Unlocking the Invisible: The Power of Hyperspectral Imaging in Food Industries

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ABSTRACT

This article examines the transformative potential of hyperspectral imaging (HSI) in the food industry, particularly for the early detection of fruit decay. Fresh fruits are vulnerable to pathogenic infections, leading to significant economic losses. Traditional laboratory methods for assessing fruit quality are often costly and time-consuming, prompting the adoption of non-destructive techniques like HSI. This review highlights the principles of HSI, including its dual-mode capabilities of reflectance and transmittance imaging, which allow for comprehensive assessments of both external and internal fruit quality attributes. Despite its advantages, challenges such as data processing complexities and hardware limitations persist. Future research should focus on integrating HSI with other non-destructive methods to enhance its effectiveness in detecting decay, contamination, and quality parameters, ultimately benefiting the fruit industry by improving food safety and reducing losses.

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INTRODUCTION

Fresh fruits are essential to the human diet, but they are susceptible to infection by pathogenic microbes or viruses, leading to significant global food losses. Phytopathogenic fungi are particularly dangerous during transportation, storage, and sales stages, as decayed fruits can spread infection to healthy ones nearby. Advanced laboratory-based methodologies, such as mass spectrometry and gas and liquid chromatography, are cost-intensive and time-consuming, limiting their application potential. Recently, non-destructive methods like spectroscopy, hyperspectral imaging, and electronic nose have been implemented to detect decayed fruit (Tian *et al.*, 2021). Hyperspectral imaging, an emerging technology, has been explored for evaluating fruit quality since its first application for surface defect detection in apples.

There is a need for a comprehensive literature review on fruit early decay detection using hyperspectral imaging. This article aims to summarize current applications of hyperspectral imaging technology in detecting decaying fruit, providing fundamentals on hardware settings, data processing pipelines, and algorithms (Liu *et al.*, 2020). Early detection is crucial to prevent huge economic losses to the fruit industry, making hyperspectral imaging a valuable tool for real-world applications.

Hyperspectral Imaging Configurations

Hyperspectral imaging, broadly speaking, is a type of spectral imaging technology that integrates imaging and spectroscopy to obtain 3-D data cubes, which contain 2-D spatial and one-dimensional (1-D) spectral information from products. It is closely related to another spectral imaging technology, called multispectral imaging, which also has been used for food quality and safety assessment s (Lodhi *et al.*, 2019).

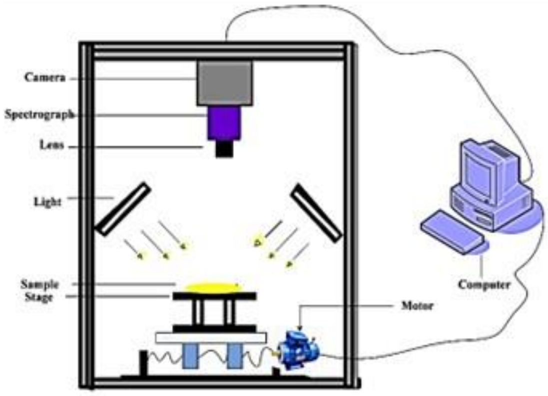
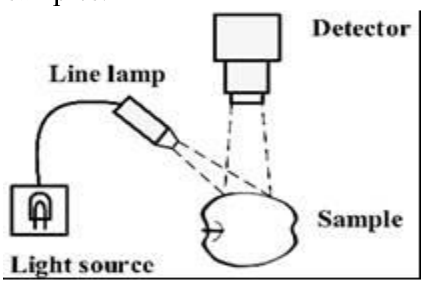


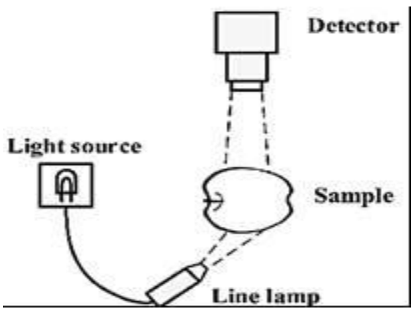
Figure 1. Schematic representation of the hyperspectral imaging system (Wang *et al.*, 2016)

There are three **sensing modes** to assess food quality and safety:

Reflectance: Measures light reflected from the surface, effective for external quality but limited for internal assessment. **Transmittance**: Measures light passing through the product, ideal for internal defects but requires high-intensity light and sensitive detectors. **Interactance**: Balances between reflectance and transmittance, suitable for sublayer property assessment but may not suit small samples.



Reflectance



Transmittance

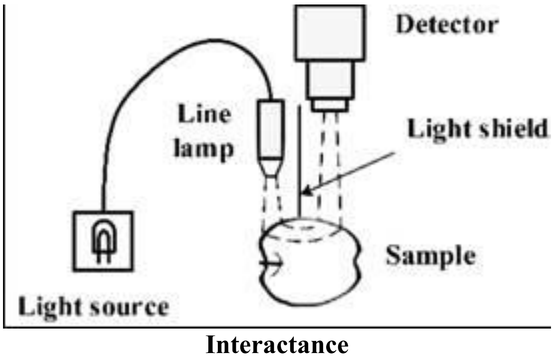


Figure 2. Mechanism of hyperspectral imaging (Lu *et al*, 2017).

Integrated reflectance and transmittance imaging leverages the strengths of both techniques to enable comprehensive assessment of horticultural products. This dual-mode imaging approach facilitates simultaneous analysis of external attributes, such as coloration, size, and surface imperfections, as well as internal features like firmness and subsurface defects. In this system, visible light reflectance imaging is utilized to evaluate surface properties, whereas red to near-infrared (NIR) transmittance imaging penetrates deeper into the tissue, making it possible to detect and quantify internal characteristics (Cen *et al*., 2014).

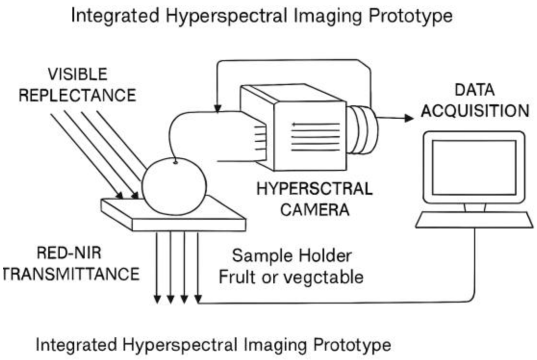


Figure 3. Schematic of an integrated hyperspectral reflectance and transmittance imaging prototype.

Researchers at the USDA Agricultural Research Service (USDA/ARS) in Beltsville, Maryland, have developed an innovative hyperspectral imaging approach that integrates both reflectance and fluorescence techniques to evaluate food quality and safety. This advanced system, designed to work seamlessly with commercial fruit sorting equipment, enables the detection of both fecal contamination and surface imperfections on apples by utilizing measurements from fluorescence and reflectance imaging. Notably, the system features a highly sensitive electron-multiplying CCD (EMCCD) camera to capture low-light images effectively, supporting rapid and reliable inspection in real-time fruit processing environments.

Figure 4. Schematic illustration of hyperspectral reflectance and fluorescence line scan imaging system

The setup employed an electron-multiplying CCD (EMCCD) camera in combination with two distinct light sources: a quartz tungsten-halogen (QTH) lamp and a high-intensity UV-A lamp, which enabled the system to collect both fluorescence and reflectance measurements. A comparable configuration utilized a 408nm diode laser to excite fluorescence, together with a focused QTH beam for reflectance evaluation, to investigate apple maturity indices. Nonetheless, the results from this approach for key parameters-firmness, titratable acidity, and soluble solids content (SSC)-were less satisfactory than those obtained using standard point spectroscopy, as reported by Sun *et al*. (2019).

CONCLUSION

Hyperspectral imaging (HSI) is a promising technology for assessing and ensuring fruit quality by simultaneously measuring and visualizing physicochemical components. While the technique has made significant progress in estimating quality attributes, detecting contaminants, and evaluating maturity stages, challenges such as focusing, scanning parameters, image processing, and data analysis remain. HSI, which combines spectral and spatial information, is effective for early detection of fruit decay but faces obstacles like system hardware limitations, large data files, and complex data processing. Future research should aim to overcome these hurdles, potentially integrating HSI with other nondestructive methods like the electronic nose and lowfield nuclear magnetic resonance. Ultimately, the goal is to achieve simultaneous detection of damages, surface contamination, infections, and quality parameters, making HSI a valuable tool for real-world applications in the fruit industry.

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