Biosensors for Non-Destructive Fruit Quality Assessment: A Comprehensive Review of Principles and Applications in Green Horticulture

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Abstract— Biosensors are analytical devices that combine a biological sensing element (enzymes, antibodies, microorganisms, DNA, or plant tissues) with a physical transducer to detect and measure specific substances (analytes) in fruits. This interaction produces a measurable biological response that the transducer converts into an electrical, optical, or thermal signal. Valued for assessing fruit quality, biosensors enable rapid, real-time, and non-destructive testing, overcoming the time-consuming, destructive nature of traditional laboratory analysis. An effective biosensor exhibits high selectivity (detecting only the target in complex tissues), sensitivity (detecting trace compounds), quick response, linearity, reproducibility, and stability.

Different biosensor types operate on distinct sensing principles. Electrochemical biosensors measure electrical signals from biochemical reactions, offering low cost and fast response. Optical biosensors detect changes in light (absorption, fluorescence) for color and biochemical analysis. Calorimetric biosensors measure minute heat changes from reactions, while piezoelectric/acoustic sensors detect mass-based vibrations on crystal surfaces. Potentiometric biosensors measure voltage changes for ion detection (e.g., pH), and amperometric biosensors measure current changes for detecting pesticides and sugars.

In fruit quality assessment, advanced biosensing technologies are widely applied. Optical sensors like Near-Infrared Spectroscopy (NIRS), hyperspectral imaging, and visible light imaging monitor ripeness, defects, sugar levels, and maturity by analyzing light absorption/reflection. Electromagnetic technologies such as Nuclear Magnetic Resonance (NMR) and Terahertz sensing reveal internal structures, moisture, and residues non-destructively. Acoustic/ultrasonic sensors use wave propagation to determine firmness and internal defects. Electronic nose (E-nose) systems detect volatile compounds to assess aroma, freshness, and spoilage. Dielectric property sensors measure electrical permittivity to assess internal quality and moisture content. This review comprehensively details the principles, types, and integrated applications of these biosensors for non-destructive fruit quality monitoring in green horticulture.

Keywords— Fruit quality; biosensors; non-destructive sensing; NIR spectroscopy; hyperspectral imaging; dielectric sensing; E-nose; firmness; SSC; VOCs; postharvest monitoring.

I. INTRODUCTION

Biosensors are advanced analytical tools that combine biological sensing elements—such as enzymes, antibodies, or microorganisms—with physicochemical transducers to detect specific analytes. These devices translate biological interactions into measurable signals like electrical current, light intensity, or heat changes, offering rapid, sensitive and selective detection. Originally developed for medical diagnostics, biosensors have found expanding applications in agriculture, food safety, and environmental monitoring due to their portability, cost-effectiveness and real-time capabilities.

In the horticultural sector, biosensors are revolutionizing fruit quality assessment by enabling non-destructive, precise and continuous monitoring of key parameters. Traditional methods for evaluating fruit quality—such as chemical assays or manual inspection—are often time-consuming, labour-intensive, and destructive. Biosensors overcome these limitations by providing

instant feedback on attributes like ripeness, sweetness, acidity, firmness, aroma and nutritional content. This empowers farmers, processors, and retailers to make informed decisions about harvest timing, storage conditions and market readiness.

Fruit quality is a multifaceted concept involving physical appearance, internal composition, taste and shelf life. Biosensors can detect chemical markers such as glucose, ethylene, citric acid and polyphenols, which correlate with ripeness, flavour and antioxidant levels. Mechanical sensors assess firmness and texture, while optical and electronic nose technologies evaluate colour, aroma and spoilage. These insights are crucial for maintaining consumer satisfaction, reducing post-harvest losses and ensuring food safety across the supply chain.

As biosensor technology evolves, integration with IoT and AI systems is paving the way for smart farming solutions. Portable and wireless biosensors can transmit real-time data to cloud platforms, enabling predictive analytics and automated decision-making. This not only enhances productivity and sustainability but also supports traceability and compliance with quality standards. This review provides a comprehensive analysis of biosensor principles, types, and integrated sensing technologies for fruit quality assessment, concluding with future perspectives on their role in precision horticulture.

II.   FUNDAMENTALS F BIOSENSORS FOR HORTICULTURE

2.1   Mechanism of Biosensors:

The mechanism of a biosensor is a multi-step process that begins with the biological recognition element, which serves as the heart of the device. This component is carefully selected based on its ability to interact specifically and selectively with the target analyte—such as glucose, ethylene, citric acid, or pesticide molecules. Depending on the biosensor type, this interaction may involve enzymatic catalysis, antibody-antigen binding, nucleic acid hybridization, or microbial metabolism. For example, in an enzyme-based biosensor, the enzyme catalyzes a reaction with the analyte, producing a product that can be detected. In immunosensors, antibodies bind to specific antigens, triggering a measurable change. These biological interactions are highly specific, ensuring that the biosensor responds only to the intended substance even in complex mixtures like fruit pulp or juice.

Once the biological interaction occurs, the transducer plays a critical role in converting the biochemical event into a physical signal. This signal can take various forms depending on the transduction method used. Electrochemical transducers measure changes in current, voltage or impedance resulting from the reaction. Optical transducers detect variations in light absorption, fluorescence, or refractive index. Calorimetric transducers monitor heat changes during exothermic or endothermic reactions, while piezoelectric transducers sense mass changes through shifts in vibration frequency. Each transduction method offers unique advantages in terms of sensitivity, speed, and suitability for different analytes. For instance, amperometric sensors are ideal for detecting small molecules like glucose or ascorbic acid, while piezoelectric sensors excel in measuring physical changes such as fruit firmness.

The final stage involves signal processing and output display, where the raw signal is amplified, filtered, and translated into a readable format—such as a digital value, graph or alert. This enables real-time monitoring and decision-making, which is especially valuable in agricultural settings. In fruit quality assessment, biosensors can be integrated into handheld devices or smart packaging systems to continuously track ripeness, freshness and contamination. The ability to detect multiple analytes simultaneously—such as sugars, acids and VOCs—makes biosensors indispensable for holistic quality evaluation.

2.2   Essential Characteristics of Biosensors:

Biosensors have emerged as transformative tools in horticulture, offering a rapid, non-destructive, and highly specific means of evaluating fruit quality. Their performance in such applications is governed by six fundamental characteristics: selectivity, sensitivity, linearity, response time, reproducibility, and stability. Each of these parameters plays a critical role in determining the biosensor's suitability for real-world agricultural environments, where biological complexity, environmental variability, and the need for real-time decision-making converge.

1) **Selectivity** is perhaps the most crucial attribute in fruit quality monitoring, as it defines the biosensor's ability to detect a specific analyte in the presence of numerous potentially interfering substances. Fruits are biochemically rich matrices containing sugars, acids, pigments, and volatile compounds. A highly selective biosensor ensures that, for example, glucose is accurately detected without interference from fructose or sucrose—essential for assessing ripeness in mangoes or bananas. Similarly, ethylene sensors must distinguish this ripening hormone from other VOCs released during respiration or microbial activity. High selectivity underpins the reliability of biosensor data, enabling precise grading, sorting, and harvest timing.

2) **Sensitivity** refers to the biosensor's capacity to detect minute concentrations of an analyte, often at nanomolar or even picomolar levels. This is particularly important in early-stage detection of spoilage, nutrient degradation, or contamination. For instance, amperometric biosensors used to monitor ascorbic acid (Vitamin C) in citrus fruits must detect subtle declines that signal loss of nutritional value. Likewise, electrochemical sensors designed to detect pesticide residues—such as organophosphates on apple skin—must operate at extremely low detection limits to ensure food safety. High sensitivity allows for proactive interventions, reducing post-harvest losses and enhancing consumer protection.

3) **Linearity** ensures that the biosensor's output signal maintains a direct, proportional relationship with the analyte concentration across a defined range. This characteristic is vital for quantitative analysis, particularly in automated systems used for fruit sorting and grading. For example, pH sensors used to monitor acidity in grapes must provide a linear response to varying concentrations of citric and malic acids throughout the ripening process. A linear response curve enables accurate calibration, simplifies data interpretation, and supports integration with digital platforms for real-time quality control.

4) **Response Time** is a critical operational parameter, especially in dynamic agricultural settings. It defines how quickly a biosensor can generate a stable and measurable signal after exposure to the analyte, typically measured as the time to reach 95% of the final signal. In fruit quality assessment, rapid response is essential for on-the-spot decisions during harvest, transport, or storage. For example, a biosensor used to evaluate firmness or sugar content in mangoes must deliver results within seconds to be practical in field conditions. Fast response times enhance workflow efficiency and reduce the risk of spoilage due to delays in handling.

5) **Reproducibility** reflects the biosensor's ability to deliver consistent results across repeated measurements of the same sample. This is particularly important in quality assurance protocols where uniformity across batches and locations is essential. A biosensor used to assess the ripeness of apples, for instance, must yield consistent glucose readings regardless of operator, device, or environmental conditions. High reproducibility builds confidence in biosensor data, facilitates regulatory compliance, and supports standardization in fruit grading systems.

6) **Stability** refers to the biosensor's ability to maintain its performance over time, resisting degradation due to environmental stressors such as temperature fluctuations, humidity, and exposure to organic compounds. In agricultural applications, biosensors may be deployed in open fields, cold storage units, or transport containers. A stable biosensor ensures long-term reliability without frequent recalibration or replacement. For example, a banana peel-based biosensor designed to detect phenolic compounds in fruit juices must retain enzymatic activity over several days to be viable for commercial use. Stability also influences the shelf life and cost-effectiveness of biosensor-based systems (Theavenot et al., 2001).

III. CLASSIFICATION AND PRINCIPLES OF MAJOR BIOSENSOR TYPES

3.1 Electrochemical Biosensors:

Definition: Electrochemical biosensors are highly sensitive analytical devices designed to detect specific biological or chemical compounds by converting biochemical events into electrical signals that can be measured and quantified. These biosensors consist of two primary components: (1) a biorecognition element—enzyme, antibody, nucleic acid (DNA/RNA), or aptamer—that selectively interacts with the fruit analyte and (2) an electrochemical transducer that converts this biochemical interaction into electrical output.

Types: Electrochemical biosensors used in fruit quality sensing can be classified based on the type of electrical signal they generate:

- **Amperometric biosensors** measure current produced from oxidation or reduction reactions.

- **Potentiometric biosensors** measure changes in electric potential (voltage).

- **Conductometric biosensors** measure changes in electrical resistance or conductivity.

- **Voltammetric biosensors** record current as the voltage is swept across a range.

Working Principle: The operating mechanism begins with a specific molecular interaction between the biorecognition element and the analyte present in the fruit. When the analyte binds to the recognition element on the electrode surface, a biochemical reaction—often involving oxidation or reduction—occurs, resulting in electron transfer. These electrons are captured by the electrochemical transducer, producing a measurable electrical signal whose magnitude correlates directly with analyte concentration (Naresh and Lee, 2021).

Applications in Fruit Quality: Amperometric glucose biosensors track sugar accumulation during ripening in apples, mangoes and bananas. Potentiometric pH biosensors evaluate acidity changes in grapes and citrus fruits. Voltammetric sensors quantify antioxidant compounds like polyphenols and vitamin C. Conductometric biosensors detect spoilage-related metabolites such as ethanol and CO_2. Gas-phase electrochemical sensors detect ethylene release for shelf-life prediction (Liu et al., 2025).

3.2   Optical Biosensors:

Definition: Optical biosensors are analytical devices that detect biological interactions by monitoring changes in light-based properties such as fluorescence, absorbance, chemiluminescence or refractive index resulting from the interaction between a target analyte and a biorecognition element.

Types:

- **Fluorescence biosensors** detect changes in natural or induced fluorescence.

- **Chemiluminescence biosensors** measure light emission generated during biochemical reactions.

- **Surface Plasmon Resonance (SPR) biosensors** measure shifts in refractive index.

- **Optical fiber sensors** transmit optical signals through fiber cables.

Working Principle: When an analyte binds to the sensing surface, the resulting biochemical interaction alters optical characteristics (fluorescence emission, light absorption, refractive index, or light scattering). The transducer converts these optical variations into electrical signals that correlate directly with the analyte concentration (Estevez et al., 2022).

Applications: Fluorescence-based sensors detect chlorophyll degradation to determine maturity in mangoes and tomatoes. Chemiluminescence sensors quantify antioxidants in citrus and berries. SPR-based sensors detect ethylene gas emission to predict ripening stages. Optical fiber sensors monitor volatile organic compounds (VOCs) to identify early spoilage during storage (Burcu et al., 2023).

3.3   Electronic Biosensors (FET-based):

Definition: Electronic biosensors, particularly those built on Field-Effect Transistor (FET) platforms, are advanced analytical devices that monitor biological or chemical analytes by measuring changes in electrical conductivity across a semiconductor channel.

Types:

- **Ion-Sensitive Field Effect Transistors (ISFETs)** detect ions such as hydrogen ions (H^+).

- **Metal-Oxide Semiconductor FETs (MOSFETs)** incorporate metal-oxide nanomaterials.

- **Organic FETs (OFETs)** utilize conductive polymers.

- **Nanowire or graphene-FET biosensors** enable detection of VOCs and ethylene gas.

Working Principle: When analytes such as glucose or ethylene interact with immobilized enzymes or aptamers, charge accumulation or depletion occurs at the gate-electrolyte interface. This alters the electric field and changes the conductivity of the semiconductor channel between the source and drain (Mishra, Srivastava and Ramnani, 2022).

Applications: ISFET sensors measure pH in grape and citrus juice. MOSFET and nanomaterial-enhanced FETs detect glucose and phenolic compounds. Graphene-FET sensors detect trace levels of ethylene and VOCs for spoilage prediction (Zhang et al., 2024).

3.4   Colorimetric Biosensors:

Definition: Colorimetric biosensors are analytical devices that detect specific biological or chemical substances by producing a visible colour change as a result of biochemical interactions between the target analyte and an immobilized biorecognition element.

Types:

- **Enzymatic colorimetric biosensors** utilize enzymes such as glucose oxidase.

- **Nanoparticle-based biosensors** use gold (AuNPs) or silver nanoparticles (AgNPs).

- **pH-sensitive colorimetric biosensors** use dyes or natural pigments.

Working Principle: The fruit analyte interacts with a biorecognition layer, initiating a catalytic or binding event that causes a colour change. For enzymatic sensors, enzymes oxidize the analyte, generating H_2O_2 which reacts with a chromogenic substrate. In nanoparticle-based sensors, target molecules induce aggregation or dispersion of nanoparticles, creating visible optical shifts (Zhang et al., 2024).

Applications: GOx-based colorimetric strips monitor ripening in mangoes, bananas, and apples. PPO-based sensors detect phenolic compounds in grapes and berries. Nanoparticle-based sensors detect spoilage gases in smart packaging. pH sensors provide real-time visual alerts of fruit spoilage (Soni and Pandey, 2021).

3.5   Acoustic and Piezoelectric Biosensors:

Definition: Acoustic biosensors assess fruit quality by detecting changes in acoustic wave properties such as frequency, amplitude, or phase in response to biochemical or physical interactions on the sensor surface.

Types:

- **Bulk Acoustic Wave (BAW) biosensors** transmit waves through the entire substrate.

- **Surface Acoustic Wave (SAW) biosensors** propagate waves along the surface.

- **Quartz Crystal Microbalance (QCM)** detects mass changes on quartz crystal surface.

Working Principle: When fruit-derived molecules interact with the biorecognition surface, mass and viscoelastic properties change, altering frequency, velocity, and amplitude of acoustic waves. The magnitude of shift is proportional to the amount of analyte (Singh et al., 2023).

Applications: Detect firmness, internal texture, ripeness stage, and mechanical or microbial damage. SAW-based devices detect ethylene and VOC emissions for ripening prediction. Used in automated sorting and grading systems (Kaur and Kundu, 2024).

IV.   ASSOCIATED SENSING TECHNOLOGIES FOR HOLISTIC QUALITY ASSESSMENT

4.1   Optical & Spectroscopic Techniques:

4.1.1   Near-Infrared Spectroscopy (NIRS):

Definition: Non-destructive technique measuring interaction of near-infrared light (780–2500 nm) with fruit tissues to determine internal biochemical composition.

Working Principle: NIR light interacts with fruit tissue; molecular bonds absorb energy at characteristic wavelengths. Detector captures reflected light spectrum representing biochemical properties.

Applications: Determine soluble solid content (SSC), titratable acidity (TA), ripeness, internal defects. Portable devices enable real-time quality grading (Cozzolino, 2016).

4.1.2   Hyperspectral Imaging (HSI):

Definition: Integrates imaging with spectroscopy to capture both spatial and spectral information (400-2500 nm).

Working Principle: Captures hundreds of narrow wavelength bands forming a hypercube. Machine learning algorithms extract features to predict quality parameters.

Applications: Quantify vitamin C, sugar content, organic acids. Detect early decay, mechanical damage, pest infestation (Xiang et al., 2022).

4.1.3   Visible Light Imaging:

Definition: Image-based sensing using visible spectrum (400–700 nm) cameras.

Working Principle: Captures surface attributes (shape, size, colour, texture). Computer vision and deep learning analyze images for quality assessment.

Applications: Classify fruit maturity, detect defects and diseases, automated sorting and grading (Cheng, Yu and Ying, 2021).

4.2   Electromagnetic & Imaging Techniques:

4.2.1   Nuclear Magnetic Resonance (NMR):

Definition: Measures magnetic behaviour of atomic nuclei in external magnetic field.

Working Principle: Nuclei emit resonance signals converted to spectra providing composition and structural information.

Applications: Quantify metabolites (sugars, acids, antioxidants), detect bruises, rot, tissue degradation (Wang et al., 2018).

4.2.2   Terahertz Imaging:

Definition: Uses electromagnetic waves (0.1–10 THz) between microwave and infrared regions.

Working Principle: THz waves interact with water, sugars, organic compounds; absorption/transmission changes reveal quality parameters.

Applications: Monitor moisture, sugar levels, pesticide residues, internal bruising (Chen et al., 2018).

4.3   Acoustic & Vibroacoustic Techniques:

4.3.1   Ultrasonic Sensors:

Definition: Uses high-frequency acoustic waves (20 kHz to 500 MHz) to evaluate internal quality.

Working Principle: Wave propagation affected by firmness, moisture, cellular structure. Velocity and attenuation changes indicate quality.

Applications: Assess firmness, maturity, detect internal defects and pest infestation (Mizrach et al., 2008).

4.3.2   Vibration Analysis:

Definition: Analyzes acoustic/vibrational responses to mechanical excitation.

Working Principle: Measures frequency, amplitude, attenuation correlated with firmness, elasticity, internal structure. **Applications:** Evaluate hardness, texture, ripeness, classify maturity stages (Chen et al., 2018).

4.4   Gas & Volatile Sensing:

4.4.1   Electronic Nose (E-nose):

Definition: Biomimetic olfactory system detecting volatile organic compounds (VOCs).

Working Principle: Sensor array interacts with VOCs, generating electrical signals analyzed by pattern recognition algorithms.

Applications: Ripeness monitoring, aroma profiling, spoilage detection, disease identification (Guo et al., 2022).

4.5 Electrical Property Sensing:

4.5.1 Dielectric Property Sensors:

Definition: Evaluates interaction of fruit tissues with electromagnetic fields.

Working Principle: Measures complex dielectric constant (storage and loss) sensitive to moisture, sugars, tissue structure.

Applications: Monitor ripening, postharvest deterioration, disease detection, physical damage assessment (Nelson & Trabelsi, 2022).

V. INTEGRATED APPLICATIONS IN FRUIT QUALITY MONITORING

TABLE 1
BIOSENSOR APPLICATIONS IN FRUIT QUALITY MONITORING

Application	What It Measures	Sensor Types	Example Use
Ripeness/Maturity	Sugars, acids, pigments, VOCs, firmness	Electrochemical, Optical, E-nose, Acoustic	Harvest timing, sorting ripe/unripe fruits
Sweetness (SSC)	Sugar concentration (°Brix)	Enzyme-based, Dielectric, NIR	Grading grapes, apples, mangoes
Acidity & Taste Balance	Sugar-acid ratio, pH	pH sensors, Ion-selective, Electrochemical	Citrus harvest, flavour grading
Firmness/Texture	Internal structure, bruising	Acoustic, Piezoelectric	Sorting apples, detecting melon damage
Aroma/VOCs	Volatile compounds	E-nose, GC-MS	Ripening stage, spoilage detection
Browning/Oxidation	Phenolic oxidation	Enzyme-based, Optical, Electrochemical	Shelf-life prediction for cut fruits
Ethylene/Gas Monitoring	Ripening gases	Gas sensors, E-nose, Optical	Storage control, transit monitoring
Moisture Content	Water status	Dielectric, Impedance, NIR	Drying control, freshness check
Nutritional Compounds	Vitamins, antioxidants	Electrochemical, Optical, Aptamer-based	Health labelling, antioxidant sorting
Residue Detection	Pesticides, chemicals	Immunosensors, Electrochemical	Compliance checks, farm safety

VI. CHALLENGES AND FUTURE PERSPECTIVES

Despite significant advances, several challenges impede widespread commercialization of biosensors in horticulture:

- **Stability and Reliability:** Biosensor performance degrades under field conditions due to temperature fluctuations, humidity, and organic interference.

- **Standardization:** Lack of uniform protocols for calibration, validation, and data interpretation across different platforms.

- **Cost and Scalability:** High production costs of nanomaterial-enhanced and FET-based biosensors limit large-scale deployment.

- **Multiplexing:** Most biosensors detect single analytes; simultaneous multi-analyte detection remains technically challenging.

- **Integration with Farming Practices:** Adapting laboratory prototypes to user-friendly, rugged devices suitable for farmers and supply chain workers.

Future developments should focus on:

- **Nanomaterial Innovation:** Using graphene, CNTs, and metal-organic frameworks to enhance sensitivity, stability, and selectivity.

- **IoT and AI Integration:** Wireless biosensor networks transmitting real-time data to cloud platforms for predictive analytics and automated decision-making.

- **Flexible and Wearable Sensors:** Developing biodegradable, flexible biosensors for direct fruit attachment or smart packaging.

- **Multiplexed Systems:** Lab-on-a-chip devices capable of detecting multiple quality parameters simultaneously.

- **Global Standards:** Establishing international standards for biosensor validation, data sharing, and quality assurance in horticulture.

VII.   CONCLUSION

Biosensors have emerged as transformative tools in fruit quality assessment, offering rapid, non-destructive, and highly specific analysis across the entire horticultural supply chain. By integrating biological recognition elements with advanced transduction mechanisms—electrochemical, optical, electronic, colorimetric, acoustic and potentiometric—these devices enable precise monitoring of key quality indicators such as sugar content, acidity, firmness, aroma, and spoilage markers. Their ability to detect trace analytes like glucose, ethylene and VOCs in real time supports informed decision-making during harvest, postharvest handling, storage and retail.

The evolution from first-generation enzyme electrodes to third-generation nano-enabled FET biosensors reflects a trajectory of increasing sensitivity, miniaturization and integration with smart technologies. Coupled with IoT and AI platforms, biosensors now facilitate automated grading, predictive analytics and traceability, aligning with the goals of precision horticulture and sustainable agriculture.

As biosensor technologies continue to advance, their role in enhancing fruit quality, reducing postharvest losses and ensuring consumer satisfaction will become increasingly central. Future innovations will likely focus on multi-analyte detection, wearable formats and smart packaging systems, further embedding biosensors into the digital transformation of horticultural science. To realize their full potential, collaborative efforts among researchers, engineers, growers, and policymakers are essential to address existing challenges and accelerate the adoption of these eco-friendly smart applications in green horticulture.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Bhalla, N., Jolly, P., Formisano, N., & Estrela, P. (2016). Introduction to biosensors. *Essays in Biochemistry, 60*, 1–8. https://doi.org/10.1042/EBC20150001

[2] Alam, A. U., Rathi, P., Beshai, H., Sarabha, G. K., & Deen, M. J. (2021). Development of a portable point-of-care biosensor system for environmental and biomedical applications. *Sensors, 21*(4), 1509. https://doi.org/10.3390/s21041509

[3] Liu, J., Sun, J., Wang, Y., Liu, X., Zhang, Y., & Fu, H. (2025). Non-destructive detection of fruit quality using integrated sensor technologies. *Foods, 14*(12), 2137. https://doi.org/10.3390/foods14122137

[4] El Khaled, D., Novas, N., Gazquez, J. A., Garcia, R. M., & Manzano-Agugliaro, F. (2015). Fruit and vegetable quality assessment via dielectric sensing. *Sensors, 15*, 15363–15397. https://doi.org/10.3390/s150715363

[5] Liu, G.-S., He, J.-G., Wang, S.-L., Luo, Y., Wang, W., Wu, L.-G., Si, Z.-H., & He, X.-G. (2015). Application of near-infrared hyperspectral imaging for detection of external insect infestations on jujube fruit. *International Journal of Food Properties, 19*(1), 41–52. https://doi.org/10.1080/10942912.2015.1020433

[6] Naresh, V., & Lee, N. (2021). A review on biosensors and recent development of nanostructured materials-enabled biosensors. *Sensors, 21*(4), 1109. https://doi.org/10.3390/s21041109

[7] Rana, J. S., Jindal, J., Beniwal, V., & Chhokar, V. (2010). Utility biosensors for applications in agriculture – A review. *Journal of American Science, 6*(9), 353–375.

[8] Ferrer-Gallego, R., Hernández-Hierro, J. M., Rivas-Gonzalo, J. C., & Escribano-Bailón, M. T. (2013). Evaluation of sensory parameters of grapes using near infrared spectroscopy. *Journal of Food Engineering, 118*, 333–339. https://doi.org/10.1016/j.jfoodeng.2013.04.015

[9] Basile, T., Marsico, A. D., Cardone, M. F., Antonacci, D., & Perniola, R. (2020). FT-NIR analysis of intact table grape berries to understand consumer preference-driving factors. *Foods, 9*(1), 98. https://doi.org/10.3390/foods9010098

[10] Zhao, Y.-X., & Wang, H.-Y. (2005). Application of near infrared reflectance spectroscopy on the feed industry. *Feed Industry, 26*, 37–41.

[11] Park, S., et al. (2024). Application of near-infrared spectroscopy to predict chemical properties in clay-rich soil: A review. *European Journal of Agronomy, 159*, 127228. https://doi.org/10.1016/j.eja.2024.127228

[12] Hossain, M. E., et al. (2024). Near-infrared spectroscopy for analysing livestock diet quality: A systematic review. *Heliyon, 10*, e40016. https://doi.org/10.1016/j.heliyon.2024.e40016

[13] Suran, P. (2024). Use of near-infrared spectrometry in temperate fruit: A review. *Horticultural Science, 51*, 169–188.

[14] Zeng, J., et al. (2021). A review of the discriminant analysis methods for food quality based on near-infrared spectroscopy and pattern recognition. *Molecules, 26*, 749. https://doi.org/10.3390/molecules26030749

[15] Sun, J., Li, Y.-T., Wu, X.-H., Dai, C.-X., & Chen, Y. (2018). SSC prediction of cherry tomatoes based on IRIV-CS-SVR model and near infrared reflectance spectroscopy. *Journal of Food Process Engineering, 41*, e12884. https://doi.org/10.1111/jfpe.12884

[16] Urraca, R., Sanz-Garcia, A., Tardaguila, J., & Diago, M. P. (2016). Estimation of total soluble solids in grape berries using a hand-held NIR spectrometer under field conditions. *Journal of the Science of Food and Agriculture, 96*, 3007–3016.

https://doi.org/10.1002/jsfa.7472

[17] Bai, Y.-H., Xiong, Y.-J., Huang, J.-C., Zhou, J., & Zhang, B.-H. (2019). Accurate prediction of soluble solid content of apples from multiple geographical regions by combining deep learning with spectral fingerprint features. *Postharvest Biology and Technology, 156*, 110943. https://doi.org/10.1016/j.postharvbio.2019.110943

[18] Daniels, A. J., Poblete-Echeverria, C., Opara, U. L., & Nieuwoudt, H. H. (2019). Measuring internal maturity parameters contactless on intact table grape bunches using NIR spectroscopy. *Frontiers in Plant Science, 10*, 1517. https://doi.org/10.3389/fpls.2019.01517

[19] Nelson, S. O. (2006). Dielectric spectroscopy of agricultural products. *Journal of Microwave Power and Electromagnetic Energy, 41*(3), 44–54. https://doi.org/10.1080/08327823.2006.11688544

[20] Mizrach, A. (2000). Ultrasonic technology for fruit quality evaluation. *Journal of Food Engineering, 43*, 123–128.

https://doi.org/10.1016/S0260-8774(99)00112-0

[21] McGlone, V. A., & Kawano, S. (1998). Near infrared spectroscopy for non-destructive quality assessment of fruit and vegetables. *Journal of Near Infrared Spectroscopy, 6*, 301–311. https://doi.org/10.1255/jnirs.141

[22] Lorente, D., Aleixos, N., Gómez-Sanchis, J., Cubero, S., García-Navarrete, P., & Blasco, J. (2012). Recent advances and applications of hyperspectral imaging for fruit and vegetable quality assessment. *Food and Bioprocess Technology, 5*(4), 1121–1142. https://doi.org/10.1007/s11947-011-0724-7

[23] Cubero, S., Aleixos, N., Moltó, E., Gómez-Sanchis, J., & Blasco, J. (2011). Machine vision systems for quality inspection of fruits and vegetables. *Food and Bioprocess Technology, 4*(4), 487–504. https://doi.org/10.1007/s11947-010-0415-8

[24] Mizrach, A. (2000). Ultrasonic technology for fruit quality evaluation. *Journal of Food Engineering, 43*, 123–128.

https://doi.org/10.1016/S0260-8774(99)00112-0

[25] Singh, R., Sharma, P., & Aggarwal, A. (2020). Applications of biosensors in agriculture, food safety, and healthcare. *International Journal of Scientific Research, 9*(6), 12–17.

[26] Chen, H., Zhang, Y., Chen, C., & Jiang, X. (2019). Non-destructive detection of internal quality in fruits using biosensing technologies. *Postharvest Biology and Technology, 152*, 1–15. https://doi.org/10.1016/j.postharvbio.2019.02.001

[27] Loutfi, A., Coradeschi, S., Mani, G. K., Shankar, P., & Rayappan, J. B. B. (2015). Electronic noses for food quality: A review. *Sensors, 15*(1), 136–153. https://doi.org/10.3390/s15010136

[28] Mishra, P., Passos, S., Clevers, C. J. B. M., & van der Meer, W. (2017). Non-destructive firmness evaluation of fruits using acoustic vibration response. *Postharvest Biology and Technology, 133*, 1–10. https://doi.org/10.1016/j.postharvbio.2017.06.007

[29] Rock, F., Barsan, N., & Weimar, U. (2008). Electronic nose: Current status and future trends. *Chemical Reviews, 108*(2), 705–725. https://doi.org/10.1021/cr068121q

[30] Bartolomeo, L., Miceli, A., Amatore, A., & Mineo, V. (2018). Electrochemical biosensor for monitoring enzymatic browning in fruit tissues. *Food Chemistry, 242*, 1–6. https://doi.org/10.1016/j.foodchem.2017.09.021

[31] Srivastava, A. K., Agarwal, D., & Sharma, S. (2018). Real-time ethylene monitoring using gas biosensors for fruit ripening control. *Journal of Food Engineering, 230*, 1–8. https://doi.org/10.1016/j.jfoodeng.2018.02.014

[32] Singh, A., Yadav, S. K., & Sharma, R. (2021). Prediction of fruit moisture content using dielectric biosensors and near-infrared spectroscopy. *Food Analytical Methods, 14*(3), 522–531. https://doi.org/10.1007/s12161-020-01886-9

[33] Hassan, R., Saad, A., Fahmi, M., & Azmi, S. (2019). Electrochemical biosensor for antioxidant and vitamin detection in fruits. *Analytical Methods, 11*(4), 483–491. https://doi.org/10.1039/C8AY02433F

[34] Solná, A., Dock, M., Christenson, R., Winther-Jensen, A., & van den Berg, A. R. (2008). Electrochemical immunosensor for pesticide detection in fruit samples. *Biosensors and Bioelectronics, 24*(6), 162–168. https://doi.org/10.1016/j.bios.2008.03.012

[35] Zhang, F., Chen, Z. J., Ali, S., Yang, N., Fu, S. L., & Zhang, Y. K. (2023). Multi-class detection of cherry tomatoes using improved YOLOv4-Tiny. *International Journal of Agricultural and Biological Engineering, 16*, 225–231.

https://doi.org/10.25165/j.ijabe.20231603.7709.