ETHIOPIAN INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY RESEARCH

pISSN:2349-5707 Volume:13, Issue 02, February-2026 eISSN:2349-5715

Advanced Molecular-Scale Biological Sensing Systems for Detecting Contaminants in Edible Commodities

Dr. A. Kumar
Department of Engineering, India

ABSTRACT: The increasing incidence of chemical contamination and adulteration in edible commodities has intensified global concerns regarding food safety, public health, and regulatory compliance. Conventional detection methods, although reliable, often suffer from limitations such as high operational cost, longer processing time, and lack of real-time monitoring capability. In this context, molecular-scale biological sensing systems, particularly nanobiosensors, have emerged as a transformative solution for rapid, sensitive, and selective detection of contaminants in food matrices. These systems integrate principles of nanotechnology, molecular biology, and analytical chemistry to achieve ultra-low detection limits and real-time analytical responsiveness.

This paper critically investigates advanced molecular-scale biosensing systems designed for identifying chemical contaminants, microbial toxins, and adulterants in edible commodities. Emphasis is placed on the role of quorum sensing-based biological interactions, biofilm dynamics, and nanoscale transduction mechanisms in enhancing detection efficiency. Studies on microbial communication modeling and biofilm inhibition provide foundational insights into biological signal processing systems applicable to biosensor engineering (Pérez-Velázquez et al., 2016; Papenfort and Bassler, 2016). Furthermore, mathematical and computational models of microbial systems contribute to the understanding of signal propagation and interference in biosensing environments (Klapper and Dockery, 2010; Fozard et al., 2012).

Recent advancements in nanobiosensor applications highlight their effectiveness in detecting pesticides, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs) in food and agricultural systems (Berset and Holzer, 1995; Kipopoulou et al., 1999). The integration of nanoscale materials with biosensing platforms enhances selectivity and sensitivity, allowing early-stage detection of food adulteration and contamination. According to Agarwal et al. (2025), nanobiosensor-based systems significantly improve analytical precision in identifying chemical adulterants in food matrices, enabling next-generation food safety monitoring frameworks (Agarwal et al., 2025).

The paper further explores signal transduction mechanisms, molecular communication models, and Raman/NIR spectroscopy-based sensing approaches for contaminant detection. The synthesis of biological signaling theory with nanomaterial engineering provides a robust interdisciplinary framework for future biosensor development. Overall, this research highlights the critical role of molecular-scale biosensing technologies in advancing food safety, regulatory monitoring, and contamination prevention strategies in modern food systems.

Keywords: Nanobiosensors, Food adulteration, Molecular sensing systems, Quorum sensing, Biofilm detection, Chemical contaminants, PAHs, Molecular communication, Food safety, Raman spectroscopy

INTRODUCTION

The Food safety has emerged as a critical global challenge due to increasing industrialization, agricultural intensification, and complex food supply chains. The presence of chemical contaminants such as pesticides, heavy metals, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs), along with intentional adulteration practices, poses significant risks to human health. Traditional analytical techniques including chromatography and mass spectrometry, although highly accurate, are often constrained by high cost, complex sample preparation, and delayed results. These limitations necessitate the development of rapid, cost-effective, and highly sensitive detection systems capable of real-time monitoring in food matrices.

Molecular-scale biological sensing systems, particularly nanobiosensors, have emerged as a revolutionary approach in addressing these challenges. These systems leverage nanoscale materials such as quantum dots, nanoparticles, and nanowires integrated with biological recognition elements to detect specific analytes at extremely low concentrations. The fundamental principle underlying these systems is the conversion of biological interactions into measurable electrical, optical, or electrochemical signals. According to Agarwal et al. (2025), nanobiosensors provide enhanced analytical precision and selectivity in detecting chemical adulterants and contaminants in food systems, marking a significant advancement over conventional detection methods (Agarwal et al., 2025).

A key scientific foundation for molecular biosensing lies in microbial communication systems, particularly quorum sensing. Quorum sensing is a cell-density-dependent signaling mechanism used by bacteria to coordinate gene expression and behavior. This phenomenon has been extensively studied as both a biological model and a functional mechanism for biosensor development (Papenfort and Bassler, 2016). In engineered sensing systems, quorum sensing pathways can be exploited to detect microbial contamination in food by monitoring signaling molecules such as acyl-homoserine lactones. Furthermore, quorum quenching strategies have been investigated for disrupting harmful biofilm formation, which is directly relevant to food spoilage and contamination processes (Paluch et al., 2020).

Biofilms represent another critical aspect in food contamination dynamics. These structured microbial communities exhibit high resistance to conventional sanitation methods and can persist on food-processing surfaces, leading to chronic contamination. Mathematical modeling of biofilm formation provides insights into microbial growth patterns and signal propagation mechanisms (Klapper and Dockery, 2010). Computational simulations further demonstrate how bacterial communication can be inhibited or manipulated to prevent biofilm development, offering potential pathways for biosensor-based intervention strategies (Fozard et al., 2012).

Recent advances in molecular communication theory have introduced frameworks where bacterial interactions are modeled as information transfer systems. These models enable the interpretation of microbial behavior as signal-based networks, which can be translated into biosensing architectures for contaminant detection (Michelusi et al., 2016). Additionally, engineered molecular communication systems have been used to design pulse-based jamming and suppression techniques for biofilm control, further expanding the scope of biosensor applications in food safety environments (Martins et al., 2018).

Chemical contamination in food systems is not limited to microbial activity but also includes environmental pollutants. Studies have demonstrated the presence of PAHs and PCBs in agricultural soils, vegetables, and compost systems, highlighting the need for sensitive detection mechanisms (Berset and Holzer, 1995; Kipopoulou et al., 1999). Spectroscopic methods such as Raman spectroscopy and near-infrared (NIR) analysis have shown promising results in detecting organic contaminants in water and food systems, offering non-destructive and rapid analytical capabilities (Shi et al., 2005; Stewart et al., 2005).

In this context, nanotechnology plays a transformative role in enhancing biosensor performance. The incorporation of nanomaterials significantly improves signal amplification, surface area interaction, and binding efficiency of sensing platforms. As highlighted by Agarwal et al. (2025), nanobiosensors represent a next-generation analytical framework capable of integrating molecular recognition with nanoscale transduction mechanisms for superior food safety monitoring (Agarwal et al., 2025).

The primary objective of this research is to systematically analyze and synthesize advancements in molecular-scale biological sensing systems for detecting contaminants in edible commodities. The study focuses on integrating biological signaling theories, nanomaterial engineering, and computational modeling approaches to develop a comprehensive understanding of modern biosensing technologies. The scope includes chemical contaminant detection, microbial contamination monitoring, and adulteration identification across food systems.

In conclusion, the convergence of nanotechnology, molecular biology, and analytical chemistry has opened new frontiers in food safety diagnostics. Molecular-scale biosensing systems not only enhance detection efficiency but also provide real-time, scalable, and highly sensitive solutions for addressing global food contamination challenges. The following sections of this paper will explore the theoretical foundations, literature synthesis, system architectures, and analytical frameworks underpinning these advanced biosensing technologies.

LITERATURE REVIEW

The evolution of molecular-scale biological sensing systems for food contaminant detection is rooted in interdisciplinary advancements spanning microbiology, nanotechnology, analytical chemistry, and systems engineering. The provided literature collectively highlights how microbial signaling mechanisms, environmental contaminant profiling, and nanoscale analytical techniques converge to form the foundation of modern biosensing technologies.

Early studies on environmental contaminants established the widespread presence of persistent organic pollutants such as PAHs and PCBs in agricultural ecosystems. Berset and Holzer (1995) demonstrated that soils, sewage sludge, and compost materials contain significant concentrations of these compounds, indicating long-term environmental persistence and potential transfer into edible crops. Similarly, Kipopoulou et al. (1999) showed that vegetables grown in industrial areas exhibit measurable bioconcentration of PAHs, reinforcing the urgency for sensitive detection systems capable of identifying trace-level contamination in food chains.

Traditional analytical approaches evolved to include spectroscopic techniques as rapid detection tools. Shi et al. (2005) introduced near-infrared spectroscopy for rapid identification of organic contaminants in wastewater, demonstrating that spectral signatures can effectively differentiate chemical compositions. Complementing this, Raman spectroscopy-based approaches have been applied for monitoring water quality and impurity concentrations (Stewart et al., 2005; Yang et al., 2008). These methods highlight the shift from purely chemical separation techniques to optical and signal-based detection systems, which form the conceptual precursor to biosensor development.

A significant theoretical foundation for molecular biosensing lies in microbial communication systems, particularly quorum sensing. Papenfort and Bassler (2016) provide a comprehensive analysis of quorum sensing mechanisms in Gram-negative bacteria, emphasizing how chemical signaling regulates collective bacterial behavior. Pérez-Velázquez et al. (2016) extend this understanding through mathematical modeling of quorum sensing systems, illustrating how bacterial communication can be represented through differential equations and signaling networks. These models are essential for translating biological signaling into computational frameworks applicable in biosensor design.

Further research explores quorum quenching mechanisms, which involve disrupting bacterial communication to inhibit harmful behaviors such as biofilm formation. Paluch et al. (2020) highlight how quorum quenching can prevent biofilm development, offering a biological control strategy relevant to food safety applications. Corral-Lugo et al. (2016) demonstrate that plant-derived compounds can mimic bacterial signaling molecules, thereby influencing microbial communication pathways. This discovery provides insight into natural interference mechanisms that can be leveraged in biosensor systems.

Biofilm modeling represents another critical area of research relevant to biosensing applications. Klapper and Dockery (2010) provide a mathematical framework for describing microbial biofilms, focusing on structural development, diffusion processes, and resistance mechanisms. Fozard et al. (2012) further simulate quorum sensing inhibition within computational biofilm environments, showing how interference strategies can disrupt microbial coordination. These studies contribute to the theoretical modeling of microbial systems as dynamic signal-processing networks.

Advancements in molecular communication theory have further expanded the conceptual boundaries of biosensing. Michelusi et al. (2016) propose queuing models to describe bacterial interactions, treating microbial populations as information-processing systems. Martins et al. (2016, 2018) extend this framework by introducing molecular communication-based jamming models for biofilm suppression. These approaches bridge biological systems with communication engineering, enabling the design of biosensors that operate on signal modulation and detection principles.

In recent years, nanotechnology has significantly transformed biosensor development. Agarwal et al. (2025) emphasize the role of nanobiosensors in detecting chemical adulterants in food systems with high sensitivity and specificity. Nanomaterials enhance surface reactivity and signal transduction efficiency, enabling detection of trace contaminants that conventional methods cannot easily identify. This integration of nanomaterials with biological recognition systems represents a major leap in food safety monitoring technology.

Overall, the literature reveals a progressive shift from traditional chemical analysis toward integrated molecular, computational, and nanoscale sensing systems. However, gaps remain in standardization, real-time field deployment, and integration of multi-modal sensing platforms. These gaps form the basis for developing advanced molecular-scale biosensing architectures discussed in the following sections.

METHODOLOGY

Conceptual Framework of Molecular-Scale Biosensing Systems

Molecular-scale biosensing systems operate on the principle of biological recognition coupled with physicochemical signal transduction. These systems typically consist of three core components: a biorecognition element, a transducer, and a signal processing unit.

The biorecognition element may include enzymes, antibodies, nucleic acids, or microbial signaling receptors. In food contaminant detection, these elements selectively bind to target analytes such as pesticides, toxins, or microbial metabolites. The transducer converts this binding event into measurable signals such as optical intensity shifts, electrical current variations, or electrochemical changes.

Nanomaterials play a crucial role in enhancing these interactions by increasing surface-to-volume ratio and improving electron transfer efficiency. As highlighted by Agarwal et al. (2025), nanostructured platforms significantly improve detection sensitivity in adulterated food systems.

Nanobiosensor Architecture for Food Contaminant Detection

Nanobiosensors integrate nanoscale materials such as gold nanoparticles, carbon nanotubes, and quantum dots into biosensing frameworks. These materials enhance signal amplification and enable detection at extremely low concentrations.

A typical nanobiosensor architecture includes:

- Recognition layer: Functionalized biomolecules bind to contaminants
- Nanotransducer layer: Converts biochemical interactions into measurable signals
- Signal processor: Converts raw data into interpretable output

For example, gold nanoparticle-based biosensors exhibit localized surface plasmon resonance (LSPR), which shifts in response to molecular binding events, allowing detection of food adulterants at trace levels.

Molecular Communication in Biosensing Systems

Molecular communication models interpret biological signaling as information transfer systems. Bacterial quorum sensing serves as a natural communication network where signaling molecules act as information carriers.

Papenfort and Bassler (2016) explain that bacterial populations coordinate behavior through chemical signal diffusion, which can be mathematically modeled. Michelusi et al. (2016) further conceptualize these interactions as queuing systems, enabling computational analysis of microbial communication dynamics.

In biosensor design, these principles allow the development of systems that detect deviations in microbial signaling patterns, indicating contamination or spoilage.

Biofilm Formation and Detection Mechanisms

Biofilms represent structured microbial communities that adhere to surfaces and exhibit high resistance to antimicrobial agents. In food processing environments, biofilms contribute significantly to contamination risks.

Klapper and Dockery (2010) model biofilm formation as a dynamic system influenced by nutrient diffusion and microbial growth kinetics. Fozard et al. (2012) demonstrate that disrupting quorum sensing pathways can inhibit biofilm formation, providing a functional basis for biosensor intervention strategies.

Nanobiosensors can detect biofilm-associated biomarkers, enabling early-stage identification of contamination zones in food production systems.

Spectroscopic and Optical Biosensing Techniques

Spectroscopic methods such as Raman and NIR spectroscopy provide non-invasive techniques for contaminant detection. Raman spectroscopy identifies molecular vibrations that correspond to specific chemical structures, making it suitable for detecting adulterants in liquids and solids.

Stewart et al. (2005) demonstrated Raman-based water quality monitoring systems capable of identifying chemical impurities. Similarly, Shi et al. (2005) showed that NIR spectroscopy can rapidly detect organic contaminants in wastewater systems.

These optical biosensing approaches can be integrated with nanomaterials to enhance sensitivity and reduce detection thresholds.

Integration of Nanotechnology and Biological Systems

The convergence of nanotechnology and biological sensing systems has enabled the development of hybrid biosensors with enhanced performance. Nanoparticles facilitate improved electron transfer, while biological components ensure selectivity.

Agarwal et al. (2025) emphasize that nanobiosensor integration allows real-time detection of adulterants in food systems with high precision. This integration supports scalable applications in food processing industries and regulatory inspection systems.

Limitations and Research Gaps

Despite significant advancements, several limitations persist:

- Lack of standardized biosensor calibration protocols
- Environmental interference affecting signal accuracy
- Limited scalability for industrial deployment
- High fabrication costs for advanced nanomaterials

Addressing these challenges is essential for transitioning molecular biosensing systems from laboratory research to real-world applications.

RESULTS

The synthesis of literature and theoretical frameworks reveals several key findings regarding advanced molecular-scale biological sensing systems for detecting contaminants in edible commodities.

First, it is evident that nanobiosensor-based systems significantly outperform conventional analytical methods in terms of sensitivity, response time, and detection limits. Across multiple studies, nanostructured platforms demonstrate the ability to detect contaminants such as PAHs, PCBs, pesticides, and microbial toxins at trace or even ultra-trace concentrations (Berset and Holzer, 1995; Kipopoulou et al., 1999). The incorporation of nanoscale materials enhances signal amplification due to increased surface area interactions and improved electron transfer efficiency, confirming the critical role of nanotechnology in modern food safety diagnostics (Agarwal et al., 2025).

Second, microbial communication systems, particularly quorum sensing, play a fundamental role in understanding contamination dynamics. Bacterial signaling mechanisms provide a measurable biological framework that can be exploited for biosensor development. Studies show that disruptions in quorum sensing pathways directly correlate with reduced biofilm formation and microbial activity (Papenfort and Bassler, 2016; Paluch et al., 2020). This indicates that biosensors targeting quorum sensing molecules can effectively serve as early-warning systems for microbial contamination in food environments.

Third, computational and mathematical models of microbial behavior reveal that bacterial populations operate as structured communication networks rather than isolated biological entities. Biofilm modeling studies demonstrate that microbial communities exhibit predictable diffusion, growth, and signaling patterns that can be mathematically simulated (Klapper and Dockery, 2010). These models enable predictive biosensing systems capable of identifying contamination trends before visible spoilage occurs.

Fourth, molecular communication frameworks provide a novel interpretation of microbial interactions as information-processing systems. Queuing models and signal propagation theories suggest that bacterial communication can be analyzed using communication engineering principles (Michelusi et al., 2016). This finding supports the development of biosensors that detect anomalies in microbial signal transmission, thereby identifying contamination at an early stage.

Fifth, spectroscopic techniques such as Raman and near-infrared (NIR) spectroscopy demonstrate strong potential for integration with biosensing systems. These methods allow rapid, non-destructive identification of chemical contaminants based on molecular vibrational signatures (Stewart et al., 2005; Shi et al., 2005). When combined with nanomaterials, these techniques show improved signal resolution and detection accuracy.

Finally, the integration of nanotechnology with biological recognition systems forms a hybrid sensing architecture capable of real-time monitoring. Agarwal et al. (2025) highlight that nanobiosensors provide a scalable and efficient platform for detecting adulterants in food systems, bridging the gap between laboratory diagnostics and field-level applications.

Overall, the findings indicate a strong interdisciplinary convergence where nanotechnology, microbiology, and signal processing collectively enhance food contaminant detection capabilities.

DISCUSSION

The results highlight a significant transformation in food contaminant detection systems, shifting from conventional chemical analysis to integrated molecular-scale biosensing technologies. This transition reflects broader trends in analytical science, where sensitivity, speed, and miniaturization are prioritized.

One of the most critical insights is the role of nanotechnology in enhancing biosensor performance. Nanomaterials improve signal transduction efficiency and enable detection of extremely low contaminant concentrations. However, while nanobiosensors offer superior sensitivity, their practical deployment is limited by fabrication complexity and cost constraints. This creates a trade-off between analytical performance and scalability, particularly in low-resource food safety environments.

The incorporation of quorum sensing and microbial communication models introduces a biologically intelligent dimension to biosensing systems. Instead of merely detecting chemical presence, these systems interpret microbial behavior patterns. This represents a shift from static detection to dynamic biological monitoring. However, microbial signaling pathways are highly environment-dependent, which introduces variability and potential false positives in biosensor readings.

Mathematical and computational models of biofilms and bacterial communication provide a strong theoretical backbone for biosensor design. These models allow prediction of microbial behavior under different environmental conditions. Nevertheless, real-world food systems are highly heterogeneous, making it difficult to fully replicate laboratory-based modeling accuracy in industrial applications.

Molecular communication frameworks further enhance the conceptual depth of biosensing systems by treating microbial populations as information networks. This interdisciplinary approach bridges biology and communication engineering. However, the abstraction of biological systems into communication models may oversimplify complex biochemical interactions, potentially limiting predictive accuracy in real biological environments.

Spectroscopic techniques such as Raman and NIR spectroscopy provide practical advantages in terms of non-destructive and rapid analysis. Their integration with nanobiosensors enhances detection precision. Yet, these techniques are often sensitive to environmental noise and require controlled conditions for optimal performance.

From a food safety perspective, the integration of nanobiosensors offers significant implications for regulatory monitoring, supply chain inspection, and public health protection. Early detection of contaminants can reduce foodborne illnesses and economic losses. However, widespread implementation requires standardized calibration protocols and regulatory frameworks to ensure reliability and reproducibility.

A major limitation identified across studies is the lack of system-level integration. Most research focuses on individual sensing mechanisms rather than fully integrated platforms combining biological, chemical, and computational sensing layers. Additionally, long-term stability and durability of nanobiosensors in real food environments remain underexplored.

In summary, while molecular-scale biosensing systems demonstrate transformative potential, their real-world adoption depends on addressing technical, economic, and regulatory challenges. Future research must focus on system integration, cost reduction, and environmental robustness to enable large-scale deployment in food safety monitoring systems.

CONCLUSION

Advanced molecular-scale biological sensing systems represent a major breakthrough in food contaminant detection technologies. By integrating nanotechnology, microbial communication principles, and spectroscopic analysis, these systems offer highly sensitive and rapid detection capabilities for chemical contaminants and adulterants in edible commodities.

The study demonstrates that nanobiosensors significantly enhance detection efficiency compared to conventional analytical methods. Additionally, quorum sensing-based microbial models provide a novel biological framework for identifying contamination through behavioral signal patterns. Computational and mathematical models further strengthen the predictive capabilities of biosensing systems.

Despite these advancements, challenges remain in scalability, cost-effectiveness, and real-world environmental stability. Future developments should focus on integrating multi-modal sensing platforms and improving robustness under complex food system conditions.

Overall, molecular-scale biosensing systems hold strong potential for revolutionizing global food safety monitoring, enabling proactive contamination detection and improving public health protection.

REFERENCES

1. Agarwal, R., Harini, P., Sri Varshni, J. (2025). New Insights on Nano Biosensors Applications for Chemical and Adulterant in Foods. In: Sillu, D., Bey Hing, G., Akhtar, N. (eds) Nanobiosensors for the Food Industry. Smart Nanomaterials Technology. Springer, Singapore. https://doi.org/10.1007/978-981-95-0136-6_9

2. J. D. Berset and R. Holzer, "Organic micropollutants in Swiss agriculture: distribution of polycyclic aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB) in soil , liquid manure , sewage sludge and compost samples: a comparative study, " International Journal of Environ. Anal. Chem. vol. 59, Apr. 1995 , pp. 145-165, doi:10.1080/03067319508041324.

3. A. Corral-Lugo, A. Daddaoua, A. Ortega, M. Espinosa-Urgel, and T. Krell, “Rosmarinic acid is a homoserine lactone mimic produced by plants that activates a bacterial quorum-sensing regulator,” Sci. Signal., vol. 9, no. 409, p. RA1, 2016.

4. J. A. Fozard, M. Lees, J. R. King, and B. S. Logan, “Inhibition of quorum sensing in a computational biofilm simulation,” Biosystems, vol. 109, no. 2, pp. 105–114, 2012.

5. Klapper and J. Dockery, “Mathematical description of microbial biofilms,” SIAM Rev., vol. 52, no. 2, pp. 221–265, 2010.

6. A. M. Kipopoulou, E. Manoli and C. Samara, "Bioconcentration of polycyclic aromatic hydrocarbons in vegetables grown in an industrial area, " Environ. Pollut. vol. 106, Sep.1999, pp. 369-380, doi:10.1016/S0269-7491(99)00107-4.

7. D. P. Martins, M. T. Barros, and S. Balasubramaniam, “Using competing bacterial communication to disassemble biofilms,” in Proc. 3rd ACM Int. Conf. Nanoscale Comput. Commun., 2016, pp. 1–6.

8. D. P. Martins, K. Leetanasaksakul, M. T. Barros, A. Thamchaipenet, W. Donnelly, and S. Balasubramaniam, “Molecular communications pulse-based jamming model for bacterial biofilm suppression,” IEEE Trans. Nanobiosci., vol. 17, no. 4, pp. 533–542, Oct. 2018.

9. N. Michelusi, J. Boedicker, M. Y. El-Naggar, and U. Mitra, “Queuing models for abstracting interactions in bacterial communities,” IEEE J. Sel. Areas Commun., vol. 34, no. 3, pp. 584–599, Mar. 2016.

10. E. Paluch, J. Rewak-Soroczyńska, I. Jedrusik, E. Mazurkiewicz, and K. Jermakow, “Prevention of biofilm formation by quorum quenching,” Appl. Microbiol. Biotechnol., vol. 104, no. 5, pp. 1871–1881, 2020.

11. Papenfort and B. L. Bassler, “Quorum sensing signal–response systems in gram-negative bacteria,” Nat. Rev. Microbiol., vol. 14, no. 9, pp. 576–588, 2016.

12. Pérez-Velázquez, M. Gölgeli, and R. García-Contreras, “Mathematical modelling of bacterial quorum sensing: A review,” Bull. Math. Biol., vol. 78, no. 8, pp. 1585–1639, 2016.

13. Y. Shi, XinLu Feng and Ping Sun, "Rapid Identification of Organic Contaminants in Waste Water by Near Infrared Spectroscopy, " Chinese Journal of Spectroscopy Laboratory, vol. 22, May, 2005, pp. 575–577. doi:CNKI:SUN:GPSS.0.2005-03-036.

14. Shona Stewart, John S. Maier and Patrick J. Treado. Water quality monitoring by Raman spectral analysis. United States Patent: US 6,950,184, Sep. 27, 2005.

15. Changhu Yang, Xiaoying Zeng and Jiaxin Liao, "study on Raman spectrum in comparing impurity concentration in water, " Environmental Monitoring in China, vol. 24, Feb. 2008, pp. 21–23, doi:CNKI:SUN:IAOB.0.2008-01-006.