SERS Applications in Soil Contamination Testing

Soil contamination, from heavy metals, pesticides, and polycyclic aromatic hydrocarbons (PAHs), poses serious risks to human health and ecosystems. Conventional methods such as ICP-MS, GC-MS, and HPLC remain the gold standard for confirmatory analysis, but they require sophisticated laboratory infrastructure, lengthy sample preparation, and are poorly suited to rapid field screening. [1]

Surface-Enhanced Raman Spectroscopy (SERS) addresses precisely this gap. By exploiting the electromagnetic enhancement generated at plasmonic gold or silver nanoparticle surfaces, SERS delivers molecular fingerprint detection at parts-per-billion concentrations, in complex matrices, with portable instrumentation, and without the operational burden of conventional laboratory methods. [2]

How SERS Works

When a laser excites metallic nanoparticles at their localised surface plasmon resonance frequency, the electromagnetic field in the nanogaps between particles (so-called “hot spots”) is amplified by factors of 10^8 to 10^{12}. Molecules adsorbed within these hot spots experience a corresponding amplification of their Raman scattering signal, yielding structural information sufficient for identification and quantification at trace concentrations [3] . A critical practical advantage for soil applications is that near-infrared SERS measurements largely avoid the fluorescence interference generated by humic acids and organic matter in soil extracts.

SERS for Heavy Metal Detection

Heavy metals including Pb, Hg, As, and Cd cannot be degraded in soil and accumulate in the food chain through plant uptake. Functionalized SERS substrates have achieved mercury detection limits as low as 0.45 µg/L and arsenic detection in crop tissues at 0.0273 µg/g using aminobenzeneboronic acid-labelled silver nanoparticles, with results in excellent agreement with ICP-MS ($R^2 = 0.999$ [4]. Machine learning applied to SERS datasets enables automated classification of heavy metal contamination levels across environmental samples. [5]

SERS for Pesticide Residues in Soil

Pesticide detection is currently the most extensively published application of SERS in environmental analysis [2]. For organochlorine pesticides including aldrin, dieldrin, and lindane, alkyl dithiol-functionalized gold and silver substrates achieved successful detection by creating hydrophobic hot-spot environments to recruit these non-polar analytes [6]. For glyphosate, the world’s most widely used herbicide, cysteamine-modified silver nanoparticle substrates improved detection limits by up to two orders of magnitude over unmodified substrates [7]. Convolutional neural network models combined with SERS data have achieved up to 100% classification accuracy for mixed organophosphate pesticide detection, addressing the multi-residue challenge that is central to regulatory soil monitoring.

SERS for Polycyclic Aromatic Hydrocarbons

The US EPA designates 16 priority PAHs for soil monitoring, all toxic and several carcinogenic. SERS detection of pyrene and anthracene in soil extracts using β-cyclodextrin-modified gold nanoparticles achieved recovery rates of 101.8–106.4% compared to GC-MS reference analysis, demonstrating the accuracy of SERS in real matrix conditions [8]. A 2025 PNAS study combining in silico DFT-calculated SERS reference spectra with a machine learning pipeline demonstrated identification of PAHs directly from contaminated soil extracts, overcoming the matrix complexity challenge that has historically limited PAH identification by optical methods [9].

Field Deployment with Portable Raman Systems

SERS is directly compatible with hand-held and portable Raman spectrometers, enabling on-site soil screening without laboratory infrastructure. Detection of PAHs at sub-ppb concentrations and pesticides at ppm-to-ppb levels has been validated using portable instrumentation [10]. For academics and industrial scientists, this opens the prospect of rapid triage screening of contaminated land during site assessment or remediation monitoring, with confirmatory analysis reserved for samples flagged by SERS.

Why Choose Nikalyte SERS Substrates?

Nikalyte manufactures gold and silver SERS substrates using our nanoparticle benchtop system NL-50, a physical vapour deposition process conducted entirely under vacuum.[11] This sets Nikalyte substrates apart from chemically synthesised alternatives in several key respects.

- **Ultra-pure, hydrocarbon-free nanoparticles:** Chemically synthesised nanoparticles carry residual capping agents (citrate, PVP, CTAB) that generate Raman background signals and compete with analyte adsorption. Nikalyte's vacuum-fabricated nanoparticles are free of these contaminants, delivering a cleaner spectral baseline, critical when detecting trace soil contaminants in complex extract matrices.

- **No drying required:** The paper-based substrate format accepts sample extracts directly. Measurement is immediate, reducing analyte loss and accelerating throughput for multi-sample soil screening workflows.

- **Dual substrate options:** Gold substrates (785 nm, 830 nm) minimise fluorescence interference from soil organic matter. Silver substrates (532 nm, 785 nm) deliver higher enhancement factors for analytes with strong surface affinity for silver. Both are available commercially in packs of five.

- **Independently validated performance:** Nikalyte's SERS substrates have been validated by Agilent Technologies [12] and Wasatch Photonics [13] in published application notes, confirming ppb-level sensitivity across multiple analyte classes. Bespoke substrate development is available for researchers targeting emerging soil contaminants such as PFAS, antibiotic residues, or novel pesticide metabolites.

Conclusion

SERS is not a replacement for ICP-MS or GC-MS in confirmatory soil analysis, but it is an increasingly powerful screening tool that dramatically reduces the time and cost of identifying contaminated samples. For heavy metals, pesticides, and PAHs alike, the published evidence demonstrates detection limits relevant to regulatory thresholds, in real soil matrices, with portable instrumentation. The quality of the SERS substrate remains the primary determinant of analytical performance. Ultra-pure, vacuum-manufactured substrates offer the reproducibility and clean spectral background that demanding environmental applications require.

Discover how Nikalyte SERS substrates can advance your Soil Contamination Testing. Shop SERS substrates now!

References

1. Kamaraj, M., Kiruthika, N., Saranya, T., & Aravind, J. (2025). Bibliometric analysis and impact of heavy metals contamination in soils. *Global Journal of Environmental Science and Management*. https://doi.org/10.22034/gjesm.2025.01.19
2. 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.202200003
3. Ong, T. T. X., Blanch, E. W., & Jones, O. A. H. (2020). Surface enhanced Raman spectroscopy in environmental analysis, monitoring and assessment. *Science of the Total Environment, 720*, 137601. https://doi.org/10.1016/j.scitotenv.2020.137601
4. Barimah, A. O., Chen, P., Yin, L., et al. (2022). SERS nanosensor of 3-aminobenzeneboronic acid labeled Ag for detecting total arsenic in black tea combined with chemometric algorithms. *Journal of Food Composition and Analysis, 110*, 104588. https://doi.org/10.1016/j.jfca.2022.104588
5. Srivastava, S., Wang, W., Zhou, W., Jin, M., & Vikesland, P. J. (2024). Machine learning-assisted surface-enhanced Raman spectroscopy detection for environmental applications: A review. *Environmental Science & Technology*. https://doi.org/10.1021/acs.est.4c06737
6. Kubackova, J., Fabriciova, G., Miskovsky, P., Jancura, D., & Sanchez-Cortes, S. (2015). Sensitive surface-enhanced Raman spectroscopy (SERS) detection of organochlorine pesticides by alkyl dithiol-functionalized metal nanoparticles-induced plasmonic hot spots. *Analytical Chemistry, 87*(1), 663–669. https://doi.org/10.1021/ac503672f
7. Mikac, L., Rigó, I., Škrabić, M., Ivanda, M., & Veres, M. (2022). Comparison of glyphosate detection by surface-enhanced Raman spectroscopy using gold and silver nanoparticles at different laser excitations. *Molecules, 27*(18), 5767. https://doi.org/10.3390/molecules27185767
8. Yu, Z., Grasso, M. F., Sorensen, H. H., & Zhang, P. (2019). Ratiometric SERS detection of polycyclic aromatic hydrocarbons assisted by β-cyclodextrin-modified gold nanoparticles. *Monatshefte für Chemie – Chemical Monthly, 150*(12), 2235–2243. https://doi.org/10.1007/s00604-019-3511-9
9. Ju, Y., Neumann, O., Denison, S. B., et al., & Halas, N. J. (2025). In silico machine learning–enabled detection of polycyclic aromatic hydrocarbons from contaminated soil. *Proceedings of the National Academy of Sciences of the United States of America, 122*(19), e2427069122. https://doi.org/10.1073/pnas.2427069122
10. Ni, X., Wang, Y., Zhang, M., Cui, G., Meng, X., Chen, W., Jin, M., Shao, H., Zhang, F., & Wang, C. (2025). Rapid and on-site approaches for determination of polycyclic aromatic

hydrocarbons in water and air by surface-enhanced Raman spectroscopy. *ACS Omega*. https://doi.org/10.1021/acsomega.5c00168

11. Nikalyte. (n.d.). *SERS substrates* (new). Retrieved March 10, 2026, from https://www.nikalyte.com/sers-substrates-new/
12. Agilent Technologies. (2022). *SERS analysis of fentanyl street samples* (Application Note No. 5994-6729EN). Agilent Technologies. https://www.agilent.com/cs/library/applications/an-fentanyl-resolve-sers-raman-5994-6729en.pdf
13. Wasatch Photonics. (n.d.). *SERS substrates: Application note*. Wasatch Photonics. https://wasatchphotonics.com/wp-content/uploads/WP-AN-SERS-Substrates-RevA-web.pdf