International Journal of Engineering Research and Science & Technology

www.ijerst.org

IF: 9.625

ISSN : 2319-5991





International Conference on Ensuring Global Food Safety-ICEGFS-2026

Vol. 22 No. 4(S) (2026)



ijerst.editor@gmail.com

editor@ijerst.com

International Conference on Ensuring Global Food Safety-ICEGFS-2026

ISSN 2319-5991 www.ijerst.com
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BIOCHEMICAL AND NANO-BIOSENSOR-BASED STRATEGIES FOR RAPID DETECTION OF FOOD CONTAMINANTS: CURRENT ADVANCES, CHALLENGES AND FUTURE PERSPECTIVES

Dr. B. Dhanasree
Associate Professor of Biochemistry
Silver Jubilee Government College
Cluster University
Kurnool – 518 002, Andhra Pradesh, India
Email: drdhanasree867@gmail.com

Abstract

Food safety is an essential component of public health, food security and sustainable development. Food may become contaminated with pathogenic microorganisms, pesticide residues, veterinary drug residues, heavy metals, mycotoxins, environmental pollutants and adulterants at different stages of production, processing, storage and distribution. The biochemical consequences of exposure to these hazards include oxidative stress, enzyme inhibition, disruption of cellular metabolism, genotoxicity and alterations in physiological functions. Consequently, sensitive, selective, rapid and reliable analytical approaches are required for early identification of food contaminants.

Biochemistry provides the molecular foundation for several modern food-safety technologies, including enzyme-based assays, immunoassays, nucleic-acid-based detection, aptamer-based recognition, biosensors and biomarker analysis. Conventional methods such as chromatography and mass spectrometry provide high sensitivity and confirmatory capability, whereas biosensor-based approaches offer opportunities for rapid screening and on-site detection. Integration of nanotechnology with biosensing platforms can further enhance analytical performance through increased surface area, improved signal amplification and enhanced recognition efficiency. Electrochemical, optical, fluorescence, colorimetric and surface-enhanced Raman-based systems have been investigated for the detection of pathogens, pesticides, mycotoxins, heavy metals, antibiotics and other food contaminants

This review discusses the biochemical basis of food contamination, major classes of food hazards, conventional and advanced analytical approaches, and the emerging role of nano-enabled biosensors in food-safety monitoring. Particular emphasis is placed on enzymes, antibodies, aptamers, nucleic acids, electrochemical transduction and nanomaterials. Challenges associated with food-matrix interference, validation, reproducibility, cost, regulatory acceptance and commercialization are also considered. Integrating biochemistry with analytical science, biotechnology and nanotechnology can contribute to rapid and accessible food-safety monitoring systems and support the broader goal of safe food, healthy people and a sustainable future.

Keywords: Food safety; Biochemistry; Food contaminants; Biosensors; Nanotechnology; Enzymes; Mycotoxins; Pesticide residues; Heavy metals; Foodborne pathogens.

Received: 17-09-2026 Accepted: 22-10-2026 Published: 29-10-2026

1. Introduction

Food is fundamental to human survival, health and socioeconomic development. However, food can also serve as a vehicle for pathogenic microorganisms and hazardous chemical substances. Contamination may occur during

cultivation, harvesting, processing, transportation, storage, preparation or consumption. The increasing complexity of food production and distribution has consequently made food safety a multidisciplinary challenge involving biochemistry, microbiology, chemistry, toxicology, environmental science and public health.

From a biochemical perspective, food safety is concerned not only with the presence of contaminants but also with the molecular interactions that determine their biological effects. Bacterial toxins, fungal mycotoxins, pesticides, heavy metals and veterinary drug residues can interact with enzymes, proteins, nucleic acids, membranes and cellular signalling pathways. These interactions may disturb redox balance, metabolic homeostasis and cellular integrity.

The need for rapid, sensitive and selective detection has encouraged the development of biosensors and nano-enabled analytical systems. A biosensor combines a biological recognition component with a transducer capable of converting a molecular interaction into a measurable signal. Enzymes, antibodies, aptamers and nucleic acids can provide molecular specificity, while electrochemical and optical transducers can support rapid measurement.

The conference brochure identifies chemical contaminants, food adulteration and quality control, advanced analytical techniques, biosensors and nanotechnology, foodborne diseases and pathogens, and sustainable and future food safety as important areas. This review therefore places biochemistry at the interface of these themes and examines how biochemical recognition and nanotechnology can strengthen food-safety surveillance.

2. Biochemical Basis of Food Contamination

2.1 Enzyme inhibition

Several contaminants interfere with enzymes involved in essential metabolic processes. Certain pesticide classes, for example, can inhibit enzymes associated with neurotransmission. This biochemical property can also be exploited analytically: an enzyme may be used as the recognition element in an inhibition-based biosensor, with the degree of activity loss related to contaminant concentration.

2.2 Oxidative stress

Heavy metals, pesticides and several natural toxins may disturb cellular redox homeostasis. Excessive reactive oxygen species can promote lipid peroxidation, protein oxidation, DNA damage, mitochondrial dysfunction and altered enzyme activity. Biochemical indicators of oxidative stress can therefore complement direct contaminant measurements in toxicological assessment.

2.3 Interaction with nucleic acids

Some contaminants and microbial toxins can damage DNA or alter nucleic-acid metabolism. This provides a biochemical basis for molecular detection strategies in which pathogen-specific DNA or RNA sequences are identified through amplification or hybridization.

2.4 Protein and antibody recognition

Antigen–antibody recognition provides high molecular selectivity and forms the basis of many immunochemical assays. Antibodies can be developed against toxins, microbial antigens, food proteins and other target molecules.

2.5 Aptamer recognition

Aptamers are short nucleic-acid sequences selected for specific binding to target molecules. Their chemical synthesis, potential stability and compatibility with nanomaterials make them attractive recognition elements for food-safety biosensors.

3. Major Food Contaminants of Biochemical Importance

Contaminant	Major sources	Biochemical/public-health significance	Potential detection approaches
Pesticide residues	Agricultural crops	Enzyme inhibition; oxidative stress	Enzyme assays; immunoassays; electrochemical biosensors; chromatography
Mycotoxins	Cereals, nuts, spices and stored foods	Toxic, genotoxic and metabolic effects	ELISA; LC-MS/MS; fluorescence; aptamer sensors
Heavy metals	Water, soil and environmental contamination	Enzyme inhibition; oxidative stress; cellular toxicity	AAS; ICP-MS; electrochemical sensors
Veterinary drug residues	Meat, milk, eggs and aquaculture products	Pharmacological effects; antimicrobial-resistance concerns	Immunoassays; chromatography; biosensors
Foodborne pathogens	Raw and processed foods	Infection and toxin production	Culture; PCR; immunoassay; nucleic-acid biosensors
Food adulterants	Processed and marketed foods	Quality loss and potential toxicity	Colorimetric; spectroscopic; chromatographic; biosensor methods

4. Conventional Analytical Methods

4.1 Chromatographic techniques

High-performance liquid chromatography and gas chromatography remain important techniques for separation and quantification of chemical contaminants. Coupling chromatography with mass spectrometry provides high analytical specificity and is widely used for confirmatory analysis. Their major strengths are sensitivity, selectivity and quantitative capability, whereas limitations include instrumentation cost, skilled personnel and laboratory requirements.

4.2 Spectroscopic methods

Spectroscopic approaches can provide information about molecular composition and chemical structure. They are applicable to food composition, adulteration and contaminant assessment. Complex food matrices, however, may produce overlapping signals and often require chemometric interpretation.

4.3 Immunoassays

Enzyme-linked immunosorbent assay (ELISA) is useful for screening targets for which suitable antibodies are available. The general principle involves specific target recognition followed by enzyme-mediated signal generation. Cross-reactivity, antibody quality and matrix effects must be considered during validation.

4.4 Molecular diagnostic techniques

Polymerase chain reaction (PCR) and related nucleic-acid amplification approaches enable identification of specific microorganisms. A typical workflow involves sample collection,

nucleic-acid extraction, target amplification and detection.

5. Biosensors: A Biochemical Approach to Food Safety

A biosensor can be represented as a biological recognition element coupled to a transducer and signal-processing system. The recognition element provides molecular selectivity, while the transducer converts the interaction into a measurable physical or chemical response.

- Enzymes
- Antibodies
- Aptamers
- Nucleic acids
- Whole cells
- Receptor proteins
- Biomimetic recognition molecules

6. Enzyme-Based Biosensors

Enzymes are attractive recognition elements because of their catalytic activity and molecular specificity. An enzyme sensor may detect a substrate or product generated during catalysis, whereas inhibition-based sensors measure a reduction in enzyme activity caused by a contaminant.

A simplified inhibition principle is: normal enzyme activity produces a measurable signal; exposure to an inhibitor reduces enzyme activity and consequently changes the signal. The magnitude of the change can be related to the concentration of the inhibitory compound. Cholinesterase inhibition is an established biochemical principle that has been explored for screening certain pesticide residues.

Important advantages include biological specificity, catalytic amplification and compatibility with electrochemical platforms. Limitations include enzyme instability, dependence on pH and temperature, food-matrix interference and limited operational lifetime.

7. Immunobiosensors

Immunobiosensors employ antigen–antibody interactions to recognize target contaminants. They have potential applications in mycotoxins, pesticide residues, veterinary drugs, microbial antigens and allergenic proteins. Their performance depends strongly on antibody affinity, specificity, immobilization chemistry and control of non-specific binding.

8. Aptamer-Based Biosensors

Aptamers are short DNA or RNA molecules capable of selective target binding. Compared with many biological recognition elements, they offer advantages such as chemical synthesis, potentially high stability and compatibility with diverse sensor architectures. Their combination with magnetic nanoparticles can facilitate target capture and separation, while aptamers provide molecular recognition.

9. Electrochemical Biosensors

Electrochemical biosensors convert biochemical interactions into electrical signals. Major formats include amperometric, potentiometric, voltammetric and impedance-based systems. Their potential for miniaturization, portability and rapid measurement makes them attractive for decentralized food-safety screening.

Nanostructured electrodes can increase effective surface area and facilitate electron transfer. However, sensor performance must be established in actual food matrices, because electroactive compounds and complex sample components may interfere with the analytical response.

10. Optical and Fluorescence Biosensors

Optical biosensors use changes in absorbance, fluorescence, luminescence, refractive index or Raman scattering. Fluorescent and surface-enhanced Raman approaches can provide sensitive molecular detection, while colorimetric formats may be particularly attractive for low-resource and field settings because results can

potentially be interpreted visually or using a smartphone camera.

11. Role of Nanotechnology in Food-Safety Biosensing

Nanotechnology can improve biosensor performance by providing high surface area, enhanced electron transfer, catalytic activity, signal amplification and optical properties. Frequently investigated materials include gold and silver nanoparticles, magnetic nanoparticles, quantum dots, graphene and graphene oxide, carbon nanotubes, metal oxides and nanocomposites.

A critical consideration is that improved analytical performance must be balanced against material safety, reproducibility, environmental impact, manufacturing complexity and regulatory requirements. The future development of food-safety nanobiosensors should therefore consider both analytical efficiency and responsible nanotechnology.

12. Biosensors for Mycotoxin Detection

Mycotoxins are toxic fungal metabolites that may contaminate cereals, nuts, dried fruits, spices and other commodities. Important examples include aflatoxins, ochratoxin A, fumonisins, zearalenone, deoxynivalenol and patulin. Their occurrence and low acceptable concentrations make rapid screening important.

Immunosensors, aptasensors, electrochemical platforms, fluorescence systems and surface-enhanced Raman approaches have been investigated for mycotoxin detection. Nano-enabled platforms may improve sensitivity by increasing recognition-element loading or amplifying optical and electrochemical signals.

13. Biosensors for Pesticide Residues

Pesticide residues may remain on crops or enter food through environmental pathways. Enzyme inhibition provides a direct biochemical principle for screening certain pesticide classes. A practical sensor can compare enzyme activity in a control with activity in the presence of an unknown sample and estimate the degree of inhibition.

Although rapid biosensing has considerable potential, confirmatory chromatographic analysis remains important for regulatory decisions. Selectivity is a major challenge when compounds with similar inhibitory properties occur together.

14. Detection of Heavy Metals

Lead, cadmium, arsenic and mercury can enter food chains through contaminated water, soil and environmental sources. Heavy metals may bind to functional groups in proteins, inhibit enzymes, disturb redox balance and interfere with cellular metabolism.

Electrochemical methods are particularly attractive for metal-ion detection because of their compatibility with miniaturized electrodes. Nanomaterials may improve sensitivity and facilitate preconcentration or signal amplification. Atomic absorption spectrometry and inductively coupled plasma mass spectrometry remain important confirmatory techniques.

15. Foodborne Pathogens and Molecular Biosensing

Foodborne pathogens represent an important biological food-safety hazard. Culture-based microbiology remains valuable, but molecular methods can provide faster target-specific identification. Biosensors can use pathogen-specific nucleic-acid probes, antibodies or aptamers as recognition elements.

Integration with magnetic separation, nanomaterial-based amplification and portable transducers may shorten analysis time and support on-site screening. Such systems are especially promising when rapid decisions are required before distribution or processing.

16. Food Adulteration and Authentication

Food adulteration and mislabelling compromise food quality and may create health risks. Biochemical authentication can examine

proteins, enzymes, DNA, lipids and metabolites. Species-specific DNA markers can support identification of animal-derived products, while protein and metabolite patterns can assist in detecting substitution or dilution.

The combination of molecular biomarkers with biosensing platforms could provide rapid screening for authenticity. Nevertheless, validation against representative authentic and adulterated samples is essential.

17. Biochemical Biomarkers of Exposure and Contamination

Direct measurement of a contaminant can be complemented by assessment of biological responses. Potential biochemical biomarkers include lipid peroxidation products, protein oxidation, antioxidant enzyme activities, cholinesterase activity, DNA damage and metabolic changes.

Such biomarkers are valuable for mechanistic toxicology because they indicate biological effects rather than merely the presence of a contaminant. They should, however, be interpreted cautiously because many biomarkers are not specific to a single contaminant.

18. Multiplex and Integrated Food-Safety Biosensing

Real food samples may contain multiple hazards simultaneously. A future food-safety platform should therefore move toward multiplex detection rather than single-analyte measurement alone. A conceptual multiplex system could combine enzyme, antibody, aptamer and nucleic-acid recognition elements with separate electrochemical or optical channels.

A practical strategy is to use rapid biosensors for screening followed by validated laboratory methods for confirmation. This approach can combine the speed and portability of biosensing with the analytical certainty of established methods.

19. Artificial Intelligence, Smartphones and Portable Platforms

Miniaturized sensors are increasingly compatible with digital technologies. Smartphone cameras can potentially quantify colorimetric or optical responses, while machine-learning algorithms may assist with pattern recognition when multiple sensor signals are generated.

Future systems could combine sample preparation, molecular recognition, signal transduction, data processing and reporting in a portable device. Such integration could be particularly valuable for agricultural supply chains, food markets, storage facilities and resource-limited settings.

20. Indian Perspective

India has a large and diverse food system involving cereals, pulses, fruits, vegetables, dairy products, spices, meat, fish and processed foods. This diversity creates a broad requirement for food-quality and food-safety surveillance. Biochemical methods can contribute to detection of adulteration, pesticide residues, mycotoxins, heavy metals, veterinary drug residues and microbial hazards.

For practical implementation, biosensor research in India should emphasize low-cost materials, locally relevant food matrices, simple sample preparation and portable detection. Sensor results intended for regulatory use must be correlated with validated reference methods and relevant national food-safety standards. Collaboration among biochemists, microbiologists, food technologists, analytical chemists and regulatory agencies can accelerate translation from laboratory prototypes to usable monitoring systems.

21. Integration with HACCP and Food-Safety Management

Analytical technologies are most effective when incorporated into systematic preventive food-safety management. Biosensors could potentially

be used at critical control points for rapid screening. For example, grain storage could be monitored for mycotoxins, with positive samples subsequently subjected to confirmatory laboratory analysis and corrective action.

The proposed model is: hazard identification → critical control point → rapid biochemical screening → confirmatory analysis → corrective action → documentation and traceability. This connects molecular detection with preventive food-safety management rather than relying exclusively on end-product testing.

22. Challenges and Limitations

- Food-matrix interference: proteins, lipids, carbohydrates, pigments and salts can affect sensor response.
- Selectivity: structurally related compounds may cause cross-reactivity.
- Reproducibility: differences in nanomaterial synthesis and sensor fabrication can alter performance.
- Stability: enzymes, antibodies and nucleic-acid recognition elements may lose activity during storage.
- Validation: performance demonstrated in buffer systems may not translate directly to complex food matrices.
- Regulatory acceptance: analytical validation and standardization are essential before routine regulatory use.
- Cost and scalability: sophisticated nanomaterials and fabrication methods can increase production cost.
- Field usability: devices should be simple enough for consistent use by non-specialist operators.

23. Future Perspectives

- Multiplex biosensors capable of detecting several contaminants in a single test.
- Smartphone-connected optical and colorimetric sensors for decentralized testing.
- AI-assisted interpretation of complex sensor patterns.
- Microfluidic lab-on-a-chip platforms integrating sample preparation and detection.
- Safer and more environmentally sustainable nanomaterials.
- Digital traceability systems linking sensor results to food-supply-chain records.
- Multi-omics approaches for deeper characterization of food quality and contamination.
- One Health approaches linking human, animal and environmental food-safety surveillance.

24. Proposed Integrated Biochemical Model for Global Food Safety

A future-oriented model can be visualized as: Agricultural production → environmental monitoring → food harvesting and processing → biochemical screening → biosensor/nanosensor detection → rapid digital analysis → confirmatory analytical testing → risk assessment → traceability and corrective action → safe food supply.

The central concept is that biochemical recognition can provide the molecular specificity needed for rapid screening, while analytical chemistry provides confirmation and regulatory confidence. Nanotechnology and digital systems can bridge these approaches by improving sensitivity, portability and data handling.

25. Conclusion

Food safety is a multidisciplinary challenge in which biochemistry provides a fundamental understanding of the molecular interactions underlying contamination and toxicity. Enzyme inhibition, antigen–antibody recognition, nucleic-acid hybridization, aptamer binding and biochemical biomarkers provide powerful recognition mechanisms for food-safety analysis. Conventional methods such as chromatography, spectroscopy and mass spectrometry remain

essential for accurate and confirmatory analysis. Biosensors offer a complementary route to rapid and potentially portable screening, while nanomaterials can enhance recognition, signal transduction and analytical sensitivity.

The major challenge is to translate promising laboratory devices into robust systems that perform reliably in real food matrices and satisfy validation, regulatory and economic requirements. Future progress will depend on collaboration between biochemistry, analytical chemistry, microbiology, food technology, nanotechnology, data science and public-health disciplines.

The most realistic and impactful future strategy is therefore an integrated system in which biochemical biosensors provide rapid screening, conventional analytical methods provide confirmation, and digital technologies support traceability and decision-making. Such a framework can contribute to the broader objective of safe food, healthy people and a sustainable future.

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