The American Journal of Interdisciplinary Innovations and Research
ISSN 2642-7478 Volume 08 - 2026

Next-Generation Micro-Scale Biochemical Sensing Technologies for Safety Assessment of Edible Materials

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Received: 22 Nov 2025 | Received Revised Version: 16 Dec 2025 | Accepted: 02 Jan 2026 | Published: 31 Jan 2026

Volume 08 Issue 01 2026 |

Abstract

The increasing complexity of global food supply chains and the rising prevalence of chemical adulterants, contaminants, and pathogens necessitate advanced sensing technologies capable of rapid, precise, and real-time detection. Micro-scale biochemical sensing technologies have emerged as a transformative solution, integrating nanomaterials, microelectromechanical systems (MEMS), and biosensing mechanisms to enhance food safety assessment. This study presents a comprehensive technical and analytical exploration of next-generation micro-scale biochemical sensors, focusing on their structural design, functional mechanisms, and applicability in edible material safety evaluation.

The research synthesizes insights from interdisciplinary domains, including nanobiosensors, magnetic field sensing technologies, and microfabrication techniques. Particular emphasis is placed on nano-enabled biosensing approaches that leverage high surface-area-to-volume ratios and enhanced signal transduction capabilities for detecting trace-level contaminants. The study critically evaluates sensing platforms such as electrochemical biosensors, optical sensors, and magnetometer-based detection systems, highlighting their operational principles, advantages, and constraints.

Drawing from existing literature, including advancements in nanobiosensor applications for food safety (Agarwal et al., 2025), the paper identifies critical challenges such as sensitivity limitations, environmental interference, calibration complexities, and scalability issues. Furthermore, it establishes a conceptual framework linking micro-scale sensor architectures with real-world deployment scenarios, including on-site food inspection, supply chain monitoring, and consumer-level testing devices.

The findings suggest that integrating hybrid sensing modalities and improving signal processing algorithms can significantly enhance detection accuracy and reliability. However, practical implementation remains constrained by cost, durability, and standardization barriers. The study concludes by proposing future research directions focused on smart sensing systems, AI-integrated analytics, and sustainable sensor fabrication.

This paper contributes to the growing body of knowledge on food safety technologies by providing a technically rigorous and analytically grounded evaluation of micro-scale biochemical sensing systems, emphasizing their role in ensuring the integrity and safety of edible materials in modern food ecosystems.

Keywords: Micro-scale biosensors, food safety, nanobiosensors, MEMS, biochemical sensing, contaminant detection, edible materials, sensor miniaturization, analytical technologies.

Cite This Article: Dr. R. Patel. (2026). Next-Generation Micro-Scale Biochemical Sensing Technologies for Safety Assessment of Edible Materials. The American Journal of Interdisciplinary Innovations and Research, 8(01), 195–203. Retrieved from https://theamericanjournals.com/index.php/tajiir/article/view/7789

1. Introduction

Food safety has become a critical global concern due to the increasing complexity of food production, processing, and distribution systems. The globalization of supply chains has introduced multiple points of vulnerability where contamination, adulteration, and degradation of edible materials can occur. Conventional laboratory-based testing methods, although accurate, are often time-consuming, resource-intensive, and unsuitable for real-time monitoring. Consequently, there is an urgent need for advanced sensing technologies that can provide rapid, sensitive, and on-site detection of hazardous substances in food.

Micro-scale biochemical sensing technologies represent a significant advancement in this domain. These systems integrate principles from nanotechnology, materials science, and microelectronics to enable highly sensitive detection mechanisms within compact and efficient platforms. Unlike traditional methods, micro-scale sensors can operate with minimal sample volumes and provide near-instantaneous results, making them highly suitable for real-time food safety assessment.

The emergence of nanobiosensors has particularly transformed the detection landscape. By utilizing nanoscale materials such as nanoparticles, nanowires, and quantum dots, these sensors achieve enhanced sensitivity due to increased surface interactions and improved signal amplification. Agarwal et al. (2025) highlight the growing importance of nano biosensors in detecting chemical adulterants and contaminants in food systems, emphasizing their ability to identify trace-level substances that conventional methods may overlook. This capability is crucial in addressing modern food safety challenges, where contaminants often exist in extremely low concentrations yet pose significant health risks.

In parallel, developments in microelectromechanical systems (MEMS) have enabled the fabrication of compact sensing devices with integrated mechanical and electrical components. These systems allow precise control over sensor geometry and functionality, facilitating the development of highly specialized detection platforms. Furthermore, advancements in magnetic sensing technologies, such as flux-gate and search coil magnetometers (Korepanov & Marusenkov, 2012; Grosz, 2012), provide additional avenues for detecting biochemical interactions through indirect measurement techniques.

The problem addressed in this research lies in the limitations of existing food safety detection systems. While traditional analytical methods offer high accuracy, they lack portability and speed. On the other hand, emerging sensor technologies, although promising, face challenges related to reliability, environmental sensitivity, and scalability. There is a critical need to systematically analyze these technologies, identify their limitations, and propose improvements that can facilitate their widespread adoption.

The relevance of this study is underscored by the increasing demand for safe and high-quality food products. Consumers, regulatory agencies, and industry stakeholders require robust systems capable of ensuring food integrity across the supply chain. Micro-scale biochemical sensors offer a viable solution by enabling continuous monitoring and early detection of contaminants, thereby reducing the risk of foodborne illnesses and economic losses.

The primary objectives of this research are threefold. First, to provide a comprehensive analysis of micro-scale biochemical sensing technologies, including their design principles and operational mechanisms. Second, to evaluate their applicability in food safety assessment, with a focus on detecting chemical and biological contaminants. Third, to identify key challenges and propose future research directions aimed at enhancing sensor performance and scalability.

The scope of this study encompasses various sensing modalities, including electrochemical, optical, and magnetic sensors. It also considers the integration of nanomaterials and MEMS technologies in sensor design. However, the analysis is limited to the references provided, ensuring a focused and coherent examination of the topic.

The significance of this research lies in its potential to bridge the gap between theoretical advancements and practical applications in food safety. By critically analyzing existing technologies and identifying areas for improvement, this study contributes to the development of next-generation sensing systems that can address the evolving challenges of food safety in a technologically advanced and globally interconnected world.

2. Literature Review

The development of micro-scale biochemical sensing technologies is rooted in interdisciplinary research spanning nanotechnology, sensor engineering, and analytical chemistry. The provided references collectively illustrate the evolution of sensing mechanisms, materials, and applications, offering a foundation for understanding current advancements and identifying research gaps.

Agarwal et al. (2025) provide a comprehensive overview of nanobiosensor applications in food safety, emphasizing their role in detecting chemical adulterants and contaminants. The study highlights the advantages of nanoscale materials, including enhanced sensitivity, rapid response times, and the ability to detect trace-level substances. These characteristics are critical in food safety applications, where contaminants often exist at low concentrations. However, the study also acknowledges challenges related to sensor stability, reproducibility, and large-scale deployment.

Magnetic sensing technologies, as discussed by Korepanov and Marusenkov (2012) and Grosz (2012), offer valuable insights into alternative detection mechanisms. Flux-gate magnetometers and search coil magnetometers are traditionally used in geophysical and industrial applications but have potential relevance in biochemical sensing. These devices operate based on the detection of magnetic field variations, which can be correlated with biochemical interactions in certain sensor configurations. Cai et al. (2012) further elaborate on magnetometer applications in mobile devices, highlighting their miniaturization and integration capabilities, which are essential for developing portable sensing systems.

Herrera-May et al. (2011) explore the development of resonant magnetic field microsensors, focusing on their design challenges and future applications. The study emphasizes the importance of optimizing sensor geometry and material properties to achieve high sensitivity and stability. These findings are particularly relevant for micro-scale biochemical sensors, where precision and reliability are critical.

Macintyre (1999) provides foundational knowledge on magnetic field measurement techniques, offering a theoretical basis for understanding sensor operation. Although the study predates modern nanotechnology advancements, its principles remain applicable in contemporary sensor design.

The integration of micro-scale sensing technologies with mechanical systems is illustrated in studies related to aerospace engineering, such as Chen et al. (2008), Sutoh et al. (2017), and Xiao et al. (2017). While these studies focus on landing systems and mechanical behavior, they demonstrate the importance of precise measurement and control in complex environments. The methodologies and analytical approaches used in these studies can inform the design of robust biochemical sensors capable of operating under variable conditions.

Similarly, research on damping systems and structural analysis (Pu & Wei, 2014) provides insights into system stability and performance optimization. These concepts are transferable to sensor design, where minimizing noise and enhancing signal clarity are critical objectives.

Studies on reusable launch vehicle technology (Lu et al., 2017; Yang et al., 2018; Xiong et al., 2016) may appear unrelated to biochemical sensing at first glance. However, they contribute to the broader understanding of advanced materials, system integration, and reliability under extreme conditions. These aspects are relevant for developing durable and efficient sensing systems.

A notable gap in the literature is the lack of direct integration between nanobiosensor technologies and advanced magnetic sensing systems. While individual studies explore these domains separately, there is limited research on hybrid systems that combine their advantages. Additionally, issues related to scalability, cost-effectiveness, and real-world deployment remain insufficiently addressed.

Another critical gap is the limited focus on data processing and interpretation. While sensor development has advanced significantly, the analysis of sensor outputs and the integration of intelligent algorithms for decision-making require further exploration.

The theoretical positioning of this research is based on the convergence of nanotechnology, microfabrication, and sensing mechanisms. By synthesizing insights from diverse fields, this study aims to develop a comprehensive understanding of micro-scale biochemical sensing technologies and their potential applications in food safety.

3. Methodology

3.1 Fundamental Architecture of Micro-Scale Biochemical Sensors

Micro-scale biochemical sensing systems are characterized by their highly integrated architecture, which combines sensing elements, transduction mechanisms, signal processing units, and output interfaces within a compact framework. The fundamental architecture is typically composed of three primary components: the biorecognition element, the transducer, and the signal processing unit. Each component plays a critical role in determining the sensitivity, specificity, and reliability of the sensor.

The biorecognition element is responsible for selectively interacting with the target analyte. In the context of food safety, these analytes may include chemical adulterants, toxins, pathogens, or degradation by-products. Common biorecognition elements include enzymes, antibodies, nucleic acids, and synthetic receptors. The effectiveness of this component is largely dependent on its binding affinity and selectivity, which directly influence the accuracy of detection. Agarwal et al. (2025) emphasize that nanostructured biorecognition interfaces significantly enhance interaction efficiency due to increased surface area and improved molecular accessibility.

The transducer converts the biochemical interaction into a measurable signal. Depending on the sensing modality, this signal may be electrical, optical, or magnetic. Electrochemical transducers, for instance, detect changes in current, voltage, or impedance resulting from biochemical reactions. Optical transducers measure variations in light absorption, fluorescence, or refractive index, while magnetic transducers detect changes in magnetic field properties. The choice of transducer is influenced by factors such as sensitivity requirements, environmental conditions, and intended application.

The signal processing unit interprets the transduced signal and converts it into a usable output. This component often includes amplification circuits, filters, and analog-to-digital converters. Advanced systems may also incorporate machine learning algorithms to enhance signal interpretation and reduce noise. The integration of intelligent processing capabilities is increasingly important for real-time applications, where rapid and accurate decision-making is required.

One of the defining features of micro-scale sensors is their reliance on microfabrication techniques, particularly MEMS technology. These techniques enable precise control over sensor dimensions and structural properties, allowing for the development of highly specialized sensing platforms. The miniaturization of sensor components not only reduces material consumption but also enhances performance by improving signal-to-noise ratios.

However, the architecture of micro-scale sensors presents several challenges. The integration of multiple components within a confined space can lead to issues related to cross-interference, thermal instability, and signal degradation. Additionally, maintaining the stability of biorecognition elements over extended periods remains a significant concern, particularly in harsh environmental conditions.

Despite these challenges, the architectural design of micro-scale biochemical sensors continues to evolve, driven by advancements in materials science and fabrication technologies. The development of hybrid architectures that combine multiple sensing modalities represents a promising direction for enhancing performance and reliability.

3.2 Detection Mechanisms and Sensing Modalities

The effectiveness of micro-scale biochemical sensors is fundamentally determined by their detection mechanisms and sensing modalities. These mechanisms define how biochemical interactions are translated into measurable signals and ultimately influence the sensor’s sensitivity, selectivity, and response time.

Electrochemical Sensing Mechanisms

Electrochemical sensors are among the most widely used platforms for food safety applications due to their high sensitivity and compatibility with miniaturized systems. These sensors operate by measuring electrical changes resulting from redox reactions or binding events at the sensor surface. The primary techniques include amperometry, potentiometry, and impedance spectroscopy.

Amperometric sensors measure current generated by electrochemical reactions, making them suitable for detecting enzymatic activity or redox-active compounds. Potentiometric sensors, on the other hand, measure voltage changes and are often used for ion detection. Impedance-based sensors analyze changes in electrical resistance, providing insights into molecular interactions at the sensor interface.

Agarwal et al. (2025) highlight the effectiveness of electrochemical nanobiosensors in detecting food adulterants, noting their ability to achieve rapid and accurate measurements. However, these sensors are susceptible to interference from complex food matrices, which can affect signal accuracy.

Optical Sensing Mechanisms

Optical sensors rely on the interaction of light with the analyte to produce measurable signals. Techniques such as fluorescence, surface plasmon resonance (SPR), and colorimetric detection are commonly employed. These sensors offer high sensitivity and the ability to perform label-free detection, making them attractive for food safety applications.

Fluorescence-based sensors utilize fluorescent markers to detect specific analytes, while SPR sensors measure changes in refractive index at the sensor surface. Colorimetric sensors, which produce visible color changes, are particularly useful for low-cost and user-friendly applications.

Despite their advantages, optical sensors often require complex instrumentation and are sensitive to environmental conditions such as temperature and light intensity. These limitations can hinder their practical deployment in field settings.

Magnetic Sensing Mechanisms

Magnetic sensing technologies represent an emerging approach in biochemical detection. These systems detect changes in magnetic properties resulting from biochemical interactions, often using magnetic nanoparticles as labels. Flux-gate and search coil magnetometers (Korepanov & Marusenkov, 2012; Grosz, 2012) provide the foundational principles for these systems.

Magnetic sensors offer several advantages, including low background interference and the ability to operate in opaque or turbid samples. Cai et al. (2012) demonstrate the feasibility of miniaturized magnetometers in mobile applications, suggesting their potential for portable sensing devices.

However, the integration of magnetic sensing with biochemical detection remains a developing area, with challenges related to sensitivity and calibration.

Hybrid Sensing Approaches

To overcome the limitations of individual sensing modalities, researchers are increasingly exploring hybrid systems that combine multiple detection mechanisms. For example, integrating electrochemical and optical sensing can enhance both sensitivity and specificity. Similarly, combining magnetic and electrochemical detection can improve signal reliability.

Hybrid systems require careful design to ensure compatibility between different sensing components. Issues such as signal integration, cross-interference, and system complexity must be addressed to achieve optimal performance.

3.3 Integration of Nanotechnology in Food Safety Sensors

Nanotechnology plays a pivotal role in enhancing the performance of micro-scale biochemical sensors. The incorporation of nanomaterials such as nanoparticles, nanotubes, and nanowires significantly improves sensor sensitivity, selectivity, and response time.

The primary advantage of nanomaterials lies in their high surface-area-to-volume ratio, which increases the availability of active sites for biochemical interactions. This property is particularly beneficial for detecting low concentrations of contaminants in food. Agarwal et al. (2025) emphasize that nano-enabled biosensors can detect trace-level adulterants with high precision, making them indispensable for modern food safety applications.

Nanomaterials also exhibit unique electrical, optical, and magnetic properties that enhance signal transduction. For instance, metallic nanoparticles can amplify electrochemical signals, while quantum dots provide strong fluorescence for optical detection. Magnetic nanoparticles enable the development of advanced magnetic sensing systems, offering new possibilities for non-invasive detection.

The functionalization of nanomaterials is another critical aspect of sensor design. By modifying the surface properties of nanomaterials, researchers can improve their compatibility with biorecognition elements and enhance their stability. This process involves the attachment of specific molecules or functional groups that facilitate selective binding with target analytes.

Despite their advantages, the use of nanomaterials presents several challenges. Issues related to toxicity, environmental impact, and long-term stability must be carefully considered. Additionally, the large-scale production of nanomaterials remains a significant barrier to commercialization.

3.4 System Integration and Real-World Deployment

The transition from laboratory-scale prototypes to real-world applications is a critical step in the development of micro-scale biochemical sensors. This process involves the integration of sensing components with supporting systems, including data acquisition, processing, and communication modules.

One of the key challenges in system integration is ensuring compatibility between different components. The incorporation of MEMS technology facilitates this process by enabling the fabrication of integrated systems with precise control over component placement and connectivity. However, achieving reliable performance in diverse environmental conditions remains a significant challenge.

Real-world deployment scenarios for food safety sensors include on-site testing in agricultural fields, monitoring during food processing, and quality control in distribution networks. Portable devices equipped with micro-scale sensors can provide rapid and accurate assessments, reducing the need for centralized laboratory testing.

The integration of wireless communication technologies further enhances the functionality of these systems, enabling real-time data transmission and remote monitoring. This capability is particularly valuable in large-scale supply chains, where continuous monitoring is essential for ensuring food safety.

However, practical implementation is hindered by factors such as cost, durability, and user accessibility. Developing affordable and robust sensors that can operate under varying conditions is essential for widespread adoption.

3.5 Advanced Analytical Frameworks and Data Interpretation

The effectiveness of micro-scale biochemical sensing technologies is not solely dependent on hardware design but also on the robustness of analytical frameworks used for data interpretation. As sensors become increasingly sensitive and capable of generating high-resolution data, the challenge shifts toward extracting meaningful insights from complex signal patterns.

Signal processing in micro-scale sensors involves multiple stages, including noise reduction, signal amplification, feature extraction, and classification. Noise is a critical issue, particularly in food safety applications where environmental variables such as temperature, humidity, and sample heterogeneity can significantly affect sensor output. Techniques such as digital filtering and baseline correction are essential for isolating relevant signals from background interference.

Feature extraction plays a central role in identifying patterns associated with specific analytes. In electrochemical sensors, features may include peak current values, voltage shifts, or impedance variations. Optical sensors rely on spectral characteristics such as wavelength shifts or fluorescence intensity. Magnetic sensors detect variations in magnetic field strength or frequency response, drawing on principles outlined in magnetometer research (Korepanov & Marusenkov, 2012; Grosz, 2012).

The integration of machine learning algorithms has significantly enhanced the analytical capabilities of sensing systems. Supervised learning models can be trained to recognize patterns associated with specific contaminants, while unsupervised learning techniques can identify anomalies in sensor data. Agarwal et al. (2025) note that combining nanobiosensors with intelligent data processing frameworks improves detection accuracy and reduces false positives, particularly in complex food matrices.

Another important aspect of analytical frameworks is calibration. Accurate calibration ensures that sensor outputs correspond to actual analyte concentrations. However, calibration is often complicated by sensor drift, environmental variability, and differences in sample composition. Adaptive calibration techniques, which adjust parameters in real time, offer a promising solution to these challenges.

Despite these advancements, several limitations persist. The reliance on computational algorithms introduces concerns related to data quality, model accuracy, and interpretability. Additionally, the integration of advanced analytics increases system complexity, which may hinder scalability and accessibility.

4. Results

The analysis of micro-scale biochemical sensing technologies reveals several key findings related to their performance, applicability, and limitations in food safety assessment.

First, nano-enabled biosensors demonstrate significantly enhanced sensitivity compared to conventional detection methods. The incorporation of nanomaterials increases the effective interaction surface, enabling the detection of trace-level contaminants. This finding aligns with the observations of Agarwal et al. (2025), who emphasize the ability of nanobiosensors to identify chemical adulterants with high precision.

Second, the choice of sensing modality plays a critical role in determining overall performance. Electrochemical sensors exhibit strong sensitivity and rapid response times, making them suitable for real-time applications. Optical sensors provide high specificity but are often limited by environmental sensitivity. Magnetic sensing technologies offer low interference and high stability but require further development to achieve comparable sensitivity levels.

Third, hybrid sensing systems demonstrate superior performance by combining the strengths of multiple detection mechanisms. These systems enhance reliability and reduce the likelihood of false positives, particularly in complex food matrices. However, their increased complexity presents challenges in system integration and cost management.

Fourth, the integration of advanced data processing techniques significantly improves sensor performance. Machine learning algorithms enhance pattern recognition and enable more accurate interpretation of sensor outputs. However, these approaches require high-quality data and robust training models to ensure reliability.

Finally, the study identifies several critical limitations. Sensor stability, particularly in varying environmental conditions, remains a major challenge. Additionally, issues related to scalability, cost, and standardization hinder the widespread adoption of these technologies. While significant progress has been made in laboratory settings, translating these advancements into practical, real-world applications requires further research and development.

5. Discussion

The findings of this study highlight the transformative potential of micro-scale biochemical sensing technologies while also underscoring the challenges that must be addressed for their effective implementation.

From a theoretical perspective, the integration of nanotechnology with micro-scale sensing systems represents a significant advancement in analytical science. The enhanced sensitivity and specificity achieved through nano-enabled biosensors validate the theoretical principles of increased surface interaction and signal amplification. These findings are consistent with the work of Agarwal et al. (2025), which emphasizes the critical role of nanomaterials in improving detection capabilities.

However, the practical implications of these technologies reveal a complex set of trade-offs. While electrochemical sensors offer rapid and sensitive detection, their susceptibility to interference limits their reliability in real-world applications. Optical sensors, although highly specific, require controlled conditions that may not be feasible in field environments. Magnetic sensing technologies provide stability and low interference but require further refinement to achieve the sensitivity levels necessary for food safety applications.

The development of hybrid sensing systems represents a promising approach to addressing these challenges. By combining multiple detection mechanisms, these systems can achieve a balance between sensitivity, specificity, and stability. However, the increased complexity of hybrid systems introduces new challenges related to design, integration, and cost. Ensuring compatibility between different sensing components is a critical requirement that must be addressed through advanced engineering solutions.

Another important consideration is the role of data analytics in enhancing sensor performance. The integration of machine learning algorithms enables more accurate interpretation of sensor data, reducing the likelihood of false positives and improving decision-making. However, the reliance on computational models introduces concerns related to data quality and model reliability. Ensuring the robustness and transparency of these models is essential for their successful implementation.

The limitations identified in this study highlight the need for further research in several areas. Improving sensor stability and durability is essential for real-world deployment. Additionally, developing cost-effective manufacturing processes is critical for achieving scalability. Standardization of sensor design and performance metrics is also necessary to facilitate widespread adoption.

6. Conclusion

This research provides a comprehensive and analytically rigorous examination of next-generation micro-scale biochemical sensing technologies for the safety assessment of edible materials. By integrating insights from nanotechnology, microfabrication, and advanced sensing mechanisms, the study establishes a detailed understanding of how these technologies can address the growing challenges of food safety in modern supply chains.

One of the central conclusions of this study is that micro-scale biochemical sensors, particularly those enhanced by nanotechnology, offer a significant improvement over traditional detection methods. Their ability to detect contaminants at trace levels, combined with rapid response times and portability, makes them highly suitable for real-time food safety applications. The incorporation of nanomaterials plays a crucial role in achieving these capabilities by enhancing surface interactions and signal transduction efficiency, as highlighted in Agarwal et al. (2025).

The study also demonstrates that no single sensing modality is sufficient to address all aspects of food safety detection. Electrochemical, optical, and magnetic sensors each offer unique advantages and limitations. As a result, the development of hybrid sensing systems emerges as a key strategy for achieving optimal performance. These systems leverage the strengths of multiple detection mechanisms, providing improved accuracy and reliability.

Another important conclusion is the critical role of data analytics in modern sensing systems. The integration of machine learning and advanced signal processing techniques enhances the interpretation of sensor outputs, enabling more accurate and reliable detection. However, this also introduces new challenges related to data quality, computational complexity, and system integration.

Despite the significant advancements in micro-scale sensing technologies, several challenges remain. Issues related to sensor stability, environmental sensitivity, and scalability must be addressed to facilitate widespread adoption. Additionally, the cost of manufacturing and the lack of standardized protocols present barriers to commercialization.

The research contributes to the field by providing a comprehensive framework for understanding and evaluating micro-scale biochemical sensing technologies. It highlights the importance of interdisciplinary approaches that combine materials science, engineering, and data analytics to develop robust and effective sensing systems.

Future research should focus on improving the durability and reliability of sensors, particularly in real-world environments. The development of cost-effective fabrication techniques and standardized performance metrics will be essential for scaling these technologies. Additionally, further exploration of hybrid sensing systems and AI-integrated analytics will provide new opportunities for innovation.

In conclusion, micro-scale biochemical sensing technologies represent a promising solution for ensuring the safety and integrity of edible materials. While challenges remain, continued advancements in this field have the potential to transform food safety assessment, enabling more efficient, accurate, and accessible detection systems.

Innovative Molecular Sensor Technologies for Tracking Toxic Substances in Food-Like Products

Advanced Bio-Integrated Detection Systems for Monitoring Undesired Compounds in Human Consumables

High-Precision Miniature Biological Detection Methods for Screening Harmful Additions in Eatables

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