

Advanced Surface-Enhanced Raman Spectroscopy and Nanobiosensor Technologies For Ultra-Sensitive Detection of Chemical Contaminants in Food Systems

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Received: 02 Jan 2026 | Received Revised Version: 20 Jan 2026 | Accepted: 02 Feb 2026 | Published: 28 Feb 2026

Volume 08 Issue 02 2026 |

Abstract

The increasing prevalence of chemical contaminants in food systems, including heavy metals and pesticide residues, necessitates the development of highly sensitive, rapid, and reliable detection technologies. This research article provides a comprehensive and integrative analysis of advanced nanotechnology-driven sensing systems, with a primary focus on surface-enhanced Raman spectroscopy (SERS) and nanobiosensor platforms. Drawing exclusively from the provided references, the study evaluates the theoretical foundations, material innovations, detection mechanisms, and practical applications of nanosensors in food safety. The methodology employs a qualitative synthesis of interdisciplinary research encompassing nanomaterials, spectroscopy, biosensing, and green analytical chemistry. The findings reveal that SERS-based detection systems, particularly those utilizing hybrid nanostructures such as Au@AgPt nanoparticles, graphene composites, and nanorod arrays, demonstrate exceptional sensitivity and selectivity for detecting trace levels of heavy metals and pesticide residues. Additionally, emerging nanomaterials such as MXenes and organic chemical nanosensors offer novel pathways for enhanced signal transduction and multifunctional sensing. The integration of nanobiosensors with environmentally sustainable sample preparation techniques further enhances analytical efficiency while reducing ecological impact. However, challenges related to reproducibility, standardization, and real-world implementation remain significant. The discussion explores the broader implications of these technologies for food safety, regulatory frameworks, and public health, emphasizing the need for interdisciplinary collaboration and innovation. The study concludes that the convergence of SERS technology, nanobiosensing, and green analytical approaches represents a transformative paradigm for ensuring food safety in complex and globalized food systems.

Keywords: SERS, nanobiosensors, food safety, pesticide detection, heavy metals, nanotechnology, spectroscopy.

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Cite This Article: Ananya R. Mehta. (2026). Advanced Surface-Enhanced Raman Spectroscopy and Nanobiosensor Technologies For Ultra-Sensitive Detection of Chemical Contaminants in Food Systems. The American Journal of Applied Sciences, 8(2), 88–91. Retrieved from <https://theamericanjournals.com/index.php/tajas/article/view/7769>

1. Introduction

The modern global food system is characterized by unprecedented complexity, driven by industrial-scale production, extensive supply chains, and the increasing demand for diverse and processed food products. While

these developments have enhanced food availability and accessibility, they have also introduced significant challenges related to food safety, particularly in the context of chemical contamination. Among the most concerning contaminants are pesticide residues and heavy metals, which can accumulate in food products

and pose serious health risks to consumers. These contaminants are often present at trace levels, necessitating highly sensitive detection methods capable of identifying minute concentrations with high specificity (Pang et al., 2016).

Traditional analytical techniques, such as chromatography and mass spectrometry, have long been considered the gold standard for detecting chemical contaminants in food. However, these methods are often limited by their complexity, high cost, and requirement for extensive sample preparation. Furthermore, they are not well-suited for rapid or on-site detection, which is increasingly important in modern food safety management systems. These limitations have driven the exploration of alternative approaches, particularly those based on nanotechnology and advanced spectroscopic techniques (Li et al., 2024).

Surface-enhanced Raman spectroscopy (SERS) has emerged as one of the most promising techniques for the detection of chemical contaminants in food. SERS enhances the Raman scattering signal of molecules adsorbed on nanostructured metallic surfaces, enabling the detection of analytes at extremely low concentrations. The enhancement effect is primarily attributed to localized surface plasmon resonance, which amplifies the electromagnetic field near the surface of the nanostructures (Song et al., 2020). This phenomenon allows for the identification of specific molecular fingerprints, making SERS a powerful tool for qualitative and quantitative analysis.

Recent advancements in nanomaterials have significantly improved the performance of SERS-based sensors. Hybrid nanostructures, such as Au@AgPt nanoparticles and graphene-based composites, have been shown to provide enhanced sensitivity and stability, enabling the detection of heavy metal ions such as mercury and lead at ultra-trace levels (Song et al., 2020; He et al., 2021). Similarly, the development of flexible and transparent SERS substrates has facilitated in situ detection of pesticide residues on food surfaces, representing a major step forward in practical applications (Liu et al., 2022).

In addition to SERS, nanobiosensors have gained considerable attention for their ability to detect a wide range of analytes through the integration of biological recognition elements with nanomaterials. These sensors leverage the specificity of biological interactions, such as

antigen-antibody binding or nucleic acid hybridization, to achieve high selectivity in detection. Advances in nanomaterials, including MXenes and organic nanosensors, have further expanded the capabilities of biosensing platforms by enabling multifunctional detection and improved signal transduction (Wu et al., 2023; Mahmoud et al., 2023).

The application of nanotechnology in food safety is not limited to detection but also extends to sample preparation and analysis. Green analytical chemistry approaches, which emphasize sustainability and environmental friendliness, have been increasingly integrated with nanotechnology to develop efficient and eco-friendly detection methods. Nanomaterials can be used to enhance extraction efficiency, reduce solvent usage, and improve overall analytical performance (Sharma et al., 2022; El-Maghraby et al., 2022).

Despite these advancements, several challenges remain in the implementation of nanotechnology-based detection systems. Issues related to reproducibility, standardization, and regulatory approval pose significant barriers to widespread adoption. Additionally, the complexity of food matrices and the potential for interference from other compounds present challenges for accurate detection (Valenzuela-Amaro et al., 2023).

The existing literature provides extensive insights into individual technologies and their applications; however, there is a lack of comprehensive studies that integrate SERS and nanobiosensor technologies within a unified framework for food safety. This research aims to address this gap by providing a detailed and integrative analysis of advanced detection systems, with a focus on their theoretical foundations, material innovations, and practical implications.

2. Methodology

The methodology employed in this research is based on a qualitative and integrative analytical framework designed to synthesize insights from the provided literature. The approach is interdisciplinary, encompassing concepts from nanotechnology, spectroscopy, analytical chemistry, and food safety science. The primary objective is to construct a comprehensive understanding of advanced detection technologies and their applications in food systems.

The first stage of the methodology involves a thematic classification of the literature into key domains,

including SERS-based detection, nanobiosensor technologies, nanomaterials for sensing, and green analytical methods. Each domain is analyzed in depth to identify the underlying principles, technological advancements, and application areas.

The second stage focuses on the analysis of nanomaterial properties and their role in enhancing detection performance. This includes an examination of metallic nanoparticles, graphene-based materials, MXenes, and hybrid nanostructures. The analysis considers factors such as surface morphology, electronic properties, and interaction mechanisms with target analytes (Li et al., 2024).

The third stage involves the evaluation of detection mechanisms, with a particular emphasis on SERS and biosensing techniques. This includes a detailed examination of signal enhancement mechanisms, detection limits, and specificity. The study also explores the role of chemometric models in improving quantitative analysis (Jiao et al., 2020).

The fourth stage addresses the integration of nanotechnology with green analytical chemistry. This includes the use of nanomaterials for sample extraction and preparation, as well as the development of environmentally sustainable detection methods.

Finally, the methodology includes a critical assessment of challenges and limitations, as well as the identification of future research directions. This comprehensive approach ensures a holistic understanding of the current state of nanotechnology-based food safety systems.

3. Results

The results of this study demonstrate that SERS-based detection systems offer unparalleled sensitivity and specificity for the detection of chemical contaminants in food. The use of nanostructured metallic surfaces, such as Au@AgPt nanoparticles, enables the amplification of Raman signals, allowing for the detection of analytes at extremely low concentrations (Song et al., 2020).

Graphene-based SERS substrates have been shown to provide additional enhancement through chemical interactions and improved stability. The combination of graphene with metallic nanostructures results in dual-enhancement effects, significantly improving detection performance for heavy metal ions such as lead (He et al., 2021).

The study also highlights the effectiveness of SERS in detecting pesticide residues. Nanostructures such as Ag@ZnO nanofibers and silver nanoparticles have been successfully used to detect pesticides such as deltamethrin and fipronil, demonstrating high sensitivity and reliability (Jiao et al., 2020; Ly et al., 2019). Flexible SERS substrates further enable in situ detection on food surfaces, enhancing practical applicability (Liu et al., 2022).

Nanobiosensors have also demonstrated significant potential in food safety applications. These sensors leverage biological recognition mechanisms to achieve high selectivity, while nanomaterials enhance signal transduction. Emerging materials such as MXenes offer multifunctional sensing capabilities, including optical and electrical detection (Wu et al., 2023).

Green analytical approaches have been successfully integrated with nanotechnology to improve sample preparation and reduce environmental impact. Nanomaterials enhance extraction efficiency and enable the development of sustainable detection methods (Sharma et al., 2022).

4. Discussion

The findings of this study highlight the transformative potential of SERS and nanobiosensor technologies in food safety. The ability to detect contaminants at ultra-trace levels represents a significant advancement over traditional methods, enabling more effective monitoring and risk management.

However, the implementation of these technologies is not without challenges. Reproducibility remains a major concern, as variations in nanostructure fabrication can affect sensor performance. Standardization of methods and materials is essential to ensure consistent and reliable results.

Another important consideration is the complexity of food matrices, which can interfere with detection and reduce accuracy. Advanced data analysis techniques, such as chemometric modeling, are needed to address these challenges.

Future research should focus on the development of robust, cost-effective, and user-friendly detection systems that can be deployed in real-world settings. The integration of nanotechnology with digital systems and artificial intelligence presents promising opportunities

for enhancing food safety.

5. Conclusion

This study demonstrates that advanced nanotechnology-based detection systems, particularly SERS and nanobiosensors, offer significant improvements in the detection of chemical contaminants in food. These technologies provide high sensitivity, specificity, and potential for real-time monitoring, making them valuable tools for ensuring food safety.

While challenges remain, continued research and innovation are expected to overcome these barriers and enable the widespread adoption of these technologies. The integration of nanotechnology with sustainable and digital approaches represents a promising pathway for the future of food safety.

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