Biomass Conversion and Biorefinery
https://doi.org/10.1007/s13399-024-05433-4

ORIGINAL ARTICLE

Chemical processing and waste management using SERS: a nanovative gateway for sustainable and robust bioremediation for agricultural lands

Syed Muhammad Zaigham Abbas Naqvi[1,2] · **Muhammad Awais**[1,2] · **Zhang Wei**[1,2] · **Junfeng Wu**[1,2] · **Vijaya Raghavan**[3] · **Jiandong Hu**[1,2] · **M. Ijaz Khan**[4,5]

Received: 19 July 2023 / Revised: 3 February 2024 / Accepted: 10 February 2024

Abstract

Chemical processing and waste management are of paramount importance in the field of agriculture. As the global population continues to grow, the demand for food production is increasing, placing significant pressure on agricultural systems. Chemical processing and waste management pose significant challenges to environmental sustainability and agricultural productivity. Traditional methods of bioremediation often fall short in providing efficient and robust solutions. However, surface-enhanced Raman spectroscopy (SERS) has emerged as a game-changing technology in the field of chemical processing and waste management. This review explores the application of SERS in chemical processing and waste management, focusing on its role in monitoring and assessing pollutants, optimizing remediation strategies, and ensuring sustainable practices. It also provides an introduction to the background of SERS particularly for environmental scientists and determines the recent literature regarding the detection of various types of environmental pollutants operating this system. The SERS signals were used to calculate the amount of heavy metal pollution including lead (Pb) and cadmium (Cd) with a limit of detection of 8 ppb for Pb and 9.3 ppb, respectively. The limits of detection achieved for SERS detection of ultralow concentrations of three dithiocarbamate fungicides showed the detectability at concentrations below 1 nM. Furthermore, soil and water remediation methods and the application of nano-bioremediation have been summarized. Additionally, it highlights the integration of SERS with advanced techniques, such as bioremediation and nanotechnology, to develop environmentally friendly and economically viable solutions for agricultural land remediation.

Keywords Waste management · SERS · Nanotechnology · Sustainable farming · Nanoparticles

✉ Muhammad Awais
dr.muhammad.awais@henau.edu.cn

✉ Jiandong Hu
jdhu@henau.edu.cn

✉ M. Ijaz Khan
scientificresearchglobe@gmail.com

Syed Muhammad Zaigham Abbas Naqvi
zaigham@stu.henau.edu.cn

Zhang Wei
zwz04@163.com

Junfeng Wu
jfwu@henau.edu.cn

Vijaya Raghavan
vijaya.raghavan@mcgill.ca

[1] Department of Electrical Engineering, Henan Agricultural University, Zhengzhou 450002, China

[2] Henan International Joint Laboratory of Laser Technology in Agriculture Sciences, Zhengzhou 450002, China

[3] Department of Bioresource Engineering, Faculty of Agriculture and Environmental Studies, McGill University, Sainte-Anne-de-Bellevue, QC H9X 3V9, Canada

[4] Department of Mechanical Engineering, Lebanese American University, Beirut, Lebanon

[5] Department of Mathematics and Statistics, Riphah International University, I-14, Islamabad 44000, Pakistan

1 Introduction

Sustainable farming methods require careful handling of chemicals and trash [1]. The chemical, physical, and biological interactions within waste result in the generation of gases, nutrients, and elements. The waste components encompass a diverse range of substances, such as heavy metals, humic compounds, ammonia nitrogen, chlorinated salts, organic pollutants, biodegradable and non-biodegradable chemicals, and numerous others [2]. Soil fertility, crop health, waste reduction, and the adoption of sustainable agriculture techniques all benefit greatly from proper chemical processing and waste management. Pesticide residues can be disposed of or treated safely if proper waste management procedures are followed [3]. Reduced nutrient runoff, lessened environmental effect, and maximized resource efficiency are all achieved through the use of optimal fertilizers and soil additives. Reducing the need for chemical inputs is a byproduct of proper management of agricultural waste, crop leftovers, animal manure, and waste recycling via composting or anaerobic digestion [4]. The potential for water pollution is diminished when agrochemicals are used and managed properly, and when waste is properly treated [5].

The effectiveness and long-term viability of conventional methods for waste management and cleanup are hindered by a number of scientific obstacles [6]. There is a need for specific methods to handle and dispose of hazardous waste in order to reduce the risks it poses to people and the environment. Another scientific obstacle is the difficulty in completely getting rid of toxins like persistent organic pollutants (POPs) from polluted areas [7]. In addition, the efficient and thorough management of multiple waste streams is typically difficult using conventional methods, necessitating specialized treatment technologies for each waste category. Waste collection, sorting, and processing are hampered by inadequate infrastructure and antiquated technologies [8]. In order to effectively and sustainably address these waste management and remediation issues, we need to progress novel technologies and integrate scientific research and policy development.

Sustainable bioremediation solutions for agricultural fields have been greatly aided by the implementation of surface-enhanced raman spectroscopy (SERS) (Fig. 1) [9]. In soil and water systems, SERS allows for the sensitive detection and identification of a wide range of contaminants, from heavy metals and organic pollutants to pesticides [10]. SERS' molecular-level insights, improved sensitivity, and selectivity allow for the early intervention and avoidance of environmental contamination by detecting low amounts of contaminants even in complex environmental matrices [11]. Furthermore, SERS can help in tracking the degradation or transformation of pollutants over time, which can be helpful in assessing the efficacy of bioremediation procedures. Increased efficacy and optimization of bioremediation procedures through real-time monitoring help guarantee the use of sustainable remediation methods [12, 13]. Ultimately, including SERS into bioremediation procedures promotes sustainable and strong bioremediation practices for agricultural lands by enhancing our understanding of the fate and transport of pollutants, optimizing remediation strategies, and so on [14].

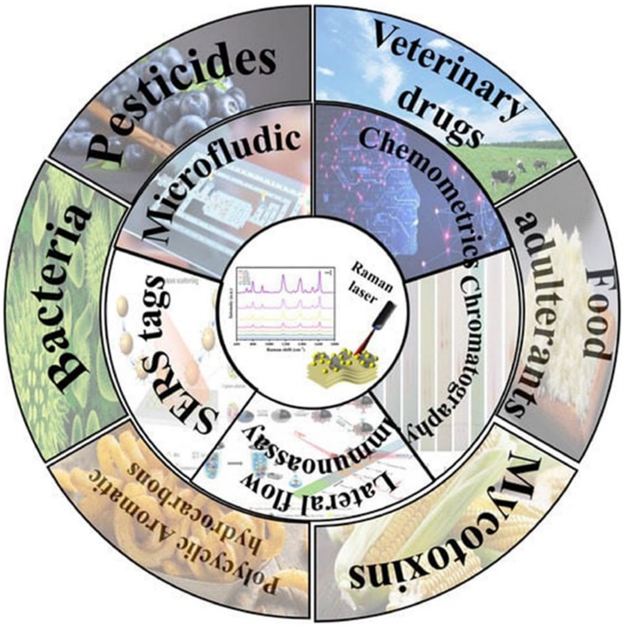


Fig. 1 Sustainable bioremediation solutions for agricultural implementation of SERS [9]

Taking all of this into account, the project was planned to first investigate how SERS can improve the longevity and resiliency of bioremediation processes through the implementation of targeted and precise remediation procedures. Second, we will examine studies and case studies that show how SERS is being used for sustainable bioremediation of agricultural lands in the context of chemical processing and waste management and, additionally, to stress the need of combining SERS with environmentally friendly methods to safeguard the health and productivity of farmland in the long run.

2 SERS, enhancement of Raman signals, advantages, and limitations of SERS in chemical analysis

The concepts of Raman spectroscopy are combined with the amplification of the Raman signal on a nanoscale metallic substrate to create SERS, a potent analytical tool.

SERS is based on the premise that improved detection sensitivity can be achieved through contact between analyte molecules and a metallic substrate, such as gold or silver nanoparticles or roughened metal surfaces [15–17]. There are two primary mechanisms at play in SERS, electromagnetic enhancement and chemical enhancement [18–20]. The SERS works on the principle of gain of energy known as anti-Stokes and energy loss (Stokes) due to inelastic scattering of photons also known as Raman scattering [21, 22]. The localized surface Plasmon resonance (LSPR) of the metallic substrate enhances the incident electromagnetic field close to the surface, leading to the electromagnetic enhancement. Increased molecular excitation and a stronger Raman scattering signal arise from this improvement. However, the Raman signal can be further amplified through a chemical process known as chemical enhancement, which includes charge transfer between analyte molecules and a metal surface [23].

SERS allows for a more in-depth understanding of molecular interactions, surface phenomena, and chemical processes, making it an invaluable tool for unraveling the intricacies of molecular systems and developing novel applications in a variety of scientific disciplines. SERS' capacity to offer molecular-level information, allowing for the identification and characterization of analyte molecules even at low concentrations, is one of its primary advantages. It has a high specificity because the Raman spectrum provides a unique fingerprint of the analyte molecules, allowing them to be identified in complex combinations [24]. Furthermore, because SERS is a non-destructive approach that requires little sample preparation, it is applicable to a wide range of applications. Its uses in detecting trace levels of contaminants, monitoring chemical reactions, investigating biological systems, and analyzing complicated mixtures have demonstrated its ability to advance scientific understanding and facilitate new solutions in a wide range of sectors [25].

2.1 Monitoring and assessment of pollutants using SERS in agricultural lands

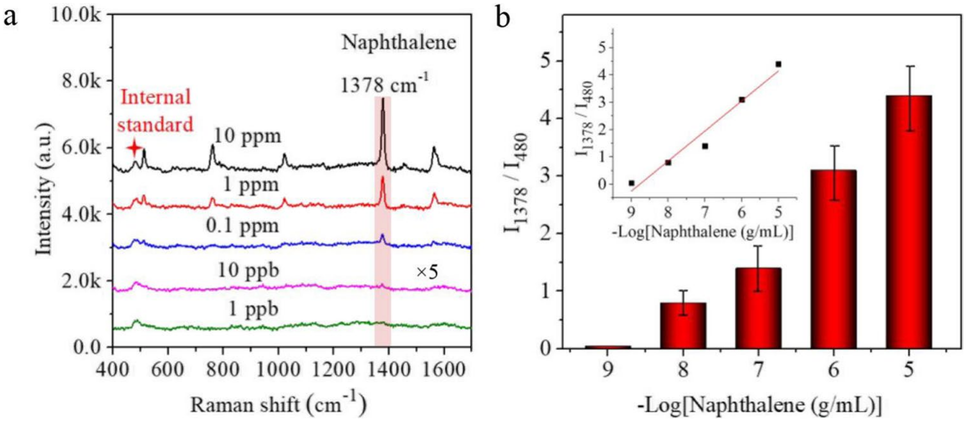
SERS has shown great promise as a method for the sensitive and selective detection of a wide range of pollutants in monitoring and evaluation efforts. SERS is an effective method for detecting and quantifying contaminants in environmental samples. Benefits of SERS in pollution monitoring include the identification of heavy metals, organic pollutants, pesticides, and dyes, among others [26]. Even in complicated environmental matrices like soil, water, and air samples, SERS can detect these pollutants at low quantities [27]. Water quality evaluation and environmental management can benefit from its ability to detect, identify, and quantify contaminants in natural water bodies, industrial effluents, and wastewater treatment plants. When used for air pollution monitoring, SERS can examine the composition and concentration of pollutants by detecting and analyzing volatile organic compounds (VOCs) and particulate matter [28].

Heavy metals, herbicides, and other organic pollutants can all be detected by SERS in soil samples, making it easier to locate polluted areas and gauge the level of contamination. SERS' high-resolution mapping of pollutant distribution is useful for gauging their potential effects on ecosystems and human health [29]. In addition, sensors and systems based on SERS have been created for on-site, real-time monitoring of contaminants. Rapid detection and analysis is made possible by these portable and field-deployable technologies, allowing for environmental monitoring even in inaccessible or difficult settings [30]. SERS has the potential to provide accurate and reliable analysis of pollutants in different environmental matrices thanks to advances in nanomaterials, the development of new SERS-active substrates, enhancement strategies, and data processing algorithms [31].

Pollutant behavior, environmental risk assessment, and remediation strategy development all benefit greatly from tracking pollutant fate and movement in soil and water systems. To selectively collect target contaminants from soil samples for Raman spectral analysis, SERS-active substrates can be functionalized with suitable ligands or coatings [32]. SERS spectra with different concentrations of naphthalene, ranging from 10 ppm to 1 ppb, were analyzed, and there were no Raman peaks detected at the concentration of 1 ppb, whereas the highest Raman peak was obtained with 10 ppm concentration of naphthalene (Fig. 2) [33]. This allows for the detection and quantification of contaminants at extremely trace levels. The movement and activity of analytes in water can be monitored by introducing SERS-active probes or nanoparticles tagged with those analytes into the water. Pollutant movement and dispersion can be tracked in real time with the help of SERS techniques, which detect and analyze these probes to reveal information about the pollutants' spatial distribution and migration routes [34].

Methods based on SERS can provide insight into how contaminants are transformed in natural environments. Chemical reactions, degradation, and interactions with other environmental components can all be detected in SERS spectra as changes in the molecular structure and composition of pollutants. Knowing the rates at which pollutants break down, the paths by which they change, and how stable they are in the environment is extremely useful [35]. By combining SERS with imaging methods, we may learn about the distribution of pollutants in our water and soil at a finer spatial resolution. The spatial variability of pollutants, hotspots of contamination, and the spatial interactions between pollutants and environmental factors can all be visualized

Fig. 2 SERS detection of naphthalene molecule based on capture ligand (SH-β-CD)-modified *meso*-Au NPs. **a** SERS spectra of naphthalene with different concentrations ranging from 10 ppm to 1 ppb. **b** Ratiometric SERS intensities of I_{1378}/I_{480} versus naphthalene concentration. Insets show the linear plots for naphthalene based on the SH-β-CD-modified *meso*-Au NPs [33]



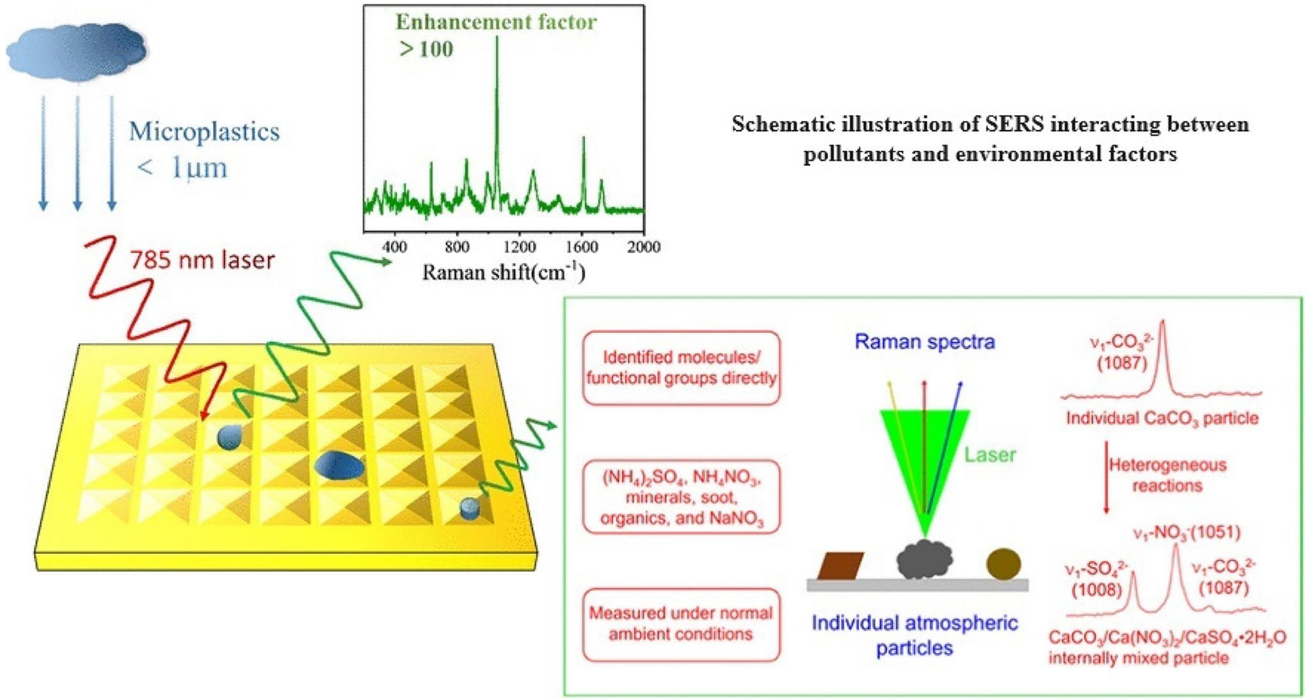


Fig. 3 Raman imaging to monitor the spatial variability of pollutants and spatial interactions between pollutants and environmental factors [36, 37]

and understood by mapping the SERS signals over a sample (Fig. 3) [36–38]. Unique capabilities for monitoring pollutant fate and transport in soil and water systems are provided by their high sensitivity, molecular specificity, and the capacity to give real-time and spatially resolved information.

2.2 Optimization of bioremediation strategies with SERS

The green synthesis techniques are non-toxic and environmentally friendly. In a study of using pig manure (PM) compost as a control, bristles were examined for changes in microbial dynamics and divergence in response to varying concentrations of coconut shell biochar. The tests were conducted with 0% (T1), 2.5% (T2), 5.0% (T3), 7.5% (T4), and 10% (T5) treatments. The outcomes showed that adding the CB amendment to the compost significantly increased the bacterial diversity and efficiency of keratin breakdown. The PM compost with the highest keratin removal rate (39.1%) and the greatest bacterial variety was the one with a 7.5% CB addition. Firmicutes and Actinobacteria were the two most prevalent phyla, accounting for 12.09% and 87.91% of the total. Clostridia (61.17% of the total) and Bacilli (23.52% of the total) were two of the most prevalent genera.

Additionally, a dimensionality analysis employing main coordinate analysis and non-metric multidimensional scaling showed that the bacterial community differed substantially between CB dosages. Most of the time, using biochar in composting altered the normal preferences of specific bacteria and altered the way organic waste, including bristles, was broken down [39].

Applying SERS methods to optimize bioremediation tactics entails applying those methods to increase the efficacy and efficiency of bioremediation procedures. In order to optimize conditions for pollutant degradation, SERS can be used to track the metabolic activities of microorganisms, a key factor in bioremediation's success. Monitoring the kinetics of biodegradation, identifying the intermediates created during the process, and evaluating the effectiveness of microbial activities are all possible with the use of SERS, which can provide real-time and in situ monitoring of pollutant degradation processes in bioremediation optimization. Metabolic activities of microorganisms can be monitored in real time with SERS-active probes or substrates that respond to specific metabolic products or enzymatic activities (Fig. 4) [40]. The attachment, colonization, and growth of microorganisms on the polluted site can be monitored by using SERS substrates or nanoparticles that have been functionalized with specific biomolecules. This method is useful for devising countermeasures to environmental conditions that play a role in microbial adhesion and biofilm formation, such as nutrient concentrations, pH, temperature, and oxygen availability.

SERS can assist in the optimization of bioremediation strategies by enabling the detection and monitoring of inhibitory substances or compounds that may impede microbial activity. Because of its ability to detect and monitor inhibitory chemicals or compounds, SERS can help optimize bioremediation procedures. Identifying harmful by-products or inhibitory substances that impact the biodegradation process is possible through analysis of the sample's Raman spectra [41]. To reduce the inhibitory effects and boost the overall remediation efficiency, this permits the modification of bioremediation settings or the deployment of additional treatment steps [42]. SERS' real-time monitoring, assessment of microbial activity, comprehension of microbial interactions, and identification of inhibitory factors all contribute greatly to the improvement of bioremediation techniques. These skills are useful for optimizing bioremediation procedures, increasing the efficiency with which pollutants are degraded, and creating long-term, cost-effective plans for cleaning up polluted areas [43].

3 Integration of SERS with nanotechnology for enhanced remediation

SERS presents a promising technique for improved remediation of contaminated environments due to its combination of unique features and the specialized functionalities of nanomaterials. The high surface-to-volume ratios of these nanomaterials boost the amplification and sensitivity of the SERS signal. In order to detect and monitor specific contaminants, they might be "functionalized" with specialized molecules or receptors. In addition, nanoparticles' surface properties can be modified to improve pollutant adsorption, resulting in easier pollution cleanup [44]. To facilitate the selective breakdown of pollutants,

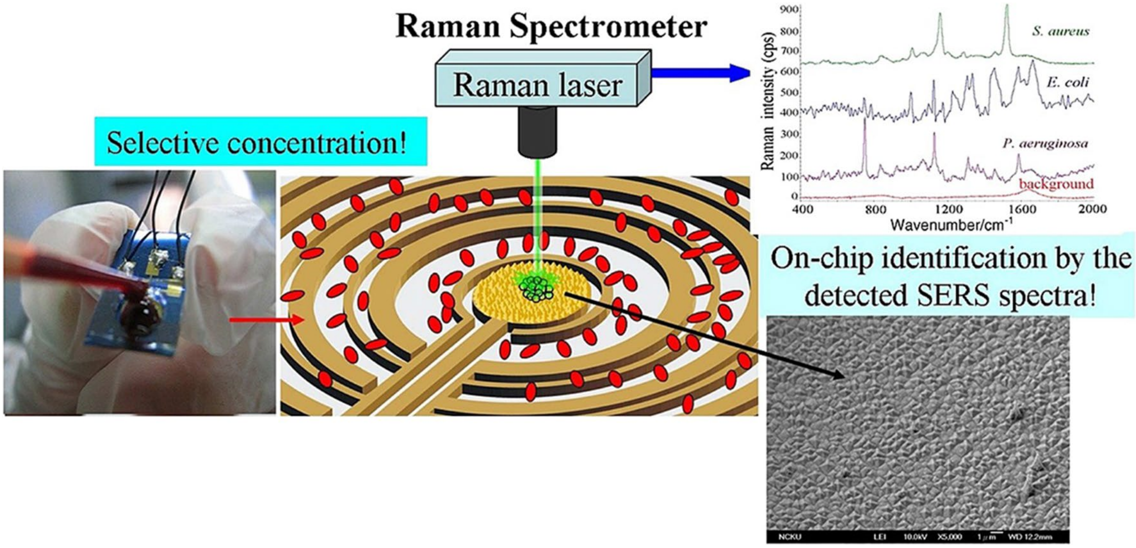
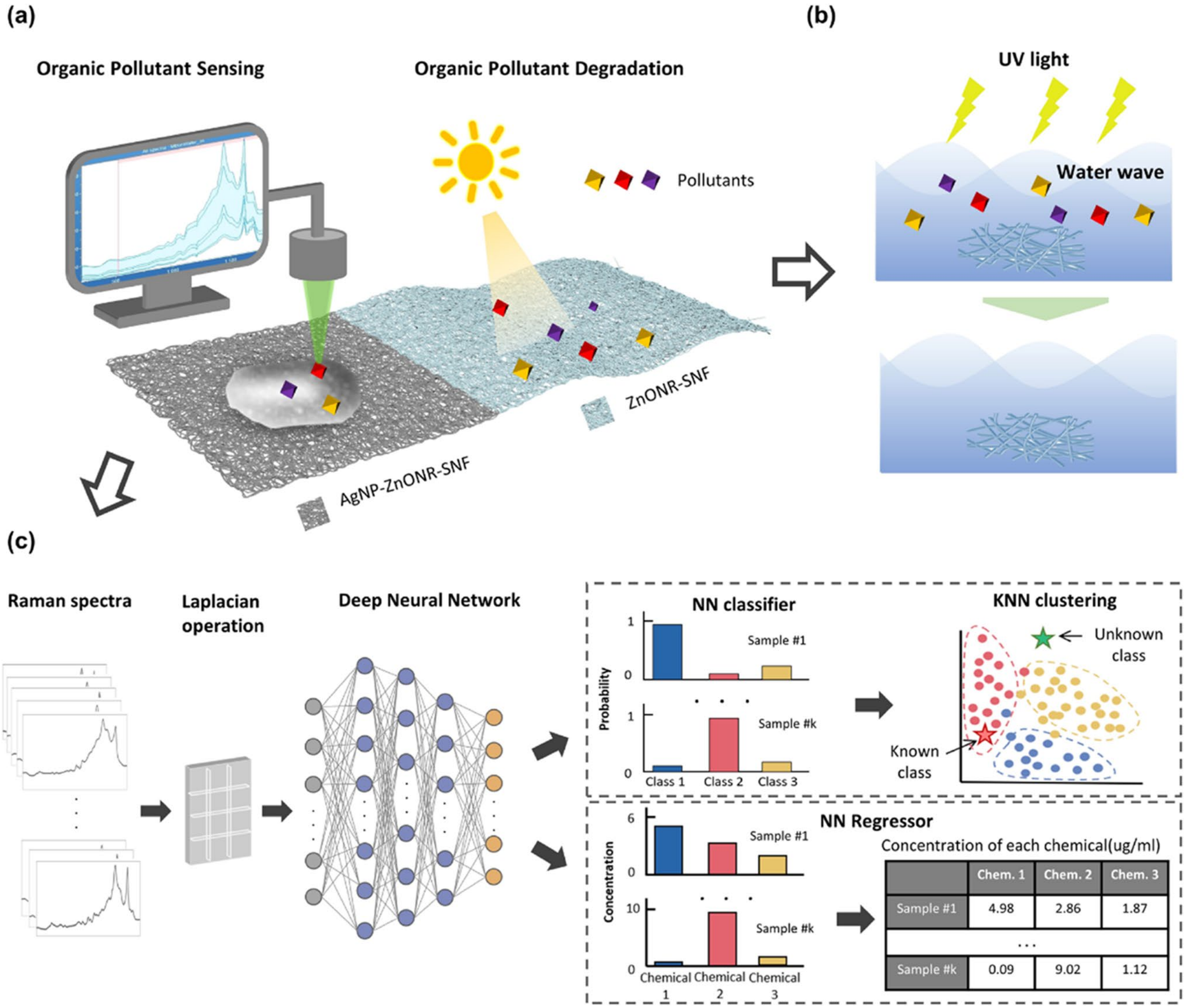


Fig. 4 Experimental setup for pathogen identification in human blood by electrokinetic concentration and surfaced-enhanced Raman spectroscopy (SERS). The scanning electron microscopy image shows the roughened gold surface at the center electrode [40]

functionalized nanoparticles can transport remedial chemicals or serve as catalysts. Nanoparticles functionalized with targeted enzymes or microbial cells, for instance, can be employed to expedite the breakdown of organic pollutants (Fig. 5) [45, 46]. It is possible to precisely regulate and optimize the remediation process by using the SERS signal from the nanoparticles to track the presence and activity of the remediation agents in real time.

SERS-based sensors and probes, which combine nanomaterials with chemical recognition components, are another option [47]. When bound to particular contaminants, these sensors send out unique SERS signals. Researchers developed a biosensor for quick determination of 1,3-propanediol, lactic acid, and glycerol concentrations with a cheap cost and no environmental impact; the limit of detection for 1,3-propanediol and lactic acid was as low as 1 g/L. Glycerol, on the other hand, may be detected at concentrations as low as 4 g/L [48]. SERS substrates with improved performance can also be designed and fabricated using nanomaterials. Raman signals can be amplified and enhanced uniformly throughout a substrate with well-defined nanostructures, such as nanowires, nanotubes, or nanospheres [49]. To increase the sensitivity and consistency of detection, these substrates can be modified to enhance the interaction between analyte molecules and the SERS-active sites.

The combination of SERS with nanotechnology allows for the development of novel remediation approaches such as photocatalysis and electrochemical remediation. SERS-active nanoparticles can act as catalysts or electrode materials, allowing pollutants to be degraded via enhanced



	Chem. 1	Chem. 2	Chem. 3
Sample #1	4.98	2.86	1.87
	. . .		
Sample #k	0.09	9.02	1.12

Fig. 5 Decomposition of organic pollutants combined with functionalized nanoparticles. **a** Analysis and decomposition of pollutants. **b** Photo and piezo-catalytic decomposition procedure. **c** Machine learning integration with decomposition analysis [45]

oxidation processes or electrochemical reactions [50]. SERS signals can be used to track the progress of these remediation procedures and to optimize operating settings for maximum efficiency. A scalable composite-engineered electrode module, with a total volume of 1 m^3, is constructed using graphite-coated stainless steel and carbon felt. This module allows for the integration of bio-electrochemical systems into conventional wastewater treatment technologies. The low cost and easy scaling of this electrode module give a realistic and clear way to facilitate the transition between the success of lab investigations and full-scale implementations of bio-electrochemical systems to solve several important environmental challenges (Fig. 6) [51].

4 Sustainable practices and decision support systems

The integration of SERS data with environmental models and predictive tools holds tremendous promise for the development of sustainable environmental practices and decision support systems. Researchers can model and assess several remediation scenarios using SERS data on contamination distribution and destiny, determining the most effective and ecologically benign ways. This integration allows for the selection of remediation strategies that reduce energy use, trash creation, and ecological disruption while attaining the intended results. The integration of

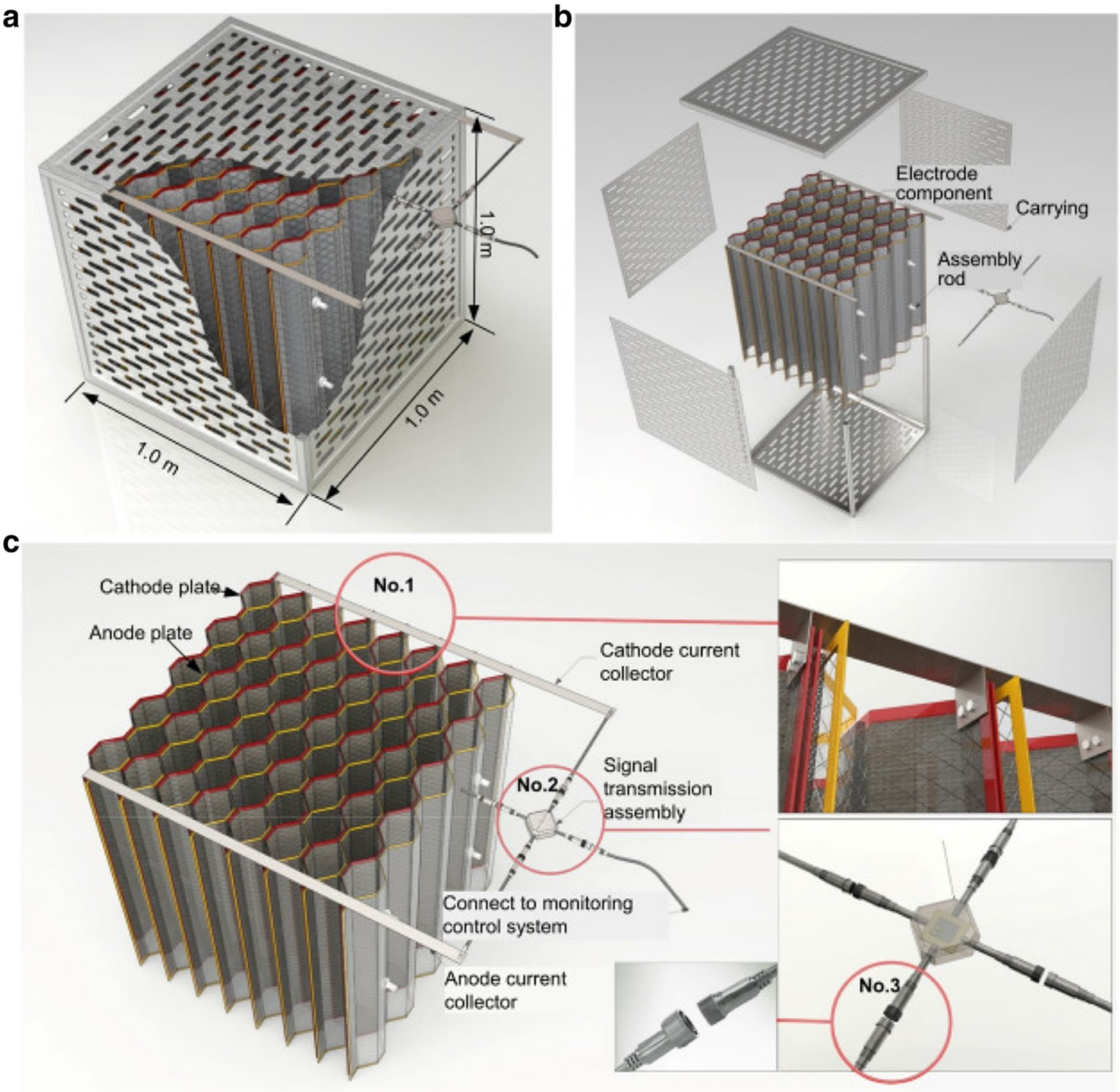


Fig. 6 **a** Conceptual global diagram of standard applicable electrode module (volume of 1 m^3 per unit); **b** disassembly diagram of applicable electrode module; **c** partial enlargement diagram; no. 1 red circle: connection method of electrode and current collector; no. 2 red circle: signal transmission assembly; no. 3 red circle: waterproof connector [51]

SERS data with risk assessment and cost-benefit analysis methods promotes informed environmental management decision-making. SERS data is useful for determining pollutant concentrations, regional distribution, and transformation processes. Decision-makers can statistically analyze the possible risks connected with pollutants and prioritize cleanup activities depending on their severity by adding this data into risk assessment models [52]. Furthermore, cost-benefit analysis algorithms can use SERS data to evaluate the economic feasibility of various remediation approaches, taking into account aspects like as implementation costs, long-term monitoring expenses, and potential societal benefits.

A sustainable and biodegradation study was designed using bio-stimulation technique for the enhancement of pollutants degradation and used gas chromatography-mass spectroscopy technique to detect pollutants from solid waste. Results showed a significance difference in the physico-chemical characteristics of waste after bio-stimulation technique. Higher values of pH, total suspended, and total dissolved solids were found to be 9.2 ± 0.02, 1547 ± 23 mg/kg^{-1}, and 76 ± 0.67 mg/kg^{-1} before bio-stimulation, respectively, which were reduced to 7.1 ± 0.01, 41 ± 0.01 mg/kg^{-1}, and 789 ± 03 mg/kg^{-1} respectively after the application of bio-stimulation. The detected pollutants such as hexadecane, hexasiloxane, and pentadecane were degraded through bio-stimulation [2]. This study proposed soil protection technique using bio-stimulation, whereas detection process can be improved by integration of SERS.

Environmental models and predictive tools are critical for comprehending and forecasting the behavior of pollutants in the environment. SERS data integration with these instruments enhances their accuracy and dependability, resulting in more effective decision support systems. Researchers can replicate the transportation and transformation of pollutants, examine potential exposure pathways, and anticipate their long-term implications by adding SERS data into fate and transport models. This integration improves the ability to assess the efficacy of various remediation procedures and forecast their effects under diverse circumstances [53]. SERS data can be utilized to monitor environmental conditions and pollutant activity in real time. Decision-makers can watch changes in contaminant concentrations, assess the efficiency of remediation operations, and make timely modifications if SERS data is integrated with monitoring systems. This real-time feedback loop enables adaptive management, in which remediation procedures can be updated based on observed data, enabling long-term and responsive environmental management [54]. Another review study was designed to get a critical insight for bioremediation of polycyclic aromatic hydrocarbons. This study provided critical review about different remediation technologies especially green synthesis methods, but integration of SERS can provide real-time and sensitive detection remediation services [55].

5 Field applications and case studies of SERS-based approaches

Field applications of SERS-based approaches for heavy metal pollution remediation, pesticide/herbicide detection/remediation, and SERS integration with bioaugmentation/biostimulation techniques are described below.

5.1 SERS-based approaches for remediation of heavy metal contaminants

The pervasive and poisonous nature of heavy metal contamination makes it a major environmental issue. The use of SERS-based methods shows promise as a tool for identifying and eliminating metal pollution. For example, in a field application study by Zou et al. [56], SERS was utilized for the in situ detection and monitoring of heavy metals in soil and water. SERS probes were specifically engineered to attach to heavy metals of interest, resulting in a spectrally distinct signal. The SERS signals were used to calculate the amount of heavy metal pollution. The electrochemistry of bismuth (Bi) working electrodes was investigated using cyclic voltammetry in a variety of non-deaerated buffer solutions. Pb(II) and Cd(II) were detected and quantified inside the microchannels using static anodic stripping voltammetry, with a limit of detection of 8 ppb for 60-s deposition for Pb(II) and 0.986 and 9.3 ppb, respectively, for Cd(II) throughout a concentration range of 25–400 ppb. Case studies of in situ Cd(II) detection in soil pore and ground water, as well as online direct measurement of Cd(II) content in cell culture media, have been used to describe the uses of this sensor chip. This real-time monitoring technique enabled accurate and rapid assessment of heavy metal contamination levels, allowing for more targeted cleanup actions.

5.2 Pesticide and herbicide detection and remediation using SERS

Pesticides and herbicides are hazardous to ecosystems and human health. For the identification and treatment of these pollutants in environmental matrices, SERS-based techniques have been used. In a case study conducted by Saute et al. [57], SERS was utilized for the rapid detection of pesticide residues on agricultural produce. To improve the Raman signals of pesticides and allow for sensitive and selective detection, SERS-active substrates were created. The use of gold nanorods as substrates for solution-based SERS in the detection of ultralow concentrations of three dithiocarbamate fungicides was described. Thiram, ferbam, and ziram each had detection limits of 11.00 ± 0.95 nM, 8.00 ± 1.01 nM, and 4.20 ± 1.22 nM, respectively. Quantitative precision for thiram was 34.43 ± 0.95 nM, for ferbam it was 25.61 ± 1.01 nM, and for ziram it was 12.94 ± 1.22 nM. The limits of detection achieved show that all three dithiocarbamates are detectable at concentrations below 1 nM. On-site analysis was made possible by the combination of SERS with portable spectroscopic instruments, which allowed for prompt detection of contaminated samples and enabled for suitable corrective measures to be taken.

Degradation of pollutants can be aided by bioaugmentation and biostimulation methods, which respectively introduce microorganisms and stimulate native microbial populations. By combining SERS with these methods, bioremediation processes can be better monitored and optimized. During bioaugmentation and biostimulation at a site with polluted soil, SERS was utilized to monitor the breakdown of petroleum hydrocarbons. SERS probes were developed to detect and track the decomposition of individual hydrocarbon molecules in real time. Optimizing the bioremediation process and speeding up the breakdown of pollutants, the SERS data allowed for adjustments to microbial inoculation and nutrient supplements [58].

Case studies and field applications demonstrate the usefulness of SERS-based approaches in the elimination of heavy metal pollutants, the elimination of pesticides and herbicides, and the combination of SERS with bioaugmentation and biostimulation. For the sake of protecting agricultural lands and the environment, these methods offer crucial insights into the creation of long-term, effective restoration techniques. In a field study conducted by Esmaielzadeh Kandjani et al. [59], heavy metal–contaminated soil was treated using SERS-based strategies. Heavy metals like lead, cadmium, and mercury were chosen as targets for the development of SERS probes. Heavy metal concentrations and distributions in the contaminated soil samples were determined using SERS analysis. Because of the schottky junction photocatalyst's self-cleaning properties, even a simple SERS active ZnO/Ag nanoarray can detect mercury (Hg^{2+}), remove Hg^{2+}, and be fully regenerated, both from Hg^{2+}contamination when heat-treated and from the SERS marker when exposed to UV. In order to ensure the efficient and long-term removal of contaminants from agricultural areas, SERS analysis enabled real-time monitoring of heavy metal levels during the restoration process.

In a field application described by Parisi et al. [60], pesticide and herbicide pollution in agricultural soils was identified, and then cleaned up using SERS-based methods. To improve the Raman signals of specific pesticides and herbicides, SERS-active substrates were used. In situ galvanic replacement of a pre-patterned copper substrate in a microfluidic channel was used to create a microfluidic device with integrated silver nanoparticles (AgNPs). As a highly active Raman substrate, the integrated microfluidic device with AgNPs can be used for in-channel surface-enhanced Raman scattering (SERS). The microfluidic device contains everything needed to prepare the SERS active substrate and conduct subsequent SERS experiments, streamlining their incorporation and application. The in situ manufactured SERS active substrate is ideal for real-time detection of pesticides because of its high sensitivity, apparent enhancement factor of 2.2×10^7, high resilience, and reusability. The as-developed microfluidic-SERS system was shown to be capable of detecting pesticides and herbicides at concentrations as low as 5 ppb, including Carbofuran and Alachlor. This paves the way for the development of a high-performance microfluidic-SERS integrated sensing system. Soil flushing and phytoremediation were two of the targeted remediation strategies conducted after SERS research revealed excessive pollutant levels in the soil.

Increases in sensitivity on the order of 10^{10} to 10^{14} have been recorded thanks to the selective spectrum amplification provided by SERS. While this means that SERS can identify single molecules in theory, actually achieving this level of signal amplification is challenging. The EPA reports a sensitivity of 0.45 μg/L for mercury, 2.4 μg/L for propranolol, 0.35 μg/L for 17-estradiol, 500 μg/L for perfluorooctanoic acid, and 37 μg/L for general pesticide markers for inorganic pollutants. Each of these cases demonstrates significant promise for the identification of contaminants at concentrations that have an impact on the environment [31]. Four-mercaptopyridine (4-MPy) was incorporated into a unique gold nanoparticles/e indium tin oxide (AuNPs/ITO) film to serve as both a Raman reporter and a Hg^{2+} ions capture agent to create 4-MPy/AuNPs/ITO chips. A high detection sensitivity of 0.1 nM was used to conduct a quantitative analysis of Hg^{2+} ions in the range of 10^{-5} to 10^{-10} M. The supportive results are shown in Fig. 7. The LOD was as low as 1 ppt [61, 62]. Heavy metal pollution cleanup, pesticide and herbicide detection, and remediation are just a few examples of the real-world uses of SERS-based techniques illustrated by these case studies. They demonstrate the value of such methods in encouraging environmentally sound agricultural waste management and resolving pressing environmental issues.

6 Challenges and future perspectives

Technological and analytical problems of SERS, long-term monitoring and sustainability of remediated agricultural lands, and collaborative effort for expanding SERS applications are only a few of the obstacles that must be overcome before SERS can be fully integrated into chemical processing and waste management. There are some technological and analytical hurdles that need to be overcome before SERS

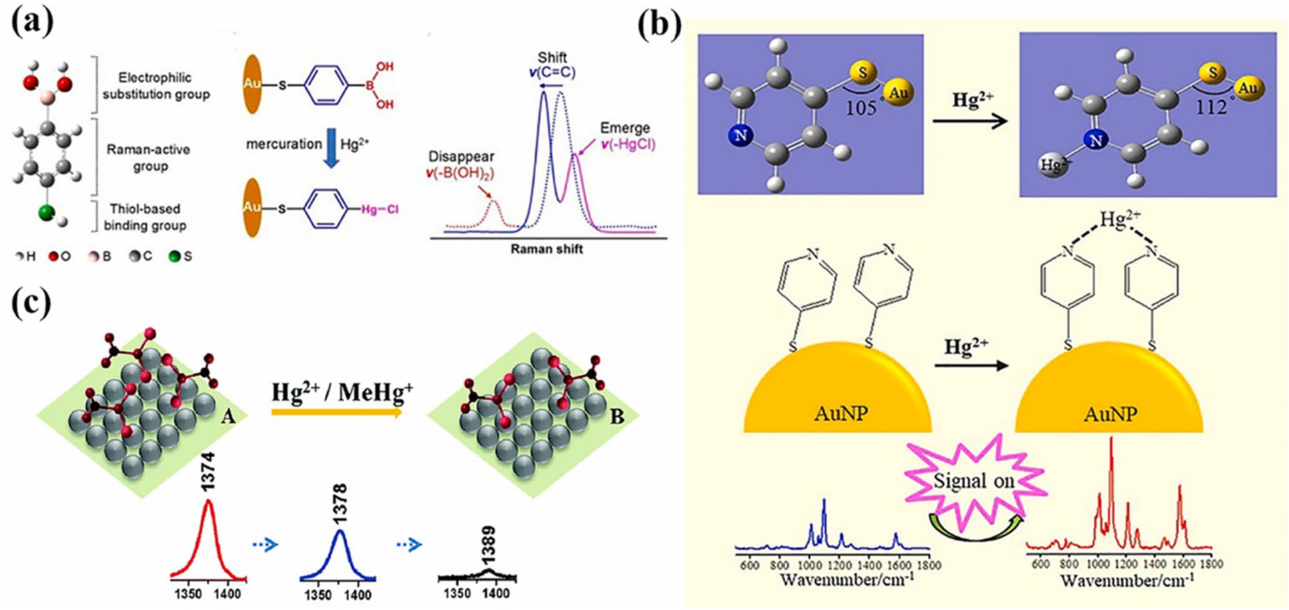


Fig. 7 Detection of Hg^{2+} through SERS-active MREs reacting with Hg^{2+} ions. **a** Recognizing Hg^{2+} ions through electrophilic substitution reaction between Hg^{2+} and 4-MPBA. **b** Recyclable 4-MPy/AuNPs/ITO chips for Hg^{2+} ion detection. **c** SERS frequency-shift method to determine Hg^{2+} or $MeHg^{+}$ via binding with dimethyldithiocarbamic acid sodium salt (DASS) [61]

can fully realize its potential. The intensity and consistency of Raman signals can be affected by factors such as substrate preparation and experimental circumstances, making it difficult to reliably reproduce SERS signals [63]. To overcome this obstacle, it will be necessary to standardize SERS methodologies and procedures and to create trustworthy and robust substrates. The accessibility and use of SERS for on-site analysis can also be improved by the creation of portable and field-deployable SERS systems.

Continuous monitoring of contaminant levels and ecosystem health is necessary for achieving sustainable and long-term rehabilitation of agricultural fields. In this context, SERS' ability to detect contaminants with high specificity and low background noise is crucial. However, there are obstacles with the cost-effectiveness of long-term monitoring and the long-term stability and endurance of SERS substrates. To assure the longevity of remedied agricultural lands, future research should concentrate on creating durable and reusable SERS substrates and cost-effective monitoring systems [64]. To further the uses of SERS in chemical processing and waste management, cooperation and knowledge sharing among researchers, industry professionals, policymakers, and regulatory bodies are essential. By encouraging multidisciplinary teams, scientists can pool their knowledge of other fields to solve the difficult problems that arise in SERS-based remediation. To further promote innovation and drive the use of SERS in various environmental applications, knowledge sharing channels such as conferences, seminars, and scholarly publications are utilized.

Key elements in the future development and deployment of SERS in chemical processing and waste management include addressing technological hurdles, assuring long-term monitoring and sustainability, and fostering collaboration and knowledge exchange. SERS has the potential to considerably contribute to the development of sustainable and strong bioremediation strategies for agricultural areas if these limitations can be overcome and its promise is fully realized. The use of SERS in the chemistry and garbage industries has a bright future. Substrates for SERS will become more sensitive and stable as nanotechnology, materials science, and analytical instruments continue to advance [65]. These advancements will make SERS signals more reproducible and reliable, making it a more useful tool for monitoring and detecting pollution. In addition, SERS has enormous potential for automated data analysis, real-time monitoring, and decision-support systems when combined with other developing technologies like machine learning and artificial intelligence.

7 Conclusion

SERS provides a potent and flexible instrument for the detection, monitoring, and remediation of contaminants, making it an indispensable part of the chemical processing and waste management industries. In this essay, we have discussed the many facets of SERS as they relate to effective and long-lasting bioremediation of farmland. Understanding the fate and transport of contaminants in soil and water systems requires a technology with specific benefits, and SERS fits the bill. It is very sensitive, selective, and capable of analyzing complicated mixtures. Pollutant distributions can be mapped and quantified with SERS, allowing for more effective cleanup tactics and pinpointed interventions. In addition, the remediation efficiency is increased by enhanced adsorption and degradation of pollutants when SERS is combined with nanotechnology. Nanoparticles, as has been established in a plethora of research, exhibit unique properties such as enhanced catalysis, adsorption, and reactivity. Because it is more intelligent, safe, ecologically friendly, inexpensive, and green, the combination of these two technologies, called nano-bioremediation, has the potential to drastically revolutionize the field of environmental remediation in the long run.

Acknowledgements The authors are thankful to Henan Agricultural University.

Author contribution Syed Muhammad Zaigham Abbas Naqvi has written and compiled the whole draft. Zhang Wei provided resources to perform experiments, and Junfeng Wu and Vijaya Raghavan helped the group with data curation and project management. M. Ijaz Khan has performed sample collection and data analysis. Muhammad Awais and Jiandong Hu have supervised this research.

Funding This work was supported by the National Natural Science Foundation of China (grant number 32071890, 31671581) and the Henan Center for Outstanding Overseas Scientists (No. GZS2021007).

Data availability Data sharing is not applicable, and any queries regarding data availability will be entertained by corresponding author.

Declarations

Ethical approval Not applicable.

Conflict of interest The authors declare no competing interests.

References

1. Kumar V et al (2018) Can productivity and profitability be enhanced in intensively managed cereal systems while reducing the environmental footprint of production? Assessing sustainable intensification options in the breadbasket of India. Agric Ecosyst Environ 252:132–147
2. Sharma P, Nadda AK, Kumar S (2023) Microbial community profiling in bio-stimulated municipal solid waste for effective removal of organic pollutants containing endocrine disrupting chemicals. Microbiol Res 267:127273
3. Demirbas A, Edris G, Alalayah WM (2017) Sludge production from municipal wastewater treatment in sewage treatment plant. Energy Sourc, Part A: Recovery, Util, Environ Eff 39(10):999–1006
4. Zhu LD, Hiltunen E (2016) Application of livestock waste compost to cultivate microalgae for bioproducts production: a feasible framework. Renew Sust Energ Rev 54:1285–1290
5. Chandra R, Dubey NK, Kumar V (2017) Phytoremediation of environmental pollutants. CRC Press, p 524
6. Atieno M et al (2020) Assessment of biofertilizer use for sustainable agriculture in the Great Mekong Region. J Environ Manag 275:111300
7. Malik B, Pirzadah TB, Hakeem KR (2022) Phytoremediation of persistent organic pollutants (POPs). In: Phytoremediation. Elsevier, pp 415–436
8. Mahpour A (2018) Prioritizing barriers to adopt circular economy in construction and demolition waste management. Resour Conserv Recycl 134:216–227
9. Wei Q, Dong Q, Pu H (2023) Multiplex surface-enhanced Raman scattering: an emerging tool for multicomponent detection of food contaminants. Biosensors 13(2):296
10. Wang P, Sun Y, Li X, Wang L, Xu Y, Li G (2021) Recent advances in metal organic frameworks based surface enhanced Raman scattering substrates: synthesis and applications. Molecules 26(1):209. https://doi.org/10.3390/molecules26010209
11. Perumal J, Wang Y, Attia ABE, Dinish US, Olivo M (2021) Towards a point-of-care SERS sensor for biomedical and agri-food analysis applications: a review of recent advancements. Nanoscale 13(2):553–580. https://doi.org/10.1039/D0NR06832B
12. Patowary R, Devi A, Mukherjee AK (2023) Advanced bioremediation by an amalgamation of nanotechnology and modern artificial intelligence for efficient restoration of crude petroleum oil-contaminated sites: a prospective study. Environ Sci Pollut Res 30(30):74459–74484
13. Singh L et al (2020) Eco-rejuvenation of degraded land by microbe assisted bamboo plantation. Ind Crop Prod 155:112795
14. Eremina OE et al (2018) Surface-enhanced Raman spectroscopy in modern chemical analysis: advances and prospects. Russ Chem Rev 87(8):741
15. Nie S, Emory SR (1997) Probing single molecules and single nanoparticles by surface-enhanced Raman scattering. Science 275(5303):1102–1106
16. Haynes CL, McFarland AD, Van Duyne RP (2005) Surface-enhanced Raman spectroscopy. ACS Publications
17. Kneipp K, Kneipp H, Kneipp J (2006) Surface-enhanced Raman scattering in local optical fields of silver and gold nanoaggregatesfrom single-molecule Raman spectroscopy to ultrasensitive probing in live cells. Acc Chem Res 39(7):443–450
18. Kim J et al (2019) "Study of chemical enhancement mechanism in non-plasmonic surface enhanced Raman spectroscopy (SERS)," Frontiers in Chemistry. Original Research vol 7
19. Campion A, Kambhampati P (1998) Surface-enhanced Raman scattering. Chem Soc Rev 27(4):241–250. https://doi.org/10.1039/A827241Z
20. Schatz GC (1984) Theoretical studies of surface enhanced Raman scattering. Acc Chem Res 17(10):370–376
21. Zhang Y et al (2022) Ultrasensitive detection of plant hormone abscisic acid-based surface-enhanced Raman spectroscopy aptamer sensor. Anal Bioanal Chem 414(8):2757–2766
22. Li X et al (2023) Exploration of efficient SERS features extraction algorithm for rapid detection of thiabendazole residues in apples. LWT 187:115310
23. Moskovits M (2005) Surface-enhanced Raman spectroscopy: a brief retrospective. J Raman Spectrosc 36(6-7):485–496
24. Cialla-May D, Zheng XS, Weber K, Popp J (2017) Recent progress in surface-enhanced Raman spectroscopy for biological and biomedical applications: from cells to clinics. Chem Soc Rev 46(13):3945–3961. https://doi.org/10.1039/C7CS00172J

25. Lin Z, He L (2019) "Recent advance in SERS techniques for food safety and quality analysis: a brief review," Current Opinion in Food. Science 28:82–87
26. Qu C, Li Y, Du S, Geng Y, Su M, Liu H (2022) Raman spectroscopy for rapid fingerprint analysis of meat quality and security: principles, progress and prospects. Food Res Int 161:111805
27. Saleh TA (2020) "Trends in the sample preparation and analysis of nanomaterials as environmental contaminants," Trends in Environmental. Anal Chem 28:e00101
28. Sivaprakasam V, Hart MB (2021) "Surface-enhanced Raman spectroscopy for environmental monitoring of aerosols," ACS. Omega 6(15):10150–10159
29. Li D, Yue W, Gao P, Gong T, Wang C, Luo X (2024) Surface-enhanced Raman spectroscopy (SERS) for the characterization of atmospheric aerosols: current status and challenges. TrAC Trends Anal Chem 170:117426
30. Guo J, Zeng F, Guo J, Ma X (2020) Preparation and application of microfluidic SERS substrate: challenges and future perspectives. J Mater Sci Technol 37:96–103
31. Ong TTX, Blanch EW, Jones OAH (2020) Surface enhanced Raman spectroscopy in environmental analysis, monitoring and assessment. Sci Total Environ 720:137601
32. Wang S et al (2020) Development of affinity between target analytes and substrates in surface enhanced Raman spectroscopy for environmental pollutant detection. Anal Methods 12(47):5657–5670. https://doi.org/10.1039/D0AY01760D
33. Zhang D, Hao R, Zhang L, You H, Fang J (2020) Ratiometric sensing of polycyclic aromatic hydrocarbons using capturing ligand functionalized mesoporous Au nanoparticles as a surface-enhanced Raman scattering substrate. Langmuir 36(38):11366–11373
34. Zong C et al (2018) Surface-enhanced Raman spectroscopy for bioanalysis: reliability and challenges. Chem Rev 118(10):4946–4980
35. Pletincx S, Fockaert LLI, Mol JMC, Hauffman T, Terryn H (2019) Probing the formation and degradation of chemical interactions from model molecule/metal oxide to buried polymer/metal oxide interfaces. NPJ Mater Degrad 3(1):23
36. Xu G et al (2020) Surface-enhanced Raman spectroscopy facilitates the detection of microplastics <1 μm in the environment. Environ Sci Technol 54(24):15594–15603
37. Wang M, Zheng N, Zhao D, Shang J, Zhu T (2021) Using micro-Raman spectroscopy to investigate chemical composition, mixing states, and heterogeneous reactions of individual atmospheric particles. Environ Sci Technol 55(15):10243–10254
38. Su M, Liu H (2018) Plasmonic nanomaterials for SERS detection of environmental pollutants. In: Hussain CM, Mishra AK (eds) Nanotechnology in Environmental Science, pp 473–514
39. Duan Y et al (2020) Succession of keratin-degrading bacteria and associated health risks during pig manure composting. J Clean Prod 258:120624
40. Stöckel S, Kirchhoff J, Neugebauer U, Rösch P, Popp J (2016) The application of Raman spectroscopy for the detection and identification of microorganisms. J Raman Spectrosc 47(1):89–109
41. Ahmed MB et al (2021) Microplastic particles in the aquatic environment: a systematic review. Sci Total Environ 775:145793
42. Dvořák P, Nikel PI, Damborský J, de Lorenzo V (2017) Bioremediation 3.0: engineering pollutant-removing bacteria in the times of systemic biology. Biotechnol Adv 35(7):845–866
43. Tarafdar A et al (2022) The hazardous threat of Bisphenol A: toxicity, detection and remediation. J Hazard Mater 423:127097
44. Amaya-González S, De-los-Santos-Álvarez N, Miranda-Ordieres AJ, Lobo-Castañón MJ (2013) Aptamer-based analysis: a promising alternative for food safety control. Sensors 13(12):16292–16311
45. Zhou J, Wu Z, Jin C, Zhang JXJ (2024) Machine learning assisted dual-functional nanophotonic sensor for organic pollutant detection and degradation in water. npj Clean Water 7(1):3
46. Feng J-R, Deng Q-X, Han S-K, Ni H-G (2023) Use of nanoparticle-coated bacteria for the bioremediation of organic pollution: a mini review. Chemosphere 313:137391
47. Hassan MM, Zareef M, Xu Y, Li H, Chen Q (2021) SERS based sensor for mycotoxins detection: challenges and improvements. Food Chem 344:128652
48. Zhao WC et al (2019) Rapid determination of 1,3-propanediol in fermentation process based on a novel surface-enhanced Raman scattering biosensor. Spectrochim Acta A Mol Biomol Spectrosc 211:227–233
49. Wang AX, Kong X (2015) Review of recent progress of plasmonic materials and nano-structures for surface-enhanced Raman scattering. Materials 8(6):3024–3052
50. Ji W, Zhao B, Ozaki Y (2016) Semiconductor materials in analytical applications of surface-enhanced Raman scattering. J Raman Spectrosc 47(1):51–58
51. Wang A-J et al (2020) Electrochemistry-stimulated environmental bioremediation: development of applicable modular electrode and system scale-up. Environmental Science and Ecotechnology 3:100050
52. Merkhofer MW (2012) Decision science and social risk management: a comparative evaluation of cost-benefit analysis, decision analysis, and other formal decision-aiding approaches. Springer Science & Business Media, p 330
53. Noyes PD, Lema SC (2015) Forecasting the impacts of chemical pollution and climate change interactions on the health of wildlife. Current Zoology 61(4):669–689
54. Beven K (2010) Environmental modelling: an uncertain future? Taylor & Francis, p 328
55. Kumari A, Upadhyay V, Kumar S (2023) A critical insight into occurrence and fate of polycyclic aromatic hydrocarbons and their green remediation approaches. Chemosphere 329:138579
56. Zou Z et al (2008) Environmentally friendly disposable sensors with microfabricated on-chip planar bismuth electrode for in situ heavy metal ions measurement. Sensors Actuators B Chem 134(1):18–24
57. Saute B, Premasiri R, Ziegler L, Narayanan R (2012) Gold nanorods as surface enhanced Raman spectroscopy substrates for sensitive and selective detection of ultra-low levels of dithiocarbamate pesticides. Analyst 137(21):5082–5087. https://doi.org/10.1039/C2AN36047K
58. Lee HK et al (2019) Designing surface-enhanced Raman scattering (SERS) platforms beyond hotspot engineering: emerging opportunities in analyte manipulations and hybrid materials. Chem Soc Rev 48(3):731–756. https://doi.org/10.1039/C7CS00786H
59. Esmaielzadeh Kandjani A, Sabri YM, Mohammad-Taheri M, Bansal V, Bhargava SK (2015) Detect, remove and reuse: a new paradigm in sensing and removal of Hg (II) from wastewater via SERS-active ZnO/Ag nanoarrays. Environ Sci Technol 49(3):1578–1584
60. Parisi J, Dong Q, Lei Y (2015) In situ microfluidic fabrication of SERS nanostructures for highly sensitive fingerprint microfluidic-SERS sensing. RSC Adv 5(19):14081–14089. https://doi.org/10.1039/C4RA15174G
61. Xu G, Song P, Xia L (2021) Examples in the detection of heavy metal ions based on surface-enhanced Raman scattering spectroscopy. Nanophotonics 10(18):4419–4445
62. Guo X et al (2020) Recyclable Raman chip for detection of trace mercury ions. Chem Eng J 390:124528
63. Pérez-Jiménez AI, Lyu D, Lu Z, Liu G, Ren B (2020) Surface-enhanced Raman spectroscopy: benefits, trade-offs and future

developments. Chem Sci 11(18):4563–4577. https://doi.org/10.1039/D0SC00809E

64. Lada ZG, Voyiatzis GA, Aggelopoulos CA (2022) A novel, green, low-cost regeneration method for surface enhanced raman scattering (SERS) solid substrates based on nanosecond pulsed cold plasma technology. Surfaces and Interfaces 34:102330
65. Liu Z et al (2017) Gold nanoparticle decorated electrospun nanofibers: a 3D reproducible and sensitive SERS substrate. Appl Surf Sci 403:29–34