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Hyperspectral Imaging (HSI) for Internal Quality Assessment of Fruits: Detection of Hidden Browning and Sugar Content (°Brix)

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1. Introduction

Consumer demand for high-quality fruits has increased the need for rapid, non-destructive methods to assess internal quality. Conventional measurements of SSC (°Brix), firmness, and internal browning are destructive and labour-intensive. Hyperspectral imaging (HSI) offers a non-destructive alternative by combining imaging and spectroscopy to capture both spatial and spectral information from fruit tissues (ElMasry et al., 2012; Gowen et al., 2007). It records reflectance across the visible and near-infrared regions (400–1700 nm), producing a three-dimensional hypercube where each pixel contains a spectrum. This enables early detection of biochemical and structural changes such as sugar accumulation, moisture variation, and tissue browning before visible symptoms appear (Zhu et al., 2017; Wan et al., 2025).

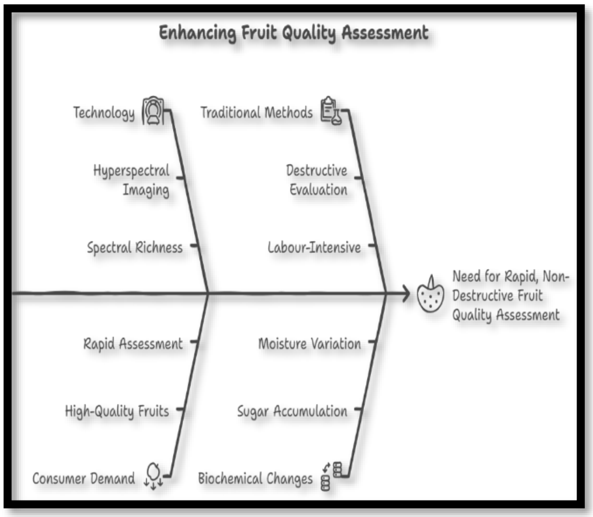

Figure 4: Enhancing Fruit Quality Assessment

2. Principles of Hyperspectral Imaging in Fruit Quality Evaluation

Hyperspectral imaging (HSI) detects internal fruit changes based on molecular absorption in the near-infrared (NIR) region, mainly from O–H, C–H, and N–H bonds associated with water, sugars, and organic acids, enabling correlations between spectral reflectance and internal composition (Cen & He, 2007; Wang et al., 2025). Internal browning alters light absorption and scattering due to phenolic oxidation, tissue degradation, and moisture redistribution, producing detectable spectral changes before visible symptoms appear (Gowen et al., 2007; Wan et al., 2025). A typical HSI system includes an illumination source, spectrograph with camera, scanning mechanism, and chemometric data analysis software, with push-broom systems widely used for fruit grading due to their high spectral resolution (El Masry et al., 2012).

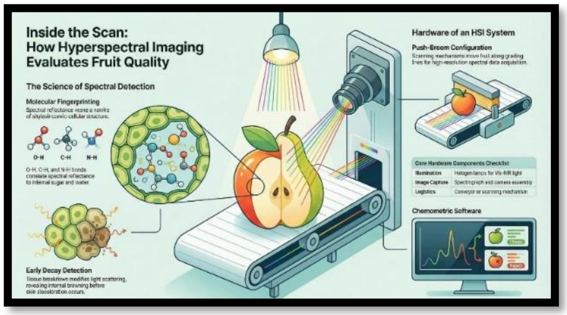

Figure 5: Hyperspectral Imaging in Fruit Quality Evaluation

Table 1. Key Internal Quality Parameters Detected by HSI

Quality Parameter	Spectral Region (nm)	Detection Basis	Typical Modeling Method	Application
Soluble Solids Content (SSC, °Brix)	900-1700	O-H and C-H bond absorption	PLSR, ANN, CNN	Sweetness grading
Internal Browning	400-1000 & NIR	Phenolic oxidation & structural change	SVM, PLS-DA, CNN	Early defect detection
Moisture Content	970, 1450	Water absorption bands	PLSR	Drying monitoring
Firmness	Vis-NIR combined	Tissue structural variation	PLSR, ANN	Ripeness prediction
Acidity (TA)	NIR region	Organic acid spectral features	PLSR	Maturity evaluation

3. Detection of Internal Browning Using HSI

Internal browning in fruits such as apple, pear, and mango often results from chilling injury, storage disorders, or mechanical damage. These changes alter phenolic content and cellular structure, leading to shifts in spectral reflectance in both visible and NIR regions (Gowen et al. 2007). Hyperspectral imaging enables pixel-level classification of healthy and browned tissues using multivariate algorithms such as Partial Least Squares Discriminant Analysis (PLS-DA) and Support Vector Machines (SVM) (El Masry et al. 2012). Studies reviewed by Wan et al. (2025) highlight HSI's ability to detect subsurface browning and quality deterioration before visible discoloration appears, demonstrating its effectiveness for early internal defect detection.

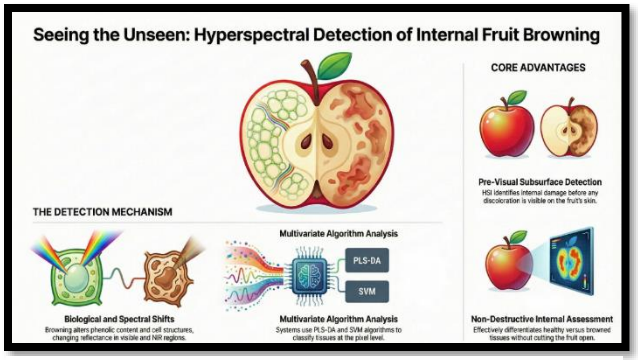

Figure 6: Detection of Internal Browning Using HSI

4. Prediction of Sugar Content (°Brix) Using HIS

Soluble solids content (SSC, °Brix) indicates fruit sweetness and maturity, but conventional refractometer measurement is destructive. Hyperspectral imaging (HSI) offers a rapid, non-destructive alternative by using spectral signatures related to sugar absorption. Sugars exhibit characteristic absorption in the NIR region (900–1700 nm) due to O–H and C–H bond vibrations, enabling SSC prediction using models such as Partial Least Squares Regression (PLSR) (Cen & He, 2007; Wang et al., 2025). Studies have shown accurate SSC prediction in fruits like kiwifruit using wavelength selection and machine learning approaches (Zhu et al., 2017; Wang et al., 2025).

5. Chemometric and Machine Learning Approaches

Hyperspectral imaging (HSI) generates high-dimensional spectral data that require chemometric and machine learning methods to analyze fruit quality attributes such as soluble solids content (SSC) and internal browning. Preprocessing techniques including Savitzky–Golay smoothing, Standard Normal Variate (SNV), Multiplicative Scatter Correction (MSC), and derivative transformations reduce noise and scattering effects (Cen & He, 2007). Models such as Partial Least Squares Regression (PLSR) predict SSC and moisture, while Support Vector Machines (SVM) classify defects. Advanced approaches like Artificial Neural Networks (ANN) and Convolutional Neural Networks (CNNs) can automatically learn spectral–spatial features, improving prediction accuracy and real-time HSI applications (Wan et al., 2025).

6. Applications Across Different Fruits

Hyperspectral imaging (HSI) is widely used for non-destructive assessment of fruit quality attributes such as soluble solids content (SSC), firmness, moisture, maturity, and internal browning. In apples, Vis–NIR wavelengths (400–1700 nm) are used to predict SSC, firmness, and acidity and detect internal disorders (Gowen et al., 2007). HSI has also been applied to kiwifruit for predicting SSC, firmness, and pH, and to persimmon for monitoring moisture and soluble solids during drying (Chen et al., 2022). Similar applications are reported for mango, peach, grape, citrus, and strawberry for evaluating ripeness, sugar content, and internal defects. Studies indicate that with appropriate wavelength selection and modeling, HSI can be effectively applied across various fruit species (El Masry et al., 2012; Wan et al., 2025).

7. Advantages of HSI in Internal Quality Assessment

Hyperspectral imaging (HSI) enables rapid, non-destructive evaluation of internal fruit quality, allowing spectral data to be captured within seconds for high-throughput analysis (Gowen et al., 2007). It can detect early biochemical and structural changes such as internal browning or chilling injury before visible symptoms appear (Wang et al., 2025). A single scan can also predict multiple quality attributes including soluble solids content, moisture, firmness, acidity, and pigments using chemometric and machine learning models. Additionally, HSI provides spatial mapping of fruit tissues and can be integrated with automated grading systems for real-time sorting in postharvest management.

Table 2. Advantages and Limitations of HSI in Fruit Quality Assessment

Advantages	Explanation	Limitations	Explanation
Non-destructive	Fruit remains intact	High equipment cost	Expensive cameras and lighting
Early detection	Identifies defects before visible symptoms	Large data volume	Requires strong computational resources
Multi-parameter prediction	Simultaneous SSC, moisture, defects	Calibration variability	Models may not transfer across varieties
Spatial mapping	Pixel-level defect visualization	Environmental sensitivity	Affected by lighting and positioning

Automation compatible	Suitable for grading lines	Standardization issues	Lack of universal protocols

8. Challenges and Limitations

Despite its potential for non-destructive fruit quality assessment, hyperspectral imaging (HSI) faces several challenges for large-scale commercial adoption. The high cost of equipment and specialized installation limits its use mainly to research institutions and high-value fruit industries (El Masry et al. 2012). HSI also produces large datasets that require advanced computational resources and efficient algorithms for real-time processing (Gowen et al. 2007). In addition, calibration models may not perform consistently across different varieties or environmental conditions, requiring calibration transfer methods (Wan et al. 2025). Sensitivity to illumination, sample positioning, and fruit surface variability can also affect spectral accuracy, while the complexity of hyperspectral data analysis and lack of standardized industrial protocols further limit widespread implementation.

9. Future Perspectives

Hyperspectral imaging (HSI) has strong potential for detecting internal browning and predicting soluble solids content (SSC), but wider commercial use requires further development. Integration with deep learning models such as CNNs can improve prediction accuracy and enable real-time detection (Wan et al., 2025; Wang et al., 2025). Current research also focuses on portable, low-cost sensors and multispectral systems targeting key wavelengths, as well as data fusion with thermal, X-ray, or fluorescence imaging to enhance defect detection. With advances in sensors and computing, HSI is expected to support smart grading systems for real-time fruit quality monitoring and traceability (Cen and He, 2007; El Masry et al., 2012; Wang et al., 2025).

Table 3. Future Development Directions

Research Area	Expected Advancement	Impact on Industry
Deep Learning Integration	Real-time spectral–spatial modeling	Improved accuracy and speed
Portable Sensors	Compact multispectral devices	Reduced cost and field usability
Multimodal Fusion	Integration with thermal/X-ray	Higher defect detection reliability
Smart Grading Systems	AI + IoT-enabled sorting	Precision supply chain management

10. Conclusion

Hyperspectral imaging has demonstrated significant capability in detecting hidden internal browning and predicting sugar content (°Brix) in fruits before external symptoms appear. By combining spectral physics with chemometric modeling, HSI enables rapid, non-destructive internal quality assessment. Continued advances in machine learning and sensor miniaturization will further enhance its applicability in postharvest technology and precision agriculture.

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