due to continuous physiological and biochemical activities. Among these, respiration is one of the most critical metabolic processes influencing postharvest quality and shelf life. During respiration, oxygen (O_2) is consumed, and organic substrates such as carbohydrates are oxidized to produce carbon dioxide (CO_2), water, and energy required for cellular maintenance (Kader, 2024). The respiration rate directly affects senescence, moisture loss, softening, colour changes, and nutritional deterioration of fresh produce. Consequently, shelf life is inversely related to respiration rate, measuring O_2 consumption and CO_2 evolution essential for postharvest handling, storage management, and packaging system design (Cameron et al., 1989; Fonseca et al., 2002).

Monitoring respiration behaviour has become increasingly important in modern postharvest technology, particularly in Modified Atmosphere Packaging (MAP), where the concentrations of O_2 and CO_2 surrounding the commodity are manipulated to reduce metabolic activity and prolong storage life. The success of MAP largely depends on maintaining an appropriate balance between product respiration and film permeability (Fonseca et al., 2002). Recent studies have demonstrated that MAP effectively reduces weight loss, maintains firmness, delays physiological deterioration, and extends the shelf life of bell peppers during refrigerated storage (Afolabi et al., 2023; Yeboah et al., 2023). Similarly, advances in MAP modelling have highlighted the importance of accurate respiration data for optimizing package atmosphere and improving storage performance of fresh horticultural commodities (Rashvand et al., 2023). Recent reviews on bell pepper postharvest technologies have further emphasized the need for

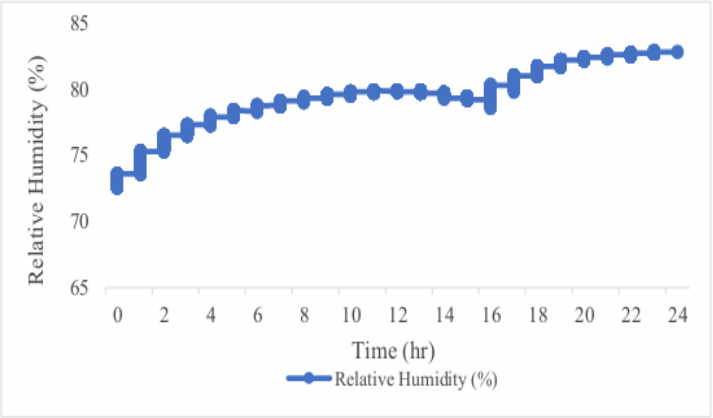

Fig. 12 Relative Humidity variations of fresh capsicum during the experimental period

4. Conclusions

The study demonstrated that the respiration rate of mature green capsicum gradually declined with increasing storage duration, indicating a reduction in metabolic activity during storage. In contrast, respiration rates increased with rising temperature, confirming the strong influence of temperature on the respiratory metabolism of fresh produce. The respiratory quotient (RQ) was found to be 0.96 at 31 ± 2°C, suggesting that carbohydrates were the predominant substrates utilized during respiration and indicating normal aerobic metabolic activity under the experimental conditions.

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