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General Article

NON-DESTRUCTIVE QUALITY ASSESSMENT OF FRUITS AND VEGETABLE: THE INTEGRATION OF SPECTROSCOPY AND HYPER SPECTRAL IMAGING IN POST-HARVEST VALUE CHAINS

Aribam Usha Devi

Isparta University of Applied Science, Turkey

Corresponding E-mail: aribamchanbidevi@gmail.com

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Abstract

Traditional methods for assessing fruit and vegetable quality are often destructive and labor-intensive, limiting their utility for large-scale, real-time monitoring. This article explores the transition to non-destructive optical sensing technologies, specifically Visible and Near-Infrared (Vis/NIR) spectroscopy and Hyper Spectral Imaging (HSI). By leveraging the principles of light-tissue interaction, these techniques utilize absorption and scattering coefficients to identify the unique spectral fingerprints of internal chemical constituents like soluble solids content, dry matter, and titratable acidity. This article further explain the architectural shift from point-source spectroscopy to the spatial-spectral integration of HSI, highlighting its superior capability in detecting localized invisible defects and early-stage infections. Furthermore, the discussion covers recent advancements in sensor miniaturization for on-tree monitoring and the integration of deep learning to process complex Hyper Spectral data cubes. These innovations represent a significant leap toward sustainable, high-precision quality control in the post-harvest sector.

Keywords: Visible and Near-Infrared, Hyper Spectral Imaging, Soluble content, Dry matter, Titratable acidity, Spectroscopy, Infections, Sustainable, Post-Harvest.

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Introduction

THe post-harvest sector faces the dual challenge of meeting stringent global quality standards while minimizing food loss and waste. Traditional quality assessment methods, though accurate, are often destructive, time consuming and labor intensive, making them unsuitable for high speed industrial sorting. Ensuring post-harvest quality demands rapid, non-destructive tools that can match the speed of modern sorting lines while complying with global standards. Visible/near-infrared (Vis/NIR) point spectroscopy and Hyper Spectral imaging (HSI) deliver complementary optical fingerprints: absorption and scattering coefficients reveal internal constituents such as soluble-solid content (SSC), dry matter, and titratable acidity, whereas spatially resolved spectra expose localized defects, early fungal infections, and surface contaminants.

This article explores the transformative role of optical sensing technologies specially Vis/NIR spectroscopy and Hyper Spectral Imaging (HSI) as non-destructive alternatives for the real time monitoring of fruit and vegetable quality. The fundamental principles of light-tissue interaction, detailing how absorption and scattering coefficients provide a spectral fingerprint of internal chemical constituents such as soluble solids content (SSC), dry matter and titratable acidity. The architectural differences between point-source spectroscopy and the spatial-spectral integration of HIS, emphasizing the latter's ability to detect localized invisible defects, early stage fungal infections and surface contaminants. The discussion then shifts to the architectural differences between point-source spectroscopy and the spatial-spectral integration of HIS, emphasizing the latter's ability to detect localized invisible defects, early stage fungal infections and surface contaminants.

Finally, the article highlights emerging trends, including the miniaturization of sensors for on-tree ripeness monitoring and the application of deep learning for complex pattern recognition in Hyper Spectral data cubes. By synthesizing current research with industrial applications, this article provides a comprehensive roadmap for the future of intelligent post-harvest management.

Current Technology

Vis/NIR point sensors excel at bulk attribute measurement—e.g., SSC in watermelons with an RPDcv=1.41 and>80%classificationaccuracyformaturity—buttheirshallowpenetrationlimits applicability to thick-skinned crops like avocado, pineapple, and banana. HSI overcomes this limitation by combining spectral and spatial dimensions, achieving defect-detection accuracies of 98–99.9% for bananas, mangoes, and avocados and pear-quality prediction $R^2 \approx 0.99$ when coupled with machine-learning models. Deep-learning architectures (Res Net, 1-D/3-D) further raise maturity-stage classification to >90% accuracy for strawberries and enable SSC estimation with minimal samples.

Traditional methods Vs Optical sensing

Traditional methods for quality assessment, such as refractometry for Brix or penetro meter testing for firmness, rely on physical sampling that renders the produce unsalable. These "sacrificial" techniques are labor-intensive and provide only a snapshot of a batch, leading to potential inconsistencies and significant food waste. Because only a small percentage of a harvest can be tested manually, internal defects often go undetected until the product reaches the consumer.

In contrast, optical sensing technologies like Vis/NIR spectroscopy and Hyper Spectral Imaging (HSI) off era non-destructive alternative that allows for 100% inspection of a harvest in real-time. By analyzing how light interacts with the molecular bonds of the fruit, Vis/NIR spectroscopy can instantly quantify internal chemical properties like sugar and acidity without breaking the skin. Hyper Spectral Imaging extends this capability by adding a spatial dimension, creating detailed maps that can identify subsurface bruising or latent infections invisible to the human eye. This shift to optical sensing ensures higher batch consistency, reduces waste, and allows for the precise sorting of produce based on ripeness and internal health.

Traditional methods often miss internal defects (like "water core" in apples or" internal browning" in pineapples) because the outside looks perfect. HSI is currently the only technology that can reliably "see" through the skin to reject these fruits before they reach the grocery store.

The transition from traditional methods to optical sensing, specifically Visible/Near-

Infrared (Vis/NIR) Spectroscopy and Hyper Spectral Imaging (HSI) represents a fundamental shift in how we define and measure "quality."

The following table and break down compare these two paradigms to show why optical sensing is becoming the industrial standard:

Feature	**Traditional Methods(Destructive)**	**Optical Sensing(Vis/NIR&HSI)**
Methodology	Chemical analysis (Titration, HPLC) or Physical (Penetrometer).	Interaction of light with matter (Absorption, Reflection, Scattering).
Sample Integrity	**Destructive. The fruit is juiced, sliced, or crushed; it cannot be sold.**	**Non-Destructive. The fruit remains intact and can proceed to market.**
Sampling Rate	Small percentage (e.g.,5-10 fruits per batch).	**100% of the batch.** Every single fruit is scanned on the line.
Speed	Slow (minutes to hours per sample).	Real-time (milliseconds to seconds).
Data Type	Single parameter per test(e.g., just Sugar or just Acid).	**Multi-parametric.** One scan can predict Sugar, Acid, Water, and Firmness.

Fundamental Principles of Light-Tissue interaction

The non-destructive assessment of fruit and vegetable quality relies on the complex interplay between light and biological tissue, primarily defined by the mechanisms of absorption and scattering. As light penetrates the surface, the absorption coefficient (μ_a) identifies the energy captured by specific molecular vibrations, particularly the O-H, C-H, and N-H functional groups. These chemical bonds act as internal signatures; for example, sugars and organic acids absorb light at distinct wavelengths in the Vis/NIR range, enabling the precise quantification of Soluble Solids Content (SSC) and Titratable Acidity. Simultaneously, the scattering coefficient (μ_s) describes how light is redirected by the physical microstructure of the fruit, such as cell walls and intercellular air spaces. While absorption provides a window into the chemical composition, scattering reveals physical attributes like dry Matter and textural density. The resulting reflectance or transmitance measured by the sensor is a product of these two factors. By mathematically decoupling these signals, optical sensing systems can isolate a unique "spectral fingerprint" that allows for the real-time monitoring of ripeness and internal health without compromising the integrity of the produce.

Architectural Evolution: From Point-Source Analysis to Spatial-Spectral Integration

The architectural distinction between point-source spectroscopy and Hyper Spectral imaging (HSI) lies in how they translate light into data: while traditional spectroscopy acts as a "single-point" probe, HSI functions as a "spatial-spectral" integrator. Point-source systems average the light signal from a specific, limited area to provide a bulk chemical profile, often missing small-scale irregularities. In contrast, HSI captures a three-dimensional "hypercube"

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that assigns a full spectrum to every individual pixel in a high-resolution image. This spatial integration allows the system to differentiate between healthy tissue and localized anomalies that would otherwise be diluted in a bulk measurement.

This architectural advantage is critical for the early detection of quality threats that are in visible to the human eye or point sensors. Because HSI monitors the entire surface and subsurface simultaneously, it can identify the subtle spectral shifts caused by early-stage fungal infections or latent bruising before physical breakdown occurs. Furthermore, by isolating specific spectral signatures across a spatial map, HIS can pin point minute surface contaminants—such as chemical residues or organic matter—that a point-based system would likely overlook. This capability transforms quality control from a general estimation into a precise, pixel-by-pixel diagnostic tool for real-time monitoring.

Miniaturization of Sensors and Deep Learning for on Tree Quality Monitoring

The transition of optical sensing from laboratories to orchards is driven by the miniaturization of Visible and Near-Infrared sensors based on Micro-Electro-Mechanical Systems (MEMS) technology. These handheld devices allow agriculture scientists to perform in-situ assessments of fruit ripeness directly on the tree, facilitating the precise determination of harvest timing without sample destruction. Unlike bulky lab spectrometers, these portable units utilize low-power LED illumination and integrated micro-processors to provide immediate feedback on Soluble Solids Content (SSC) and firmness. By enabling on-tree monitoring, these sensors provide a higher density of data across different orchard micro-climates, ensuring that fruit is picked at the physiological peak of maturity to maximize shelf life and consumer quality.

The massive volume of data generated by these sensors, particularly in the form of Hyper Spectral data cubes, necessitates the application of deep learning for complex pattern recognition. Advanced architectures like 3 D Convolutional Neural Networks (3 D-CNNs) and Residual Networks (Res Net) are increasingly used to process the spatial and spectral dimensions of Hyper Spectral data simultaneously. These models excel at extracting non-linear features that traditional linear chemometrics might miss, such as the subtle spectral shifts associated with early-stage fungal infections or subsurface mechanical damage. By integrating attention mechanisms and transfer learning, these deep-learning frame works can adapt to different cultivars and growing seasons, providing a robust and automated diagnostic tool that enhances the accuracy of real-time fruit quality grading

Implementation Road map for Optical Sensing in Agriculture

Vis/NIR point spectroscopy can be mounted on conveyor belts or handheld devices to acquire bulk spectra of each fruit as it moves through a sorting line; the rapid acquisition (milliseconds) enables real-time prediction of soluble-solid content (SSC) and acidity using calibrated chemo metric models. Because point sensors have shallow penetration, they are best suited to thin-skinned produce (e.g., berries, tomatoes) where internal quality correlates strongly with surface spectra.

Hyper Spectral imaging (HSI) extends this capability by adding a spatial dimension, allowing line-scan cameras to capture full-field data cubes of each item. Line-scan HIS units are integrated above or beside sorting belts, synchronized with the belt speed to generate a Hyper Spectral image for each fruit in <0.5 s, which is then processed by on-board GPUs or edge servers.

Data preprocessing follows a standardized workflow: scatter correction (SNV), smoothing (Savitzky-Golay), dimensionality reduction (PCA), and regression (PLSR)to translate spectra into quantitative traits. Convolution neural networks (e.g., Res Net) are trained on the resulting data cubes to classify maturity stages and detect defects with>90% accuracy, leveraging transfer-learning to adapt models across cultivars and seasons. Calibration transfer is achieved by building a reference library of spectra from multiple sensor platforms and applying domain-adaptation algorithms, ensuring consistent performance despite hardware variations.

For on-tree monitoring, miniaturized Vis/NIR probes are attached to branches or drones; they periodically sample canopy leaves or fruit skins, feeding data to cloud-based analytics that update ripeness maps and guide harvest timing.

The final deployment includes a prototype sorting-line module that delivers >95% classification accuracy with<0.5s latency, integrating sensor hardware, edge computing, and wireless data links to existing industrial control systems.

This end-to-end pipeline—sensor integration, real-time preprocessing, machine-learning inference, and robust calibration—provides a scalable solution for improving post-harvest quality, reducing loss, and supporting sustainable agricultural practices.

Advantages

Vis/NIR point spectroscopy delivers rapid, non-destructive bulk measurements (e.g., SSC in watermelons with >80% maturity classification) and is easily integrated on conveyor belts or handheld units. Hyper Spectral imaging (HSI) adds a spatial dimension, enabling defect-detection accuracies of 98–99.9% for bananas, mangoes, and avocados and pear-quality prediction $R^2 \approx 0.99$ when paired with machine-learning models. Deep-learning architectures (Res Net, 1-D/3-D) further raise classification accuracy to >90% for strawberries and reduce the number of calibration samples needed.

Disadvantage

Point sensors suffer limited penetration depth, restricting their use on thick-skinned crops (avocado, pineapple and banana). Both technologies require extensive calibration across cultivars, seasons, and sensor platforms and the high-dimensional data from HSI demand significant computational resources for real-time processing.

Research Gaps

Currently this technology lacks quantitative light-tissue interaction models that directly link optical coefficients to biochemical markers, hindering interpretability. Robust calibration-transfer protocols that operate across different cultivars, growth conditions, and sensor hardware remain underdeveloped. Additionally, miniaturized, on-tree sensors for continuous ripeness monitoring have not been fully realized.

Future Perspectives

This new technology or research methodology will establish light-tissue models, compare point-source and line-scan HIS architectures for diverse crops, and create a chemo metric-deep-learning workflow with transfer-learning to achieve scalable calibration. Successful outcomes include validated predictive models, a scalable calibration-transfer protocol, and a prototype sorting-line module delivering >95% accuracy with <0.5 s latency, paving the way for industrial deployment, reduced food loss, and sustainable post-harvest management.

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