A Comprehensive Review of Biosensors for Food Spoilage Detection Based on Specific Spoilage Markers

Neetu Gupta[1*], Sonam Khera[1], Gunjan Sardana[1]

[1] Department of Electronics Engineering, J.C. Bose University of Science and Technology, YMCA, Faridabad, Haryana- 121006, India

Abstract: Food spoilage represents a major global concern due to its significant economic, environmental, and public health implications. Conventional methods for assessing food freshness, such as sensory evaluation and microbiological culturing, are time-consuming, labor-intensive, and often incapable of providing real-time information regarding the onset of spoilage. Consequently, there is an increasing demand for rapid, sensitive, and automated detection systems capable of monitoring food quality throughout the supply chain. Biosensors have emerged as promising analytical tools for real-time detection of spoilage indicators. This review presents a comprehensive overview of biosensor technologies used for food spoilage detection based on specific spoilage markers. Biosensors are broadly categorized into chemical biosensors, microbial biosensors, and physical or optical biosensors depending on the nature of the target analyte and sensing mechanism. Chemical biosensors detect physicochemical changes such as pH variation, Volatile Organic Compounds (VOCs), and metabolites generated during food degradation. Microbial biosensors identify spoilage-causing microorganisms using immunological and nucleic acid-based detection strategies, including Enzyme-Linked Immunosorbent Assays (ELISA). Physical or optical biosensors detect variations in environmental parameters such as gas emission, temperature fluctuations, and refractive index changes. In addition, this review discusses the advantages, limitations, and challenges associated with these biosensor technologies, particularly in complex food matrices where interfering compounds may affect sensor performance. The integration of biosensors with smart packaging, Internet of Things (IoT), and portable detection platforms is also highlighted as a future direction for enhancing food safety monitoring systems.

Keywords: *Biosensors, Food Spoilage Detection, Volatile Organic Compounds, ELISA, Microbial Detection, Optical Biosensors*

1. Introduction

Food spoilage is a complex biochemical and microbiological process that results in deterioration of food quality, leading to undesirable changes in taste, odor, texture, and nutritional value. It is primarily caused by microbial growth, enzymatic degradation, oxidation reactions, and environmental factors such as temperature and humidity. According to the Food and Agriculture Organization of the United Nations (FAO, 2011), approximately one-third of all food produced globally is lost or wasted each year, representing significant economic losses and environmental concerns (Ahmed et al., 2014). Early detection of food spoilage is therefore essential to ensure food safety, maintain product quality, and reduce food waste throughout the supply chain.

*Corresponding author
Email address: neetu08@gmail.com

Received 27 September 2025; Accepted 13 April 2026
Published online 11 October 2026

©2026 JCBJETS

Traditional methods used to detect food spoilage include microbiological culturing, chemical analysis, and sensory evaluation. Although these techniques provide reliable results, they are often time-consuming, labor-intensive, and require sophisticated laboratory infrastructure. Microbiological culture methods, for instance, may take 24–72 hours to produce results, making them unsuitable for real-time monitoring applications in food processing and distribution systems (Clark & Lyons, 1962). Similarly, chemical analysis techniques such as chromatography and spectrometry require complex instrumentation and trained personnel. The increasing demand for rapid and reliable food quality monitoring has led to the development of advanced sensing technologies, particularly biosensors. A biosensor is an analytical device that integrates a biological recognition element with a physicochemical transducer to detect specific analytes and convert biological interactions into measurable signals (Arora et al., 2011). Since the pioneering work of Clark and Lyons in 1962, biosensors have evolved significantly and are now widely used in medical diagnostics, environmental monitoring, and food safety applications (Bhalla et al., 2016).

In the context of food spoilage detection, biosensors can identify various biochemical markers associated with microbial activity and metabolic degradation. These markers include Volatile Organic Compounds (VOCs), biogenic amines, microbial toxins, nucleic acids, and changes in physicochemical parameters such as pH and gas composition (Cooper, 2002). The ability of biosensors to detect these indicators rapidly and with high sensitivity makes them highly suitable for real-time food monitoring.

Biosensors used for food spoilage detection can generally be categorized into chemical biosensors, microbial biosensors, and physical or optical biosensors depending on the nature of the sensing mechanism and the type of spoilage marker detected. Chemical biosensors detect metabolites such as ammonia, hydrogen sulfide, and organic acids released during microbial metabolism. Microbial biosensors identify specific spoilage microorganisms using immunological or nucleic acid-based recognition systems. Physical and optical biosensors detect changes in physical properties such as mass, refractive index, fluorescence, or thermal signals associated with food degradation (Homola, 2008).

Recent advancements in nanotechnology, microelectronics, and smart packaging systems have further enhanced the capabilities of biosensors for food quality monitoring. Integration of biosensors with wireless communication systems, Internet of Things (IoT) platforms, and portable diagnostic devices is enabling real-time monitoring of food freshness throughout the supply chain (Tothill, 2001). These emerging technologies have the potential to significantly reduce food waste and improve food safety management. Therefore, this review provides a comprehensive overview of biosensor technologies used for food spoilage detection based on specific spoilage markers. The paper discusses different categories of biosensors, their working principles, advantages, limitations, and emerging trends in biosensor-based food monitoring systems.

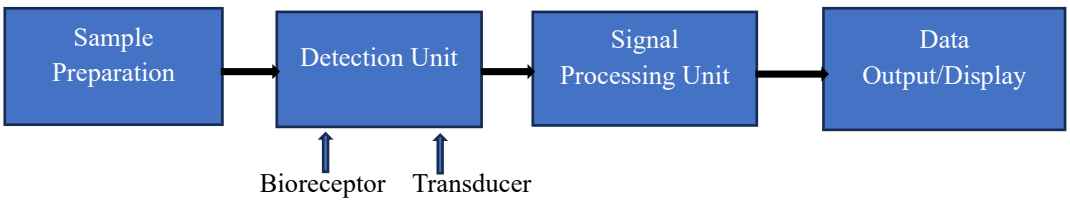


Figure 1: General Structure of a Food Analysis Biosensor System

Figure 1 gives a general structure of a food analysis biosensor system consisting of a sample preparation unit used for preparing the food sample for analysis and a detection unit, which is the core of the biosensor and responsible for actual sensing. The detection unit consists of a bioreceptor, which is a biological component that interacts specifically with the spoilage marker of interest and a transducer that converts

these interactions into measurable signals. The detection unit is followed by a signal processing unit, which interprets and analyzes the signals obtained from the detection unit. The display unit presents the results and information to the user.

2. Types of Biosensors Used for Food Spoilage Detection

This section categorizes biosensors based on the specific spoilage markers they detect—chemical, microbial, and physical—and provides an overview of their detection mechanisms.

2.1 Chemical Biosensors

Chemical biosensors detect biochemical changes associated with food spoilage, particularly the formation of Volatile Organic Compounds (VOCs), biogenic amines, and pH variations. During microbial metabolism and enzymatic degradation, various chemical compounds such as ammonia, hydrogen sulfide, and trimethylamine are produced, which serve as reliable indicators of spoilage (Clark & Lyons, 1962). Electrochemical biosensors are widely used for detecting these chemical markers due to their high sensitivity and fast response time. These sensors typically employ enzymatic or catalytic reactions that generate measurable electrical signals proportional to the concentration of the target analyte. For example, pH-sensitive electrodes can monitor the acidification process occurring in dairy and meat products during microbial fermentation.

Gas-sensing biosensors based on metal oxide semiconductors or conducting polymers have also been extensively used for detecting volatile compounds emitted during food degradation. These sensors are capable of detecting trace concentrations of VOCs released during early stages of spoilage. However, chemical biosensors may face challenges when applied to complex food matrices. Components such as fats, proteins, and salts can interfere with sensor response, leading to reduced selectivity and potential signal drift. Such interference may contribute to false positive or false negative signals, particularly in heterogeneous food samples.

2.2 Microbial Biosensors

Microbial biosensors are designed to detect specific microorganisms responsible for food spoilage and foodborne illnesses. These biosensors utilize biological recognition elements such as antibodies, nucleic acids, or enzymes to identify microbial pathogens. One of the most widely used techniques in microbial biosensing is the Enzyme-Linked Immunosorbent Assay (ELISA). ELISA-based biosensors detect microbial antigens using antigen-antibody interactions, producing colorimetric, fluorescent, or electrochemical signals proportional to the concentration of the target microorganism (Cooper, 2002).

ELISA has been extensively applied for detecting foodborne pathogens such as Escherichia coli, Salmonella enterica, and Listeria monocytogenes. The high specificity of antigen-antibody binding enables accurate detection of spoilage microorganisms even at low concentrations. Another important category includes nucleic acid-based biosensors, which detect microbial DNA or RNA sequences using techniques such as Polymerase Chain Reaction (PCR), DNA hybridization, or CRISPR-based assays. These sensors provide high sensitivity and rapid detection of microorganisms without the need for extensive culturing. Despite their advantages, microbial biosensors may encounter limitations when used in real food samples. Food matrices often contain background microflora, organic compounds, and inhibitors that may affect antibody binding or DNA amplification efficiency. These factors can reduce sensor accuracy and may contribute to false detection results.

2.3 Physical and Optical Biosensors

Physical biosensors detect changes in environmental parameters associated with food spoilage. These include temperature variations, gas emissions, mass changes, or alterations in mechanical properties of food products. Optical biosensors represent a significant subset of physical biosensors. They operate by detecting changes in optical properties such as fluorescence, absorbance, refractive index, or surface plasmon resonance. Optical sensors have gained considerable attention due to their non-destructive nature and high sensitivity. For instance, fluorescence-based sensors can detect microbial metabolites or enzymatic activity in food samples. Similarly, Surface Plasmon Resonance (SPR) biosensors are widely used for monitoring biomolecular interactions in real time.

Piezoelectric biosensors represent another class of physical biosensors. These sensors measure changes in mass or mechanical properties on the surface of a quartz crystal, enabling detection of microbial growth or gas emission during spoilage. Although optical and physical biosensors offer rapid detection and high sensitivity, their performance may be affected by factors such as sample turbidity, humidity, and variations in refractive index within complex food matrices. Figure 2 gives a pictorial classification of various types of biosensors based on specific spoilage markers.

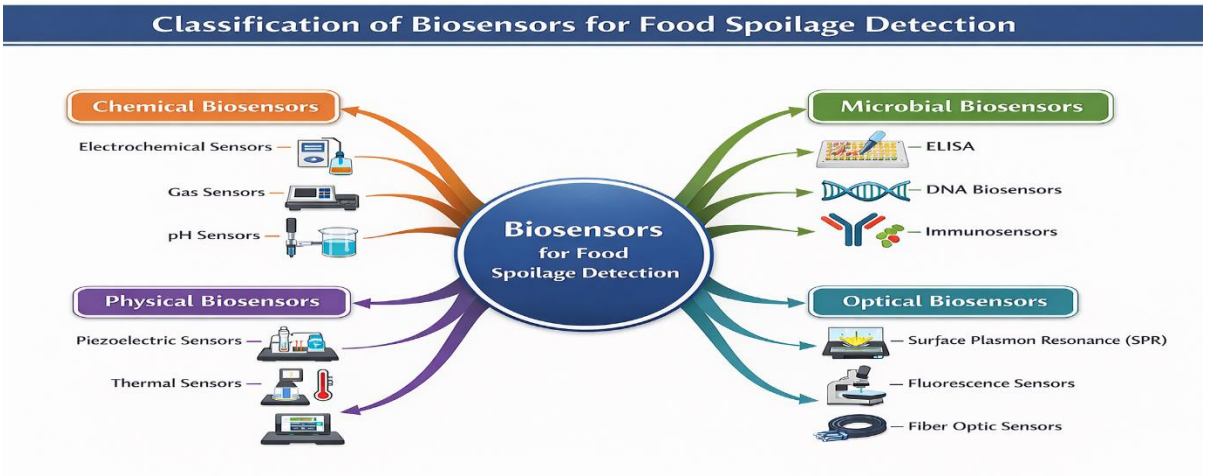


Figure 2: Types of Biosensors Based on Spoilage Markers

3. Performance Comparison and Limitations

The performance of biosensors for food spoilage detection depends on several parameters, including sensitivity, selectivity, response time, cost, and operational stability. Table 1 presents a comparative overview of the major biosensor categories along with their working principles, advantages, and limitations. While chemical biosensors provide rapid detection of metabolic by-products, they may suffer from interference caused by complex food compositions. Similarly, microbial biosensors provide high specificity but may require complex sample preparation procedures.

Table 1: Comparison chart of different kinds of Biosensors

Biosensor Type	**Target Spoilage Marker**	**Working Principle**	**Example Application**	**Advantages**	**Limitations**	**Reference**
Chemical Biosensor	Volatile Organic Compounds (VOCs), biogenic amines	Electrochemical reactions between analytes and sensing electrodes produce electrical signals	Detection of trimethylamine released during fish spoilage	Rapid response, high sensitivity	Cross-sensitivity to other gases; interference from complex food matrices	Velusamy et al., 2010
Gas Sensor (Metal Oxide Semiconductor)	Ammonia, hydrogen sulfide	Change in electrical conductivity of sensing layer due to gas adsorption	Monitoring spoilage in meat and poultry	Real-time monitoring, portable	Sensitive to humidity and temperature variations	Wilson & Baietto, 2009
Microbial Biosensor (Immunosensor)	*Escherichia coli*, *Salmonella enterica*	Antigen–antibody interaction detected through electrochemical or optical signals	Pathogen detection in dairy products	High specificity	Requires sample preparation and trained personnel	Lazcka et al., 2007
ELISA-based Biosensor	Bacterial toxins and antigens	Enzyme-linked immunological reaction producing measurable colorimetric signal	Detection of *Listeria monocytogenes* in food samples	Highly selective and widely validated	Longer analysis time compared with electrochemical sensors	Ivnitski et al., 1999
DNA Biosensor	Microbial DNA/RNA sequences	Hybridization of target nucleic acid with complementary probes immobilized on sensor	Rapid detection of foodborne pathogens	High sensitivity and specificity	DNA extraction required	Su & Li, 2004
Optical Biosensor (SPR)	Refractive index changes during biomolecular interactions	Surface plasmon resonance measures binding events in real time	Monitoring microbial contamination in food	Label-free detection	Sensitive to sample turbidity	Homola, 2008
Piezoelectric Biosensor	Mass change due to microbial growth	Quartz crystal microbalance detects frequency changes proportional to mass	Detection of microbial contamination	High precision and sensitivity	Environmental vibration interference	Cooper, 2002

Optical biosensors offer high sensitivity and label-free detection; however, their performance may be affected by environmental factors such as turbidity or background fluorescence in food samples. One of the key challenges in biosensor-based food monitoring is the occurrence of false positive and false negative responses. False positives may occur when non-target compounds produce signals similar to spoilage

markers, while false negatives may arise due to low analyte concentrations or signal suppression caused by interfering substances. Addressing these challenges requires improved sensor calibration, advanced signal processing techniques, and integration with machine learning algorithms to enhance detection accuracy.

4. Emerging Trends and Future Directions

Recent developments in nanotechnology and microelectronics have significantly enhanced the capabilities of biosensor systems. Nanomaterials such as graphene, carbon nanotubes, and metal nanoparticles are increasingly used to improve sensor sensitivity and signal amplification. The integration of biosensors with smart packaging technologies and Internet of Things (IoT) platforms is another promising direction for food quality monitoring. Smart packaging systems equipped with biosensors can continuously monitor food freshness and transmit data to mobile devices or cloud-based monitoring systems. Additionally, the development of portable biosensor devices may enable real-time monitoring of food quality throughout the supply chain, from production to consumption. Figure: 3 shows the role of biosensors at various points in the food supply chain.

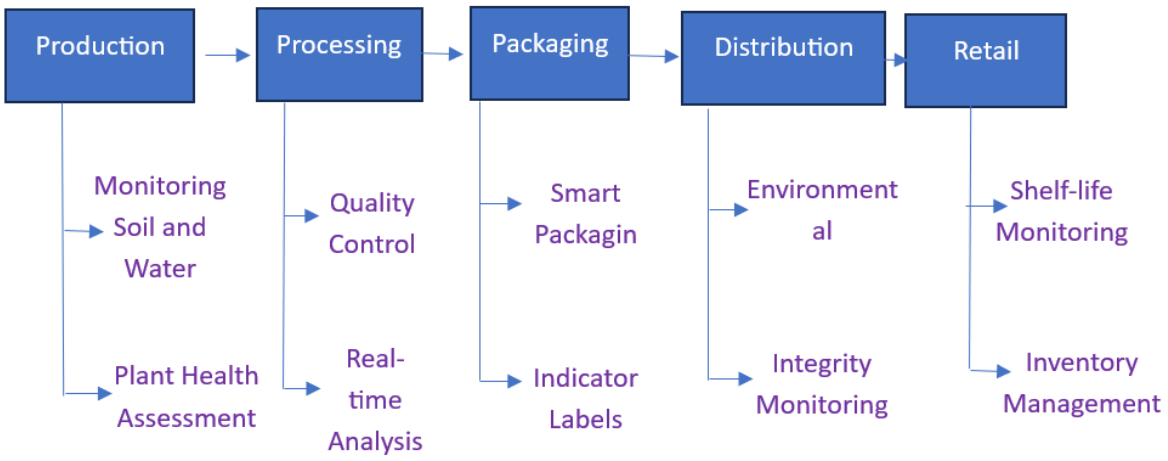


Figure 3: Integration of Biosensors in Food Supply Chain

5. Conclusion

Biosensor technology represents a powerful tool for rapid and reliable detection of food spoilage. Chemical, microbial, and physical biosensors each provide unique advantages in detecting different spoilage markers. While significant progress has been made in improving sensor sensitivity and response time, several challenges remain, particularly in complex food matrices where interfering substances may affect sensor accuracy. Future research should focus on improving sensor selectivity, minimizing interference effects, and integrating biosensor technologies with smart monitoring systems. Such advancements have the potential to significantly reduce food wastage and improve global food safety.

References

Food and Agriculture Organization. (2011). Global food losses and food waste: Extent, causes and prevention. Rome, Italy.

Ahmed, M. U., Saaem, I., Wu, P. C., & Brown, A. S. (2014). Personalized diagnostics and biosensors: A review of the biology and technology needed for personalized medicine. *Critical Reviews in Biotechnology,* 34(2), 180–196.

Arora, K., Chaubey, A., & Malhotra, B. D. (2011). Nanotechnology-based biosensors for food safety applications. *Journal of Food Science, 76(1)*, R29–R35.

Bhalla, N., Pan, Y., Yang, Z., & Payam, A. F. (2016). Opportunities and challenges for biosensors and bioelectronics in the future. *Essays in Biochemistry, 60(1),* 1–8.

Clark, L. C., Jr., & Lyons, C. (1962). Electrode systems for continuous monitoring in cardiovascular surgery. *Annals of the New York Academy of Sciences, 102(1),* 29–45.

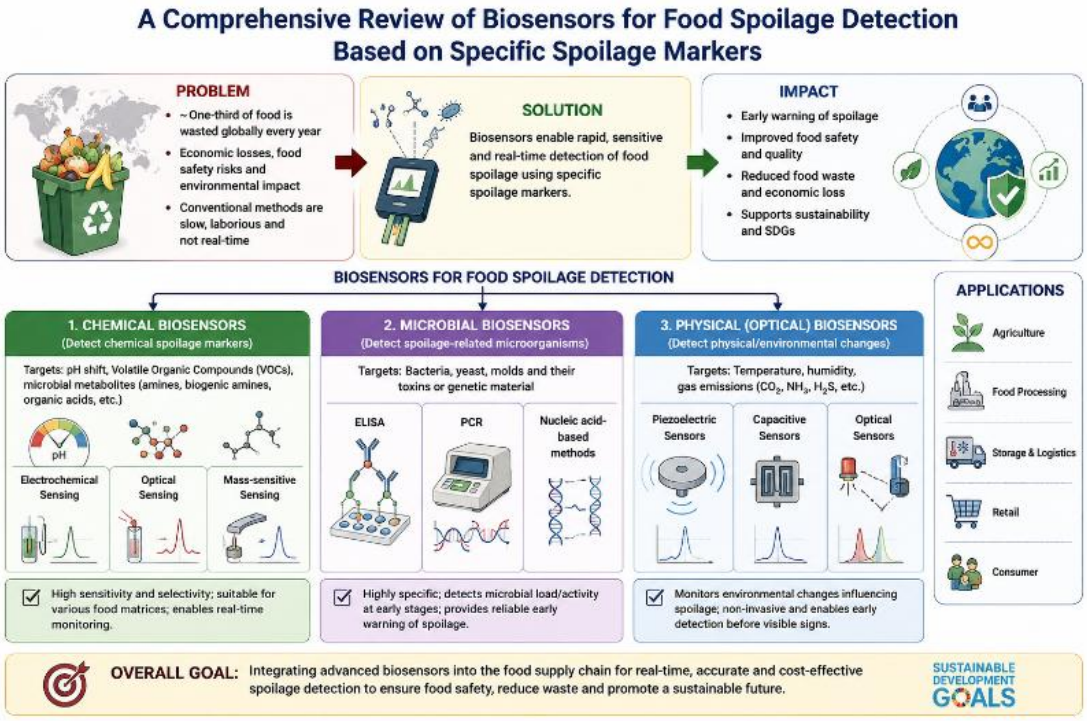
Cooper, M. A. (2002). Label-free biosensors: Techniques and applications. Cambridge, UK: *Cambridge University Press.*

Dutta, R., Hines, E. L., Gardner, J. W., & Kashwan, K. R. (2003). Electronic nose-based techniques for food quality monitoring. *Trends in Food Science & Technology, 14(9),* 378–389.

Homola, J. (2008). Surface plasmon resonance sensors for detection of chemical and biological species. *Chemical Reviews, 108(2),* 462–493.

Tothill, I. E. (2001). Biosensor developments and potential applications in the agricultural diagnosis sector. *Computers and Electronics in Agriculture, 30(1–3),* 205–218.

Graphical Abstract





Dr. Neetu Gupta is an Assistant Professor with over 20 years of academic experience in the field of engineering and technology. She is currently associated with JC Bose University of Science and Technology, YMCA, Faridabad, where she has been serving since 2007. She completed her Ph.D. from JC Bose University, M. Tech from Government Engineering College (GEC), Jabalpur, and B. Tech from HCET, Jabalpur. Her research interests include Embedded Systems, IoT, AI integration, edge computing, and smart sensing technologies, with a particular focus on real-world problem-solving. She is an active member of professional bodies including IEI, IEEE, and ISFT, and has also been nominated as a Co-opted Member of IEI Faridabad Local Centre. Dr. Gupta has contributed to academic research and is actively involved in developing next-generation frameworks in AI-integrated embedded IoT systems and security architectures.



Dr. Sonam Khera is working as an Assistant Professor in the Department of Electronics Engineering, J. C. Bose University of Science and Technology, YMCA, Faridabad. She has a rich teaching experience spanning more than 18 years. Her research interests include Mobile Communications, Wireless Sensor Networks and Internet of Things. In addition to her two patents, she has papers published in reputed International Journals and various National & International conferences. Dr. Khera has successfully led a number of workshops and expert lectures, and she actively participates in all departmental and university-level activities.



Gunjan Sardana, Assistant Professor, Electronics Engineering Department, J.C. Bose University of Science and Technology, YMCA, Faridabad, has 15 years of experience in teaching. She has authored and coauthored over 10 research papers in different academic journals and national and international conferences. She holds a master's degree in Electronics & Communication and a Bachelor's degree in Electronics and Communication Engineering from N.C. College of Engineering, Kurukshetra University, Haryana.