SERS for Rapid Pesticide Detection in Food Safety

Pesticides remain essential to global food production, protecting crops from pests and disease on a vast scale. Yet this scale carries a real human cost. A 2020 systematic review covering 141 countries estimated that around 385 million cases of unintentional acute pesticide poisoning occur worldwide each year, including roughly 11,000 fatalities, with an estimated 44% of the world's farmers and farmworkers poisoned at least once annually. [1] These figures highlight why robust monitoring of pesticide residues across the food chain matters so much for public health.

Conventional analytical methods such as GC-MS and HPLC remain the gold standard for pesticide quantification, but they come with well-documented drawbacks: they are labour-intensive, time-consuming, dependent on costly laboratory equipment, and require complex sample preparation. [2,3]

This gap has driven growing interest in Surface-Enhanced Raman Spectroscopy (SERS) as a faster, more affordable, and easier-to-deploy alternative for detecting pesticide residues present in trace amounts within complex food matrices. [3,4]

Working Principle of SERS

Raman spectroscopy is a molecular fingerprinting technique that uses the inelastic scattering of laser photons by molecular bonds to identify chemical compounds. Its main limitation, however, is inherently weak signal intensity, which restricts its sensitivity as a standalone analytical tool. SERS overcomes this by bringing the target molecule into proximity with a nanostructured metallic surface, typically gold (Au) or silver (Ag), boosting the Raman signal by several orders of magnitude. [5]

This enhancement arises chiefly from the excitation of localised surface plasmon resonance (LSPR) at the metal surface, where laser photons interact with oscillating surface electrons to generate an intense electromagnetic field. The regions where this field is strongest are known as "hot spots", and these can produce enhancement factors of up to 10^{15} relative to normal Raman scattering, a level of amplification associated with single-molecule detection. [6]

A secondary mechanism, chemical enhancement, arises from direct charge transfer between the adsorbed molecule and the metal surface, altering bond polarisability and intensifying specific Raman peaks. [7] Together, these effects allow SERS to deliver structural and molecular-level identification of target analytes at trace concentrations, with minimal sample preparation and in a non-destructive manner. [4,3]

Why SERS Is Well Suited for Pesticide Detection

Several physicochemical properties make SERS a particularly strong fit for pesticide residue analysis in food. Its characteristic fingerprinting ability allows individual pesticide compounds to be identified and differentiated with high chemical specificity, even within complex food matrices such as fruit juice, vegetable peel, and cereal extracts. [8] Its non-destructive nature also means that samples undergo no chemical alteration during analysis, an important advantage for quality control applications where sample integrity must be preserved. [3]

Both label-free and labelled detection approaches are possible for pesticide residues in food. In label-free detection, the pesticide molecule adsorbs directly onto a metallic substrate and produces its own Raman fingerprint, an approach successfully applied to organophosphate, organochlorine, and dithiocarbamate pesticide classes on food surfaces. [9]

Combining both approaches on a single analytical platform also enables the simultaneous detection of multiple pesticide residues, a valuable capability given that food samples are frequently treated with mixtures of active ingredients. [10, 1]

Recent Advances in SERS for Pesticide Detection

Significant progress has been made between 2020 and 2025 in engineering SERS substrates for improved sensitivity, reproducibility, and compatibility with real food matrices. Noble metal nanoparticle systems remain the most widely studied substrate type, with three-dimensional nanostructured architectures consistently outperforming simpler designs by packing a higher density of electromagnetic hot spots into the nano-gaps between particles. [3]

Bimetallic core-shell nanoparticle architectures have also shown promise, with silver-gold core-shell structures combining the strong plasmonic response of silver with the oxidative stability of a gold shell, improving reproducibility and shelf life. Magnetic SERS composites incorporating Fe_3O_4 have similarly been engineered to enable magnetic preconcentration of trace pesticide molecules from complex matrices, improving detection limits while allowing interfering components to be magnetically separated from the sample ahead of analysis. [3]

Paper-based SERS substrates represent another notable advance, offering a cheap, disposable sampling format. A gold nanoparticle/halloysite nanotube (AuNP/HNT) paper substrate prepared via electrostatic self-assembly achieved an LOD of 7.9×10^{-9} M for chlorpyrifos in spiked apple samples, with a recovery rate of 87.9% and an RSD of 6.1%. [11]

The pairing of SERS with aptamer-based biosensing has produced a new generation of biosensors that combine the high selectivity of nucleic acid aptamers with the sensitivity of SERS, with recent aptasensor platforms designed for pesticide residue detection in fruit and vegetables capable of eliminating sample pre-treatment while excelling at simultaneous multi-analyte detection. [1]

The convergence of SERS with lateral flow immunoassay (LFIA) strip technology has also led to semi-quantitative SERS-based strips, capable of both quantitative SERS detection and naked-eye visualisation, an appealing dual capability for food inspection settings. [10]

Sensitivity, Selectivity, and Detection Limits of SERS

Published LOD values from recent SERS studies underline the technique's potential for trace-level pesticide determination. Logan et al. coupled a handheld SERS device with the QuEChERS acetate extraction method and achieved detection limits ranging from 5 to 75 ppb (µg/kg) for four pesticide residues in spiked Basmati rice, demonstrating that handheld SERS can rival the sensitivity of laboratory-based systems. [12] Separately, the AuNP/HNT paper-based SERS substrate achieved an LOD of 7.9×10^{-9} M for chlorpyrifos, comfortably below the maximum residue levels (MRLs) set by the European Food Safety Authority (EFSA) for most food commodities. [11]

Freund and Guo developed a portable, cotton-tip SERS nanosubstrate to evaluate the effectiveness of washing methods in removing ferbam fungicide residue from peach surfaces, demonstrating the simplicity, sensitivity, and field-readiness of the approach for direct monitoring of fresh produce. [2] Studies using functionalised noble metal nanomaterial-based SERS sensors have similarly demonstrated high selectivity, achieved through a combination of the SERS effect and selective molecular adsorption mechanisms. [13]

Reproducibility remains a central challenge for SERS, and substrate developers continue to address it directly. Wen et al. demonstrated a portable SERS-based lateral flow immunosensor for multiple small-molecule pollutants with strong real-sample recoveries and low signal variability, while mesoporous silica coatings have separately been shown to improve the long-term stability of gold and silver nanoparticle SERS substrates by limiting particle aggregation, both pointing to meaningful progress in SERS reproducibility. [3, 9]

Real-World Applications of SERS for Pesticide Detection

Practical applications of SERS-based pesticide residue detection span fruit and vegetables, cereal products, and liquid foods. In fruit and vegetables, Sun et al. developed a SERS imaging technique using dynamic borohydride-reduced silver nanoparticles to map the whole-process distribution of dimethoate and cypermethrin residues across crop surfaces and internal tissue, achieving a detection limit below 1 picogram/mL. Vertex component analysis (VCA) was used to reduce the confounding effect of plant autofluorescence on imaging accuracy. [14] In cereal products, Logan et al. demonstrated the practical value of SERS coupled with QuEChERS for residue detection in Basmati rice, a globally traded commodity where residue compliance is essential. [12]

In liquid food products, an NIR-SERS feature-layer fusion model developed by Yan et al. achieved a prediction-set R^2 of 0.988 and a relative percent deviation (RPD) of 8.290 for pesticide residue detection in complex liquid matrices, demonstrating that fusing the two spectral techniques suppresses matrix interference more effectively than either method used alone. [15]

Machine learning paired with SERS has been explored across several studies as a tool for interpreting complex spectra in pesticide residue detection, although this remains an early-stage area of research. [15] Key challenges still facing the field include batch-to-batch substrate variability, signal reproducibility in complex matrix conditions, and a lack of standardisation in fabrication processes, all of which will need addressing before SERS can be widely adopted for regulatory use. That said, the progress made between 2020 and 2025 in substrate design, portable instrumentation, and residue detection capability has brought the technology to a meaningful level of technical maturity within food safety. [3]

Why Choose Nikalyte SERS for Pesticide Detection?

Nikalyte SERS substrates are built for exactly this kind of demanding, real-world residue analysis. Our gold and silver paper-based SERS substrates combine laboratory-grade sensitivity with a portable, easy-to-use format suited to both bench and field deployment. They deliver reproducible results and enhance Raman spectra by up to 1000x compared with traditional colloidal SERS, with sensitivity spanning the ppm to ppb range. [16] This means food testing laboratories, quality assurance teams, and regulatory bodies can screen for pesticide residues with confidence, without the long turnaround times associated with conventional GC-MS or HPLC workflows. The paper substrate format simplifies sample handling and remains stable during storage and transport, making frequent, routine testing more practical and more accessible across the food supply chain.

Conclusion

SERS has moved from a promising laboratory technique to a genuinely mature analytical tool for pesticide residue detection in food. Advances in substrate engineering, from 3D nanostructures to paper-based and aptamer-functionalised platforms, have steadily pushed detection limits lower while improving reproducibility and field usability. Challenges around standardisation and batch-to-batch consistency remain, but the trajectory of the past five years points clearly towards SERS playing an increasingly central role in rapid, accessible food safety monitoring.

Discover how Nikalyte SERS substrates can advance your pesticide residue research. Shop SERS substrates now!

References

1. Ashiagbor, K., Jayan, H., Yosri, N., Amaglo, N. K., Zou, X., & Guo, Z. (2025). Advancements in SERS-based systematic evolution of ligands by exponential enrichment for detection of pesticide residues in fruits and vegetables. Food Chemistry, *463*(Part 3), 141394. https://doi.org/10.1016/j.foodchem.2024.141394
2. Freund, L., Mossa, J., & Guo, H. (2025). Development of a portable SERS tool to evaluate the effectiveness of washing methods to remove pesticide residue from fruit surface. *Analytica Chimica Acta,* *1336*, 343476.. https://doi.org/10.1016/j.aca.2024.343476
3. Wen, R., Han, Y., Tang, X., Zeng, W., Zhang, S., & Wu, L. (2025). Advancing food safety with SERS: The role of noble metal nanomaterials in detecting food contaminants. *Trends in Food Science & Technology,* *160*, 10499 https://doi.org/10.1016/j.tifs.2025.104995
4. Feng, L., Yue, X., Li, J., Zhao, F., Yu, X., & Yang, K. (2025). Research advances in nanosensor for pesticide detection in agricultural products. *Nanomaterials, 15*(14), 1132. https://doi.org/10.3390/nano15141132

5. Terry, L. R., Sanders, S., Potoff, R. H., Kruel, J. W., Jain, M., & Guo, H. (2022). Applications of surface-enhanced Raman spectroscopy in environmental detection. *Analytical Science Advances, 3*(3–4), 113–145. https://doi.org/10.1002/ansa.20220000
6. Wetzel, W. (2024, October 25). *New SERS imaging technique unveils ultra-sensitive detection of pesticide residues in crops*. Spectroscopy Online. https://www.spectroscopyonline.com/view/new-sers-imaging-technique-unveils-ultra-sensitive-detection-of-pesticide-residues-in-crops
7. Xie, T., Cao, Z., Li, Y., Li, Z., Zhang, F.-L., Gu, Y., Han, C., Yang, G., & Qu, L. (2022). Highly sensitive SERS substrates with multi-hot spots for on-site detection of pesticide residues. *Food Chemistry, 381*, 132208. https://doi.org/10.1016/j.foodchem.2022.132208
8. Wang, X., Huang, S.-C., Hu, S., Yan, S., & Ren, B. (2020). Fundamental understanding and applications of plasmon-enhanced Raman spectroscopy. *Nature Reviews Physics, 2*(5), 253–271. https://doi.org/10.1038/s42254-020-0171-y
9. Wang, J.-P., Zheng, Y., Wang, X., Zhou, X., Qiu, Y., & others. (2023). *Dosage-sensitive and simultaneous detection of multiple small-molecule pollutants in environmental water and agriproducts using portable SERS-based lateral flow immunosensor*. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2023.169440
10. Ma, L., Zhou, R., Yin, L., Sun, L., Han, E., Bai, J., & Cai, J. (2025). Simultaneous detection of food contaminants using surface-enhanced Raman scattering (SERS): A review. *Foods, 14*(17), 2982. https://doi.org/10.3390/foods14172982
11. Zhang, X., Chen, L., Fang, X., Shang, Y., Gu, H., Jia, W., Yang, G., Gu, Y., & Qu, L. (2022). Rapid and non-invasive surface-enhanced Raman spectroscopy (SERS) detection of chlorpyrifos in fruits using disposable paper-based substrates charged with gold nanoparticle/halloysite nanotube composites. *Microchimica Acta, 189*(5), 261. https://doi.org/10.1007/s00604-022-05261-1
12. Logan, N., Haughey, S. A., Liu, L., Burns, D. T., Quinn, B., Cao, C., & Elliott, C. T. (2022). Handheld SERS coupled with QuEChERS for the sensitive analysis of multiple pesticides in basmati rice. *npj Science of Food, 6*, Article 3. https://doi.org/10.1038/s41538-021-00117-z
13. Yilmaz, D., Gunaydin, B. N., & Yuce, M. (2022). Nanotechnology in food and water security: On-site detection of agricultural pollutants through surface-enhanced Raman spectroscopy. Emergent Materials, 5, 105–132. https://doi.org/10.1007/s42247-022-00376-w
14. Sun, X., Zhao, Y., Zhao, Y., Liu, L., Qiao, Y., Yang, C., Wang, X., Wang, R., Qian, L., Li, Q., & Li, Y. (2024). Visual whole-process monitoring of pesticide residues: An environmental perspective using surface-enhanced Raman spectroscopy with dynamic borohydride-reduced silver nanoparticles. *Journal of Hazardous Materials, 465*, 133338. https://doi.org/10.1016/j.jhazmat.2023.133338
15. Yan, F., Zhang, R., Wang, S., Zhang, N., & Zhang, X. (2025). A pesticide residue detection model for food based on NIR and SERS. *PLOS ONE, 20*(4), e0320456. https://doi.org/10.1371/journal.pone.0320456

16. Nikalyte Ltd. (n.d.). Surface enhanced Raman spectroscopy (SERS) substrates. https://www.nikalyte.com/sers-substrates-new/