Biosensors in Postharvest Technology

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Abstract

Postharvest technology is essential for maintaining food quality, safety, and shelf life, yet significant losses occur due to poor handling, microbial contamination, artificial ripening, and inadequate storage. Fruits and vegetables experience the highest losses, amounting to around USD 750 billion annually. Traditional food analysis methods are slow, labour-intensive, and destructive, leading to delayed hazard detection and increased food waste. Biosensors have emerged as advanced tools for real-time monitoring of biochemical changes in fruits and vegetables, ensuring optimal ripening and reducing spoilage. These analytical devices use bio-recognition elements to detect specific targets, converting molecular interactions into measurable optical or electrical signals. Biosensors enable rapid and non-invasive detection of ripening agents like calcium carbide and ethephon, monitor glucose and ethylene levels for ripeness assessment, and identify spoilage markers such as polyphenols and microbial contaminants. Electrochemical and optical biosensors enhance food safety by detecting pathogens, pesticide residues, and freshness indicators. Their integration with nanomaterials improves sensitivity and selectivity, while IoT-enabled smart packaging allows real-time food quality tracking, reducing postharvest losses. Despite challenges like matrix interference, environmental variability, and limited lifespan, biosensors offer a transformative approach to food safety and sustainability. Continuous advancements in biosensor technology, nanomaterials, and IoT integration will further enhance their efficiency, making them essential in modern postharvest.

Keywords: Biological material, detection, quality control, postharvest, sensors

Introduction

Postharvest technology plays a vital role in preserving food quality, safety, and shelf life. Food loss, particularly in fruits and vegetables, accounts for 28–55% of production, amounting to an annual economic loss of $750 billion. Food safety remains a global concern, as foodborne diseases affect 600 million people yearly, causing 420,000 deaths and significant public health, economic, and social burdens. Despite adequate food production, 690 million people worldwide suffer from hunger, highlighting issues in food distribution and sustainability.

Food loss, waste, and contamination occur at various stages of the food supply chain, from production to consumption. Factors such as rapid urbanization, globalization, climate change, and changing consumer habits exacerbate these challenges, particularly in low- and middle-income countries. With 31 foodborne hazards causing 32 diseases, maintaining food safety requires robust traceability systems. Governments should enforce stricter regulations and certifications, while researchers and industries must develop improved monitoring technologies. Consumers also play a role by demanding greater transparency in food information.

Smart food traceability solutions, including food omics and biosensors, offer innovative approaches to ensuring food quality and authenticity. Biosensors, known for their accuracy and efficiency, can replace conventional food analysis methods, enabling rapid detection of foodborne pathogens and contaminants. The development of portable biosensors further enhances food safety, reducing analysis time and improving monitoring processes (Ma Z, *et.al.,*2022). Strengthening traceability and analytical technologies across the supply chain is crucial in addressing food security challenges and promoting sustainable, safe food systems globally.

2. Sensor and its types

A sensor is a device that detects physical or chemical changes and converts them into readable signals. Sensors are categorized into three types: (a) Physical sensors, which measure properties like distance, temperature, and pressure; (b) Chemical sensors, which detect chemical substances through reactions or physical properties; and (c) Biosensors, which use biological elements to analyze chemical substances.

Table 1. Applications of biosensor in postharvest technology

Applications	Type of biosensor	Biological material	Mechanism
QC in Fresh fruits and vegetables	Electrochemical, Optical	Enzyme-based biosensors (glucose oxidase for sugar, malate dehydrogenase for acidity	Biosensors offer advanced quality control for fresh fruits and vegetables by assessing sugar content, acidity, ripeness, and contamination.
Detection of microorganisms	Piezoelectric and optical	Antibodies in a bilayer lipid membrane	It offer faster detection, particularly for harmful pathogens like *Salmonella* and *E. coli*
Biosensing in Food Packaging and Supply Chain	Intelligent labels, RFID tags, Edible biosensors	Enzymes and nanoparticles are embedded via microencapsulation	They react to gas emissions (like ethylene), temperature changes, or pH levels to indicate freshness or ripeness
Detecting artificially ripened fruits	Optical, Electrochemical	Enzymatic Inhibition-Based, glucose, gas biosensors	Artificial ripening releases impurity gases which can be detect by measuring gas concentration changes in fruit packaging.
Detecting GMO based foods	Piezoelectric, Electrochemical	GM DNA/RNAs	Detecting GM genes using isothermal DNA amplification and rapid signal detection
Detection of toxins	Impedimetric, Piezoelectric	Aptamer and DNA-based biosensors	Toxins in food production, including carcinogens, odorants, and marine contaminants can be detected by biosensors in trace amounts.
Monitoring of wine quality	Electrochemical	3 different PQQ-dehydrogenases	The active form of the enzyme is regenerated via the interaction with the electrochemical mediator which is maintained in its oxidized form.
Monitoring alcohol quality	Electrochemical	Immobilized yeast or bacteria	Alcohol oxidase catalyses oxidation of ethanol into acetaldehyde and H_2O_2 in the presence of O_2 and peroxidase catalyses oxidation of the chromagen causing a colour change
Detecting food allergies	Electrochemical	IgE antibodies	On-site allergen detection by converting biological responses into electrical signals.
Detecting artificial sweetners	Electro-physiochemical	Glucose Oxidase (GOx)	Compounds like Aspartame, Saccharin, and Sucralose do not react with glucose-specific enzymes
Detecting polyphenol content	Amperometric	enzyme-based (polyphenol oxidase (PPO)	Oxidation of polyphenol content present in tea by enzyme-based biosensor
Determination of ascorbic acid in fruit juices	Potentiometric	ascorbate oxidase	Fall in oxygen consumption is detected by the electrode. Oxygen consumed is proportional to the ascorbic acid content of the sample
Detecting Monosodium glutamate levels	Electrochemical	glutamate dehydrogenase (GLDH) or glutamate oxidase (GluOx)	Biosensors comprising GluOx are simple compared to those involving GLDH because, the later involve NAD+ as a cofactor in the reaction.

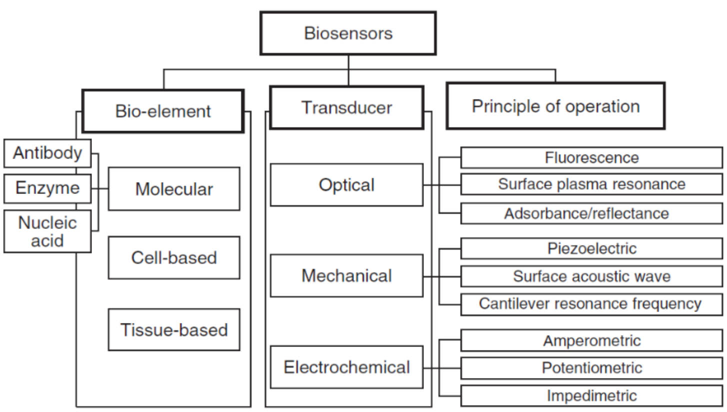
3. Biosensor

Biosensor can be defined as "analytical devices incorporating a biological material, a biological derived material or biomimic intimately associated with or within a physiochemical transducer or transducing Microsystems, which may be optical, electrochemical, thermometric, piezoelectric or magnetic" (Coulet, 1999).

3.1. Working principle

The bio detection principle involves a sensor generating a signal (e.g., voltage, heat, absorbance) in response to a detectable event, such as molecular binding. Chemical and biological sensors use receptors (e.g., enzymes, antibodies) to detect specific target molecules, while physical sensors measure inherent properties like current or temperature changes. The signal is then transduced into a digital format, which can be stored, displayed, or transmitted. Transducers, essential for signal conversion, operate through electrochemical, optical, piezoelectric, or calorimetric methods. The processed signal is amplified and used for further analysis or device control (Takhistov, 2005).

Fig. 1. Types of Biosensors



3.2. Components of a Biosensor

1. **Bioreceptor** – A biomolecule (e.g., enzymes, antibodies, DNA) that selectively binds to the target analyte, triggering a measurable response.
2. **Transducer** – Converts the biological reaction into an electrical signal, which is amplified and processed.

Transducer Mechanisms for Immobilization

- **Membrane entrapment** – A semi-permeable membrane separates the analyte and bioelement.
- **Physical adsorption** – Uses forces like van der Waals and hydrogen bonds to attach biomaterials.
- **Porous entrapment** – A porous matrix encapsulates biological material.
- **Covalent bonding** – The sensor surface has reactive groups for binding biomaterials.

Types of Transducers:

- **Optical transducer** – Measures light signals, often using Surface Plasmon Resonance (SPR) to detect analytes in real time.
- **Mechanical transducer** – Uses an acoustic wave to detect mass changes, such as in piezoelectric sensors, which track frequency shifts upon analyte binding.

Electrochemical transducer – Measures electrical property changes (e.g., ion flow) to quantify substances like glucose or DNA.

4. Future prospects

Biosensor technology is advancing with embedded systems, multi-analyte detection, microfluidics, and wearable devices for real-time food quality assessment. In agriculture, biosensors integrated with robotic systems (agrobots) enhance automation in harvesting, sorting, and quality control. Microfluidic biosensors offer portability and high sensitivity but face challenges like biofouling and biomolecule stability. Research in nanomaterials, enzyme stabilization, and immobilization techniques is crucial for improvement. In livestock and aquaculture, biosensors aid disease detection, with DNA and aptamer-based advancements. Integration with IC technology and wireless communication enables real-time monitoring. Overcoming commercialization and regulatory challenges will drive precision agriculture and sustainable farming.

5. Conclusion

Biosensors have advanced in agriculture, improving crop monitoring, food safety, and environmental assessments. However, challenges like biofouling, biomolecule stability, and sample interference hinder commercialization. Enhancing sensitivity, specificity, and cost-effectiveness is essential for wider adoption. Research in nanomaterials, enzyme stabilization, and immobilization techniques can improve performance. Integration with robotics and precision agriculture will enable real-time decision-making and higher productivity. Future efforts should focus on developing reliable, portable biosensors while addressing regulatory and market acceptance challenges. Biosensors will be key to sustainable agriculture and global food security.

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