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Ranjani M
Research Scholar, Division of Food Science and Postharvest Technology, Indian Agricultural Research Institute, New Delhi, India

Soumiya K
Research Scholar, Department of Fruit Science, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India

Dhanalakshmi S
Research Scholar, Department of Fruit Science, College of Horticulture and Forestry, Central Agricultural University, Pasighat, Arunachal Pradesh, India

Ajay Narola
Research Scholar, Division of Food Science and Postharvest Technology, Indian Agricultural Research Institute, New Delhi, India

Corresponding Author:
Ranjani M
Research Scholar, Division of Food Science and Postharvest Technology, Indian Agricultural Research Institute, New Delhi, India

Advances in non-destructive techniques for fruit quality assessment: A comprehensive review

Ranjani M, Soumiya K, Dhanalakshmi S and Ajay Narola

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Abstract
In postharvest agriculture, non-destructive techniques are reshaping the venture of fruit quality assessment. We delve into the applications of Computer Vision Systems (CVSs), Electronic Nose (E-nose) technology, Near-Infrared Spectroscopy (NIR), Magnetic Resonance Imaging (MRI), and Acoustic Techniques. CVSs utilize digital cameras and algorithms to assess colour, texture, and defects, ensuring objective and consistent food control. E-noses, with their ability to detect volatile compounds, determine ripening stages, assess geographical origins, and evaluate freshness, offer invaluable insights into fruit quality. NIR spectroscopy provides rapid and non-invasive internal quality analysis, enabling precise predictions of sugar content and facilitating real-time quality control. MRI, although promising, faces challenges in cost and system size. Additionally, acoustic techniques, particularly ultrasound and Acoustic Emission (AE), have shown potential in early insect infestation detection. This review underscores the remarkable progress and challenges in these non-destructive techniques, paving the way for enhanced fruit quality evaluation and reduced food waste.

Keywords: Computer Vision Systems (CVSs), Magnetic Resonance Imaging (MRI), Acoustic Emission (AE)

Introduction

Approximately over 30% of food and agricultural produce are estimated to be wasted during pre and postharvest stages. However, these losses are avoided if the harvesting period, ripeness, and quality factors are properly evaluated throughout the shelf life. Recent efforts have concentrated on non-destructive technologies for evaluating fruit quality characteristics Cakmak, (2019) [2]. The demand for effective, non-destructive techniques to evaluate the quality of fruits has driven advancements in technology. Among these, Computer Vision Systems (CVSs) have emerged as contactless tools, utilizing digital cameras and algorithms to objectively evaluate colour, texture, and defects in fruits. Concurrently, Electronic Nose (E-nose) technology offers a unique olfactory approach, detecting volatile organic compounds to determine ripening stages, geographical origins, and freshness. Near-infrared spectroscopy (NIR) provides rapid internal quality analysis, enabling predictions of sugar content and facilitating real-time quality control. Despite their potential, challenges persist, particularly in costly Magnetic Resonance Imaging (MRI) systems. Acoustic techniques, including ultrasound and Acoustic Emission (AE), have showcased promising applications in insect infestation detection. This review explores the diverse applications, benefits, and challenges of these non-destructive techniques, providing a comprehensive overview of their roles in modern fruit quality assessment.

Image Analysis through a Computer Vision System

Computer vision systems (CVSs) have emerged as innovative, contactless, and non-destructive technologies for the in-line grading of fruits. These systems utilize digital cameras, illumination setups, and computer algorithms to assess the visual quality of fruits. By extracting relevant visual information related to colour, texture, and defects, CVSs can classify, grade, and assess the quality of fruits. The benefits of CVS technology include objective and consistent food control, reduction in losses and waste, and increased consumer satisfaction. (Fan *et al*., 2020) [4].

Applications of CVS in Fruit Quality Monitoring

1. Color Assessment: CVS technology accurately estimates colour properties at the pixel level, providing more objective evaluations compared to standard colourimeters. For instance, CVS has been applied to assess the quality of rocket leaves and discriminate cultivation approaches. The technology achieved high accuracy in quality-level assessment and cultivation approach discrimination using advanced algorithms.

2. Fresh-cut fruits: CVS plays a crucial role in monitoring fresh-cut fruit quality, reducing food waste, and ensuring freshness in the market. It has been successfully applied in assessing various fresh-cut products like nectarines (Pace *et al*., 2011) [7], and apples (Fan *et al*., 2020) [4].

3. Internal Quality Evaluation: CVS is not limited to external appearance; it can also evaluate the inner quality of horticultural products. By analysing colour changes, CVS can estimate properties like antioxidant activity, total phenols, fruit acidity, and enzymatic activities (polyphenol oxidase and peroxidase) during storage.

4. pH and Chemical Traits Prediction: CVS methods have been developed to predict the pH values of fruits like oranges, enabling rapid and non-destructive assessment. Additionally, CVS, combined with regression models, has correlated image data to chemical traits such as total soluble solids and pH in strawberries. (Sabzi *et al*., 2020) [10].

5. Smartphone-Based Analysis: Innovative applications involve using smartphones for image analysis. For example, the RGB (Red, Green and Blue) values obtained from smartphone photos of kiwifruits were correlated with their quality parameters, providing a rapid evaluation method for postharvest quality (Li *et al*., 2022) [6].

Magnetic Resonance Imaging (MRI)

MRI is a non-ionizing imaging method that has found applications in the medical field. Unlike X-rays or computed tomography (CT) scans, MRI utilizes strong and uniform magnetic fields applied to hydrogen nuclei, primarily found in water, to generate high-resolution images. These images are produced based on the varying contrast levels of object tissues in response to the magnetic field and radio frequency waves. In the context of food quality monitoring, the application of MRI has been limited due to the high cost associated with MRI systems. Researchers have explored low-field MRI systems to detect issues such as fruit fly infestation in peaches and the presence of peach fruit moths on apple fruits. Despite its potential for non-invasive fruit and vegetable defect determination, challenges such as high costs, large size, and weight of MRI systems remain, hindering its widespread use.

E-nose (Electronic Nose)

E-nose technology mimics human olfactory perception and is equipped with electronic sensors to detect volatile organic compounds (VOCs). These sensors generate a digital VOC fingerprint that, when processed with suitable statistical tools, can provide insights into fruit quality, safety, and ripeness. E-noses are cost-effective, easy to use, and non-destructive, making them valuable tools for fruit quality assessment. (Qiao *et al*., 2022) [9].

Applications of E-nose in Fruit Quality Assessment

1. Ripening Stage Determination: E-nose technology, coupled with pattern recognition methods, has been used to determine the ripening stage of fruits like strawberries (Cozzolino *et al*., 2021) [3] and crab apples (Qiao *et al*., 2022) [9]. By analyzing aroma patterns, E-noses can distinguish between naturally and artificially ripe fruits, aiding in quality evaluation.

2. Geographical Origin Detection: E-noses, combined with chemometric strategies, are effective in classifying fruits based on their geographical origin. By analyzing volatile and odour fingerprints, E-noses can predict the geographical provenance of fruits like maca (Li *et al*., 2019) [5], providing valuable information for authentication purposes.

3. Freshness Evaluation: E-noses have been applied to assess the freshness of fruits stored in different packaging materials. By analyzing headspace profiles, E-noses can distinguish between unpackaged and packaged samples, providing insights into the effects of packaging on fruit freshness.

4. Multisensory Data Fusion: Combining data from E-noses and machine vision systems enhances the accuracy of freshness evaluation. Multisensory data fusion allows for precise classification of fruit freshness, providing valuable information for quality control during storage.

E-tongues

E-tongues an analytical instrument, offers innovative approach to assessing quality of fruits. On the other hand, e-tongue technique was developed about 20 years after e-nose technology (Sai Xu *et al*., 2018) [11]. The system of operation for e-tongue is similar to e-nose in that it is an artificial intelligence technology that detects flavour tastes using electronic sensors designed to replicate human taste perception. These devices transform molecular information from food items into visual patterns representing taste qualities. E-tongues operate based on various sensor types, including electrochemical, enzymatic, optical, and mass interaction sensors. Potentiometric E-tongues, employing ion-selective electrodes, are widely used due to their cost efficiency and high selectivity. Voltametric sensors are valuable for measuring redox-active constituents, but they face challenges related to temperature fluctuations and surface degradation. Impedimetric E-tongues eliminate the need for a standard reference electrode and offer specific chemosensitivity. Optical sensors, which operate through absorbance, fluorescence, and reflectance mechanisms, enable the examination of samples that are not discernible by electrochemical sensors. Mass sensors based on piezoelectric effects provide sensitivity, robustness, and quick response read-outs. Despite challenges such as memory effects and cross-contamination, E-tongues have shown promise in various applications, including the analysis of fruit juices and soft drinks.

In fruit juice analysis, researchers have employed voltametric E-tongues with poly (3, 4-ethylenedioxythiophene) based electrodes to differentiate between juices from the same fruit sourced from various brands. Additionally, E-tongues have been utilized to assess the impact of different processing methods on the quality parameters of strawberry juice.

Near-Infrared Spectroscopy (NIR)

NIR spectroscopy is a rapid and non-destructive technique used to analyze the chemical composition of fruits. NIR spectra provide valuable information about internal quality indices such as solid soluble content, firmness, dry matter, and internal injuries. NIR spectroscopy, including Fourier transform infrared spectroscopy (FTIR), offers high sensitivity and resolution, making it a powerful tool for fruit quality assessment.

Applications of NIR Spectroscopy in Fruit Quality Monitoring

1. Internal Quality Analysis: NIR spectroscopy is used to measure internal quality indices such as solid soluble content, density, and flesh colour in fruits like citrus and kiwifruit. By analyzing NIR spectra, models can predict sugar content, allowing for rapid and non-invasive assessment of fruit maturity.

2. Quality Profiling: NIR spectroscopy, especially in FTIR mode, is employed to discriminate fruits based on their quality attributes.

3. Real-time Quality Control: NIR spectroscopy serves as a real-time quality control tool in the food industry. By rapidly analyzing samples, it aids in assessing the chemical composition of fruits, ensuring product quality, and facilitating timely decisions in the production process.

Acoustic techniques

Acoustic technique a subset of acoustics, involves the study of sound propagation through mechanical waves in an elastic medium, causing particle displacement and vibration. In agricultural product processing, ultrasound is a widely used acoustic technique. Specifically, in detecting insect infestations, unique sounds produced by larvae during feeding or biochemical reactions in pest-infested food can be monitored. Another area of acoustics, Acoustic Emission (AE), involves detecting physical signals from materials undergoing internal changes. AE has been applied to evaluate food quality attributes like watermelon firmness and bread classification, but its use in detecting insect activity has been limited. Recent studies, however, have demonstrated promising applications in insect detection. For example, AE successfully detected codling moth activities in infested apples, achieving a high classification rate. Additionally, researchers correlated visually observed larval activities, such as chewing and movement, with synchronized signals from contact Lead zirconate titanate (PZT) sensors. These efforts demonstrated a strong correlation between vibro-acoustic signal patterns and larvae activities within apple fruits. (Adedeji *et al*., 2020) [1].

Conclusion: The integration of non-destructive techniques like Computer Vision Systems, Electronic Nose technology, Near-Infrared Spectroscopy, Magnetic Resonance Imaging, and Acoustic Techniques marks a significant stride in fruit quality assessment. These technologies enable objective, consistent, and contactless evaluations, reducing food waste and ensuring consumer satisfaction. While each method brings unique advantages, challenges such as cost, system size, and technique integration persist. Future research efforts should focus on addressing these challenges to unlock the full potential of non-destructive techniques, thereby reshaping the landscape of fruit quality assessment and enhancing the sustainability of the agricultural industry.

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