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VISIBLE AND NEAR-INFRARED SPECTROSCOPY (VIS–NIRS) FOR NON-DESTRUCTIVE ASSESSMENT OF HARVESTED HORTICULTURAL PRODUCE : A REVIEW

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ABSTRACT

Post-harvest losses of horticultural produce remain a major challenge worldwide (accounting for 20–40 % losses depending on crop and supply-chain efficiency) particularly in developing economics where inadequate infrastructure and inefficient quality system prevails. Fruits, vegetables and floricultural products are biologically active and highly perishable, undergoing rapid physiological and biochemical changes after harvest. The aim of the post-harvest management, from harvest to consumption, is to deliver a product of acceptable eating quality to the consumer, despite storage or transport. Unfortunately, the most common conventional techniques used for quality evaluation are destructive, time-consuming, and unsuitable for real-time decision-making. Non-destructive technologies (NDTs) provide rapid, objective, and repeatable assessment of both external and internal quality attributes without compromising marketability. These technologies rely on physical principles such as optical, acoustic, thermal, magnetic and electromagnetic interactions with biological issues. But non-destructive optical techniques have become central to postharvest quality assessment of fruits and vegetables, enabling rapid, in-line, and objective evaluation without compromising product integrity. Among non-destructive optical techniques, visible and near-infrared spectroscopy (Vis – NIRS) has emerged as one of the most widely adopted non-destructive techniques for evaluating quality attributes of harvested horticultural produce. Operating within the spectral range of approximately 400–2500 nm, Vis–NIRS integrates pigment-sensitive visible wavelengths with chemically informative near-infrared absorption bands to enable rapid, non-invasive assessment of both external and internal quality parameters. This review summarizes the principles, instrumentation, and applications of Vis–NIRS in postharvest systems, focusing on soluble solids content, firmness, dry matter, maturity, physiological disorders, and shelf-life monitoring. Although challenges such as calibration transfer, cultivar variability, and water absorption effects remain, Vis–NIRS continues to demonstrate strong potential for real-time grading, decision support, and supply chain optimization in fresh horticultural commodities.
Keywords **:** Non-destructive technologies; Post-harvest management; Optical techniques, Visible spectroscopy; Near- infrared spectroscopy.

Introduction

The increased awareness and sophistication of consumers have created the expectation of high quality food products and to satisfy these, it is necessary to improve quality evaluation of all attributes which can lead to the production of food products acceptable to the consumer when they are combined (Brosan and Sun, 2004).

The postharvest phase is critical for maintaining quality, minimizing losses, and ensuring consumer satisfaction in horticultural supply chains. Horticultural commodities such as fruits and vegetables are highly perishable due to high moisture content, active metabolism, and sensitivity to mechanical and physiological stresses. Quality deterioration during harvesting, storage, transportation, and marketing results in significant economic losses and food insecurity. Post-harvest quality attributes-including firmness, soluble sold contents (SSC), internal defects (bruising, cavities), physiological disorders, chemical residue and microbial spoilage determines consumer acceptance and market value. Traditional destructive methods for assessing quality parameters are labor-intensive, time-consuming, and unsuitable for large-scale screening. Non-destructive technologies have therefore attracted growing interest in recent years

Among the available approaches, optical methods have become central to non-destructive testing (NDT) of fruits and vegetables. Their popularity stems from the ability to evaluate both surface and internal characteristics quickly and without physically contacting the produce. These techniques provide rapid, contactless, and high-throughput solutions that fit well with the efficiency demands of modern supply chains. In general, optical non-destructive methods can be grouped into several categories, including machine vision systems based on RGB imaging, visible and near-infrared spectroscopy (Vis–NIRS), hyperspectral and multispectral imaging (HSI/MSI), and fluorescence imaging techniques.

Among these technologies, Vis–NIRS is widely regarded as one of the most mature and reliable tools for rapid quality evaluation. By integrating the visible (VIS) and near-infrared (NIR) regions, this technique allows simultaneous monitoring of pigment changes as well as internal biochemical composition. This dual capability makes Vis–NIRS particularly useful for harvested fruits and vegetables and supports scalable solutions for automated sorting and grading in commercial operations (Walsh *et al.*, 2020; Pandiselvam *et al.*, 2022).

Initial efforts in non-destructive quality assessment primarily relied on near-infrared spectroscopy (NIRS) to estimate internal compositional attributes (Lu and Upchurch, 1997; Abbott *et al.*, 2010). Over the last two decades, hyperspectral imaging (HSI) has further expanded these possibilities by integrating both spatial and spectral information within a single system (Türker-Kaya and Huck, 2017). More recent studies highlight the increasing integration of optical sensing technologies with artificial intelligence, which enables more robust predictive models capable of handling diverse commodities and varying environmental conditions (Patel *et al.*, 2024; Aline *et al.*, 2023).

This review therefore compiles and analyzes current applications of Vis–NIR spectroscopy for harvested fruits and vegetables, with particular attention to the evaluation of soluble solids content, dry matter, firmness, maturity, internal defects, physiological disorders, safety assessment, and shelf-life monitoring.

Advances in portable instrumentation, hyperspectral imaging, and chemometric modeling are discussed. Despite challenges such as calibration transfer and biological variability, Vis-NIR spectroscopy continues to demonstrate strong potential for real-time grading and postharvest decision support systems.

Visible (Vis) and Near-Infrared (NIR) Spectroscopy

For many years, the use of classical separation and chromatographic and spectrometric techniques such as high performance liquid chromatography (HPLC), gas chromatography (GC), liquid chromatography (LC) and mass spectrometry (MS) were initially used for the elucidation of isolated compounds from different plant matrices (Manley, 2014).

Spectroscopy methods provide operational information about the chemical and physical characteristics of fruits and vegetables by obtaining reflectance, transmittance, absorbance, or scattering of polychromatic or monochromatic radiation from the surface of the sample in the ultraviolet (UV), visible (Vis), and NIR regions of the electromagnetic spectrum.

The Vis and NIR regions of the spectrum span the ranges 400-750 nm and 750-2500 nm, respectively. Of this range, the 750-1100 nm region is referred to as the more penetrative short wave NIR (SWNIR), or Herschel region, while the 1100-2500 nm region is considered the NIR region proper (Cattaneo and Stellari, 2019; Nicolai *et al.*, 2007; Walsh *et al.*, 2020).

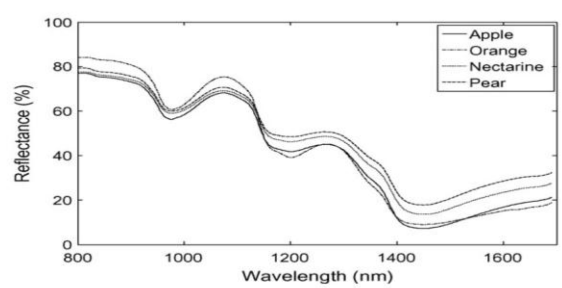

Fig. 1. Typical NIR reflectance spectra of some fruit. The NIR reflectance spectra were recorded using a Corona 45 Vis/NIR diode array spectrophotometer (Carl Zeiss Jena Gmbh, Jena, Germany) as described in Nicolaï et al. (2006a).

Visible light sensors at a wavelength from 380 to 750 nm falls in the range that is generally used for detecting external or surface features. The visible region is primarily associated with pigment absorption: Chlorophyll: ~430 nm and ~660 -680 nm; Carotenoids: 400-500 nm; Anthocyanins: 500-550 nm. Pigment degradation and synthesis during ripening and storage alter spectral reflectance, enabling maturity and senescence detection (Ncama *et al*., 2018).

Near-infrared spectroscopy (NIRS) studies the interaction between electromagnetic radiation and matter. Most absorption bands in Near infrared (NIR) radiation covers the range of the electromagnetic spectrum that extends between 780 and 2500 nm (lying between visible light with shorter wavelengths and the mid infrared (MIR) with longer wavelengths) correspond to overtones and combination bands of O-H (water), C-H (sugars and starch) and N-H (proteins) which are due to vibrational and rotational transitions. These molecular vibrations enable quantification of internal attributes such as soluble solids content (SSC), dry matter, and acidity (Nicolai *et al.*, 2007; Lin and Ying, 2009; Magwaza *et al.*, 2012).

In NIR spectroscopy, the product is irradiated with NIR radiation, and the reflected or transmitted radiation is measured. While the radiation penetrates the product, its spectral characteristics change through wavelength dependent scattering and absorption processes. This change depends on the chemical composition of the product, as well as on its light scattering properties which are related to the microstructure (Nicolai *et al.*, 2007).

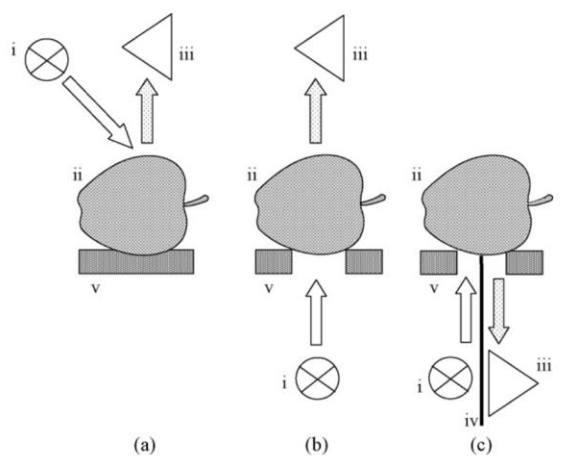

Fig. 2. Setup for the acquisition of (a) reflectance, (b) transmittance, and (c) interactance spectra, with (i) the light source, (ii) fruit, (iii) monochromator/detector, (iv) light barrier, and (v) support. In interactance mode, light due to specular reflection is physically prevented from entering the monochromator by means of a light barrier.

Visible spectroscopy (VIS; ~400 -700 nm), often combined with near-infrared spectroscopy (Vis-NIR; 400–1100/2500 nm), has emerged as a rapid, non-destructive, and cost-effective tool for postharvest quality evaluation of horticultural produce (Walsh *et al.*, 2020).

Applications of Vis-NIR spectroscopy in Harvested Horticultural Produce

Visible spectroscopy has been successfully applied to estimate maturity at harvest and predict post-storage performance. (McGlone *et al.*, 2002) demonstrated that the visible region alone (500–700 nm) could predict pre- and post-storage quality indices in 'Royal Gala' apples. Chlorophyll-related spectral features were highly correlated with firmness and SSC evolution during storage. Similarly, (Khodabakhshian and Emadi, 2017) showed that Vis/NIR spectroscopy effectively predicted maturity and internal quality parameters of pomegranate fruit, highlighting the importance of pigment-related spectral bands.

The near-infrared (NIR) region is commonly linked to the detection of internal chemical composition in agricultural products. However, the visible region also plays an important role, particularly when pigment variations are closely related to biochemical changes occurring within the fruit. For example, (Cortés *et al.*, 2017) demonstrated that diffuse reflectance VIS–NIR spectroscopy could effectively predict nectarine firmness and soluble solids content (SSC). Their findings indicated that visible wavelengths, especially those associated with chlorophyll degradation, contributed substantially to the prediction performance.

During postharvest storage, fruits undergo senescence, which leads to gradual pigment breakdown and metabolic alterations that can be detected within the visible spectral range. (Shen *et al.*, 2018) developed an online Vis/NIR system capable of distinguishing different shelf-life stages of strawberries and predicting postharvest quality attributes. In their study, spectral variations in the visible region were strongly associated with anthocyanin changes and the concurrent decline in fruit firmness.

Soluble Solids Content (SSC)

Soluble solids content (SSC) is one of the most extensively investigated quality attributes using near-infrared spectroscopy (NIRS). Magwaza *et al.* (2012) reviewed the application of NIR techniques in citrus fruit and reported reliable prediction of SSC and acidity, highlighting the potential of NIRS for rapid internal quality assessment. Similarly, Hasanzadeh and Abbaspour-Gilandeh (2022) demonstrated that Vis–NIRS combined with multivariate regression models could accurately predict several quality parameters of Red and Golden Delicious apples, including pH, titratable acidity (TA), total soluble solids (TSS), and total phenols (TP).

Velazquez (2022) also showed that NIRS is an effective, rapid, and non-destructive technique for predicting total soluble solids in strawberries, providing a sustainable alternative to conventional destructive testing methods. The study emphasized that absorption bands associated with sugars, particularly within the 900–1100 nm wavelength range, play a crucial role in TSS prediction. Although the technology proved highly suitable for evaluating key quality attributes, the authors noted that improvements in sampling strategies could further enhance model accuracy.

In addition, Maniwara *et al.* (2014) successfully applied Vis/SW-NIR spectroscopy in interactance mode to estimate SSC in passion fruit. A more recent review by Grabska *et al.* (2023) summarized advances in apple quality evaluation using Vis/NIR to NIR spectroscopy and confirmed strong predictive performance for SSC across different cultivars. Collectively, these studies indicate that wavelengths around 900–1100 nm are particularly sensitive to sugar content due to C–H overtone absorptions, making them highly relevant for SSC prediction.

Maturity and Ripeness Assessment

Visible–near infrared spectroscopy (Vis–NIRS) has been widely applied to classify harvest maturity and ripening stages in fruits. Cavaco *et al*. (2021) utilized visible–near infrared reflectance spectroscopy to assess ripening in citrus fruits, demonstrating its effectiveness in monitoring maturity-related changes non-destructively. Similarly, Minas *et al.* (2021) reported accurate single-scan NIR predictions of peach internal quality attributes, including dry matter and soluble solids content, along with physiological maturity using the index of absorbance difference (IAD). By integrating information from the visible region, which reflects pigment degradation, with signals from the near-infrared region that indicate biochemical composition, Vis–NIRS provides a more comprehensive assessment of fruit maturity. This combined spectral approach enhances the robustness and reliability of maturity prediction in harvested fruits.

Firmness and Texture

Fruit firmness is a key attribute influencing marketability and shelf-life. Its prediction using optical techniques is generally indirect, relying on correlations between spectral variations and structural changes in fruit tissues. Walsh *et al.* (2020) reported the practical application of Vis–NIRS for firmness grading in apples, mangoes, and citrus within postharvest decision-support systems. Chandrasekaran *et al.* (2019) highlighted that integrating hyperspectral imaging can further improve the prediction of mechanical properties. Pandiselvam *et al.* (2022) reviewed recent advances in NIR spectroscopy for quality and safety assessment and emphasized its capability to estimate mechanical attributes indirectly through changes in water-binding behavior and tissue structure. Thus, firmness prediction largely depends on relationships between water structure, cell wall degradation, and the corresponding spectral responses.

Dry matter

Dry matter is widely recognized as a reliable indicator of maturity in fruits such as mango and avocado. Chaudhary *et al.* (2025) conducted a systematic review on mango quality assessment using NIR and hyperspectral imaging techniques and reported accurate predictions of dry matter and total soluble solids. Earlier work by Lin and Ying (2009) documented the application of NIR spectroscopy for monitoring starch degradation in apples, highlighting its usefulness for tracking internal compositional changes during fruit development and ripening. In many cases, dry matter estimation relies on longer NIR wavelengths, typically within the 1100–2200 nm range, where absorption features related to organic compounds are more pronounced.

Detection of Physiological Disorders

Vis–NIRS has demonstrated considerable potential for detecting various internal and external disorders in fruits, including browning, rind pitting, chilling injury, and bruising. Ncama *et al.* (2018) showed that reflectance Vis/NIR spectroscopy could be used as a non-destructive tool to predict grapefruit rind pitting with good accuracy. Similarly, Magwaza *et al.* (2014) applied Vis/NIRS combined with chemometric analysis to evaluate and predict the postharvest behavior of mandarin fruit. One of the key advantages of NIR spectroscopy is its ability to penetrate fruit tissues, allowing the detection of subsurface disorders that may not be visible externally. Adedeji *et al.* (2020) reviewed several non-destructive technologies for identifying insect infestation in fruits and vegetables and highlighted NIR spectroscopy as an effective approach for detecting internal damage. Furthermore, Si *et al.* (2022) discussed the application of spatially resolved spectroscopy for internal defect detection, noting that this technique improves light penetration depth and enhances classification accuracy.

Shelf-Life Monitoring and Postharvest Decision Support

Walsh *et al.* (2020) highlighted the important role of NIRS in packhouse decision-making processes, particularly in areas such as storage allocation and fruit grading. By providing rapid and non-destructive measurements, NIRS supports more informed decisions during postharvest handling and sorting operations. Aline *et al.* (2023) reviewed spectral measurement techniques used for tropical fruits and identified Vis–NIRS as a key tool for dynamic quality monitoring throughout storage. These applications help improve postharvest management, contributing to reduced losses and more efficient logistics across the supply chain.

Hyperspectral and Imaging-Based NIR Systems

Hyperspectral imaging (HSI) extends NIRS by combining spectral and spatial data. Chandrasekaran *et al.* (2019) reviewed the potential of NIR spectroscopy and hyperspectral imaging for fruit quality and safety assessment. Xie *et al.* (2016) reviewed NIR systems for fruit quality evaluation, highlighting on-line monitoring applications. Beghi *et al.* (2017) reviewed electronic nose and Vis–NIR spectroscopy for fruit and vegetable monitoring. HSI allows pixel-level defect detection and automated grading.

Instrumentation in Postharvest NIR Applications

Common Vis–NIRS systems include benchtop FT-NIR spectrometers; portable diode-array spectrometer, fiber-optic interactance probes system, conveyor-based industrial sorting systems, hyperspectral imaging cameras. Measurement geometries are reflectance, transmittance and interactance. Interactance mode improves internal attribute detection (Magwaza *et al.*, 2012).

Chemometrics and Data Processing

Due to overlapping absorption bands, Vis–NIRS requires multivariate analysis techniques: Principal Component Analysis (PCA); Partial Least Squares Regression (PLSR); Support Vector Machines (SVM); Artificial Neural Networks (ANN). Pandiselvam *et al.* (2022) reported that machine learning significantly enhances prediction accuracy and robustness in horticultural applications.

Main Advantages of Vis-NIR Spectroscopy in postharvest management are non-destructive and rapid sampling, minimal sample preparation, multi-attribute prediction, suitable for intact produce, potential for real-time monitoring; sensitive to pigment-related ripening indicators, suitable for on-line and in-field assessment and portable and handheld instruments available.

Limitations of Vis-NIR Spectroscopy in Postharvest Management are limited strong water absorption effects, sensitivity to surface properties and skin thickness, limited penetration in thick-skinned fruits, requires frequent calibration and Influenced by skin color and temperature, requirement for robust chemometric models, Variability among cultivars and growing conditions, calibration transfer between instruments, need for large calibration datasets. Walsh *et al.* (2020) highlight that model standardization and calibration transfer remain key research priorities.

Future Perspectives

Future research directions included are smartphone-based miniaturized spectrometers, ai-driven grading systems, cloud-based spectral databases, integration with robotics and IoT, advanced hyperspectral imaging systems. Aline *et al.* (2023) suggested that Vis-NIRS will play a central role in smart postharvest management and precision horticulture.

Conclusion

Visible and Near-Infrared Spectroscopy (Vis–NIRS) has emerged as a powerful and reliable non-destructive technique for evaluating the quality of harvested horticultural produce. By integrating the visible region (associated with pigment changes) and the near-infrared region (related to molecular vibrations of chemical constituents), this technology enables rapid and non-invasive assessment of both external and internal quality attributes of fruits and vegetables. As discussed throughout the review, Vis–NIRS has been successfully applied for the prediction and monitoring of important quality parameters such as soluble solids content, firmness, dry matter, maturity, physiological disorders, and shelf-life of horticultural commodities.

Compared with conventional destructive methods, Vis–NIRS offers several clear advantages, including rapid analysis, little or no sample preparation, suitability for intact produce, and the potential for real-time or on-line quality evaluation in packing houses and along supply chains. Recent advances in portable spectrometers, hyperspectral imaging, and chemometric modeling have further strengthened the capabilities of this technology, enabled more accurate prediction of quality attributes and supported automated grading and sorting systems.

Despite these advantages, several challenges still limit the wider adoption of Vis–NIRS in postharvest management. Factors such as strong water absorption, variations in fruit skin characteristics, cultivar differences, environmental influences, and the requirement for robust calibration models and large spectral datasets can affect prediction accuracy.

Overcoming these limitations will require improved calibration transfer methods, the application of advanced machine learning algorithms, and the development of standardized measurement protocols to ensure reliable results across different conditions.

Overall, Vis–NIRS shows strong potential as a key technology in modern postharvest management and precision horticulture. Future developments, including miniaturized spectrometers, artificial intelligence–based prediction models, cloud-based spectral databases, and integration with robotics and Internet of Things (IoT) systems, are expected to further expand its practical applications. With continued technological progress and research efforts, Vis–NIRS can play an important role in reducing postharvest losses, improving quality monitoring, and supporting more sustainable horticultural supply chains.

Competing Interests

The authors declare that they have no competing interests.

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