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Hyperspectral Imaging and Early Detection of Postharvest Disorders

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Abstract: -

Postharvest losses due to bruising, chilling injury, fungal infection, and internal physiological disorders represent a major challenge to the global horticultural industry. Conventional quality assessment methods rely largely on visual inspection and destructive laboratory analyses, which are often subjective, time-consuming, and incapable of detecting internal defects at early stages. Hyperspectral imaging (HSI) has emerged as a powerful non-destructive technology that combines imaging and spectroscopy to provide both spatial and spectral information from agricultural products. By capturing reflectance information across hundreds of contiguous wavelengths, HSI enables early detection of internal defects, disease symptoms, and quality deterioration before visible manifestations occur. Integration of machine learning and artificial intelligence further enhances the predictive capability of HSI systems, achieving classification accuracies exceeding 90% in several horticultural commodities. Applications of HSI in fruits and vegetables have demonstrated significant reductions in postharvest losses, improved sorting efficiency, and enhanced food safety monitoring. This article reviews the principles, applications, implementation strategies, and future prospects of hyperspectral imaging for postharvest quality management and disorder detection.

Introduction:

Postharvest losses account for nearly one-third of global food production, with fruits and vegetables being particularly vulnerable due to their high moisture content and metabolic activity. Mechanical damage, chilling injury, fungal diseases, and internal physiological disorders often remain undetected during conventional inspection and become apparent only after significant quality deterioration has occurred. Such losses result in considerable economic burdens and reduced marketability of horticultural commodities.

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Traditional assessment methods, including visual inspection, firmness measurements, microbiological analyses, and chemical assays, are frequently destructive, labour-intensive, and unsuitable for real-time monitoring. Consequently, there is increasing interest in rapid, non-destructive technologies capable of assessing both external and internal quality attributes.

Hyperspectral imaging (HSI) combines conventional digital imaging with spectroscopy by acquiring information from hundreds of narrow and contiguous spectral bands. Unlike ordinary imaging techniques that capture only spatial information, HSI simultaneously records spectral signatures associated with chemical composition and structural characteristics of agricultural products. The technology has emerged as a promising tool for early detection of postharvest disorders, quality grading, and disease monitoring in fruits and vegetables (Huang *et al*., 2020).

Principles and Mechanisms of Hyperspectral Imaging

A hyperspectral imaging system consists of an illumination source, imaging spectrograph, detector, and image-processing software. The system captures three-dimensional datasets known as hypercubes, containing two spatial dimensions and one spectral dimension.

Most postharvest applications employ the following spectral regions:

- **Visible region (400–700 nm):** Associated with colour pigments such as chlorophyll, anthocyanins, and carotenoids
- **Near-infrared region (700–1000 nm):** Provides information on water content, tissue structure, and soluble solids.
- **Short-wave infrared region (1000–2500 nm):** Related to chemical constituents including sugars, proteins, and organic acids.

Each biological tissue possesses a unique spectral fingerprint arising from its chemical and physical composition. Postharvest disorders alter cellular integrity and biochemical composition, producing measurable changes in reflectance and absorption spectra.

Advanced chemometric techniques including principal component analysis (PCA), partial least squares regression (PLSR), support vector machines (SVM), and artificial neural networks (ANN) are employed to extract meaningful information from the large hyperspectral datasets and facilitate accurate classification and prediction (Gowen *et al*., 2007).

Field Applications and Quantitative Performance

Hyperspectral imaging has demonstrated remarkable effectiveness in detecting both external and internal quality defects across a wide range of horticultural commodities.

In apples, HSI has successfully detected bruising and internal browning before visible symptoms appear. In peaches and nectarines, near-infrared hyperspectral imaging has been used to predict firmness and soluble solids content with high accuracy. The technology has also proven effective in disease detection by identifying spectral alterations associated with early tissue degradation caused by fungal pathogens.

In citrus fruits, hyperspectral systems have accurately discriminated healthy and diseased tissues, while in leafy vegetables, HSI has been employed to monitor chlorophyll degradation, moisture loss, and senescence during storage. In potatoes, the technology has detected internal defects such as hollow heart and black spot bruising, improving grading efficiency and reducing economic losses (Patel *et al.*, 2024).

Key performance metrics include:

- Non-destructive assessment of internal and external quality attributes.
- Simultaneous evaluation of multiple physicochemical characteristics.
- Rapid image acquisition and data processing.
- Potential integration with automated sorting and grading systems.
- Improved detection of defects that are invisible to conventional inspection methods.

Implementation Strategies

Commercial implementation of hyperspectral imaging involves integration with conveyor-based sorting systems and machine learning algorithms for real-time quality assessment.

Push-broom hyperspectral imaging systems are commonly employed in packing houses, where produce moves beneath imaging sensors and spectral information is collected continuously. Artificial intelligence algorithms process the spectral data to identify defects and classify produce according to quality grades.

Cloud computing and Internet of Things (IoT) technologies further enhance the capabilities of HSI systems by enabling centralized monitoring, remote diagnostics, and real-time decision-making across multiple storage and distribution facilities.

Miniaturization of imaging sensors and declining hardware costs have significantly increased the feasibility of deploying hyperspectral imaging systems in commercial postharvest operations (ElMasry and Sun, 2010).

Future Prospects

Emerging developments in hyperspectral imaging focus on improving speed, affordability, and analytical performance.

Integration of deep learning algorithms has substantially enhanced feature extraction and classification capabilities, enabling automatic detection of complex postharvest disorders with minimal human intervention. Portable and handheld hyperspectral devices are increasingly being developed for field-level applications, allowing rapid assessment of produce quality directly at harvest and during transportation.

The combination of hyperspectral imaging with complementary technologies such as electronic noses, computer vision systems, and Raman spectroscopy is expected to provide comprehensive multi-sensor platforms for postharvest monitoring and disease detection.

Advances in artificial intelligence, cloud computing, and edge processing may facilitate the development of autonomous quality monitoring systems capable of minimizing postharvest losses and improving supply chain efficiency (Huang *et al.*, 2020).

Conclusion

Hyperspectral imaging represents a transformative non-destructive technology for postharvest quality assessment and early detection of physiological disorders and diseases in horticultural commodities. By combining imaging and spectroscopy, the technology provides comprehensive information regarding both external appearance and internal composition of produce. Integration with artificial intelligence and automated sorting systems has significantly enhanced its practical applicability and predictive performance. As instrumentation becomes more affordable and computational techniques continue to advance, hyperspectral imaging is expected to play an increasingly important role in precision postharvest management, reducing losses, improving food quality, and ensuring sustainable horticultural supply chains.

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