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Research Progress on the Application of Magnetic SERS Substrate Sensing Technology in the Rapid Detection of Foodborne Pathogens

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Abstract. Foodborne pathogen pollution constantly threatens public health security, and traditional microbial detection methods have relatively prominent shortcomings in detection speed, sensitivity and practical field application. Magnetic surface-enhanced Raman scattering (SERS) substrate sensing technology combines the magnetic separation and enrichment capability of magnetic nanomaterials with the fingerprint recognition and high-sensitivity detection characteristics of SERS spectroscopy; in the face of food sample matrices with complex components, this technology shows strong anti-interference ability and detection performance. This paper reviews the construction approach and sensing mechanism of magnetic SERS composite substrates, focuses on the practical design ideas of magnetic core materials, plasmonic resonance hotspots and biorecognition probes, and summarizes the latest research cases of this technology against common foodborne pathogens such as Salmonella, Escherichia coli, Staphylococcus aureus and Listeria. At the same time, this paper analyzes the practical problems existing in this technology at the present stage, such as insufficient substrate stability, limited specific recognition and difficulty in standardized promotion, and discusses the follow-up development ideas around the research and development of new materials, multi-target simultaneous detection, microfluidic chip integration and the development of portable intelligent detection equipment, in order to provide a reference for the iteration of food safety rapid detection related technologies.

Keywords: magnetic SERS substrate, surface-enhanced Raman scattering, magnetic separation, foodborne pathogens, biosensing, rapid detection, nanoprobes

1. Introduction

1.1. Current situation of foodborne pathogen pollution and bottlenecks of traditional detection technologies

Food safety is directly related to the health of the public, and is an important issue that cannot be ignored in the field of social public health. According to estimates, the number of people worldwide who develop foodborne diseases each year from eating contaminated food is large, and the resulting number of deaths is also large; pathogenic bacteria such as Salmonella, pathogenic Escherichia coli, Listeria monocytogenes and Staphylococcus aureus are the main triggers of this type of food safety

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incident. Foodborne diseases induced by microbial pollution have also been repeatedly reported in China; in addition to harming human health, such incidents also cause considerable socioeconomic losses.

In the face of the prevention and control pressure brought by foodborne pathogens, completing pathogen identification quickly and accurately is a key link in food safety prevention and control. However, the existing traditional detection methods still have obvious defects: the plate culture counting method, as the recognized "gold standard" of microbial detection, relies on bacterial culture and colony counting throughout the detection process; the operation steps are cumbersome, the complete detection cycle lasts as long as several days or even weeks, and when sudden food safety incidents occur, this method is difficult to meet the actual needs of emergency screening [1, 2]. Polymerase chain reaction (PCR) and enzyme-linked immunosorbent assay (ELISA) can improve the detection sensitivity and specificity to a certain extent; PCR detection needs to obtain the target gene sequence in advance, and the sample pretreatment process is cumbersome; ELISA detection is easily disturbed by background signals, and its specificity is limited. Proteins, fats and other impurities inside the food matrix can also interfere with the two types of detection technologies, causing false-positive or false-negative results [1, 3]. Based on the above practical situation, the industry urgently needs to develop a new type of rapid detection method with high sensitivity, good specificity, simple operation, and the ability to resist complex matrix interference.

1.2. Advantages and research significance of magnetic SERS sensing technology

Surface-enhanced Raman scattering (SERS) spectroscopy has a fingerprint recognition effect; the detection sensitivity can reach the single-molecule level, water molecules almost do not interfere with the detection signal, and it has now been widely used in biomolecular analysis and microorganism-related research [2, 4, 5]. Using the label-free SERS detection mode, without carrying out long-time bacterial culture, the complete Raman fingerprint spectrum of bacterial cells can be collected, completing the rapid differentiation and identification at the strain level [2]. However, when the SERS technology is directly used for the detection of food samples, how to capture and enrich the target pathogens with very low content from samples full of a large number of background interferences remains a practical problem that needs to be overcome [3, 5].

The emergence of magnetic SERS sensing technology provides a feasible solution to the above problems. This technology uses superparamagnetic nanomaterials as the separation carrier, and relies on an external magnetic field to complete the rapid separation, enrichment and washing of the target pathogens, greatly simplifying the sample pretreatment steps and weakening the interference brought by the matrix [3]. The surface of magnetic functional materials can also be modified with recognition components such as antibodies and aptamers, realizing the specific capture of pathogens; with the help of an external magnetic field to regulate the aggregation behavior of nanoparticles, stable and regulable SERS "hotspots" are constructed, further improving the detection sensitivity and result reproducibility [3, 6]. This technical approach of mutual synergy between magnetic enrichment and SERS fingerprint detection improves both the detection signal-to-noise ratio and the reliability of results, and shortens the overall detection time. Therefore, systematically sorting out the design principles of magnetic SERS substrates and summarizing their latest research results in the direction of foodborne pathogen detection has theoretical value and practical significance for promoting the implementation of food safety point-of-care testing (POCT) technology.

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2. Basic theory and sensing principles of magnetic SERS substrates

2.1. Signal enhancement mechanism of surface-enhanced Raman scattering (SERS)

At present, two SERS signal enhancement mechanisms are generally recognized in the academic community, of which the electromagnetic enhancement mechanism (EM) occupies the dominant position. After precious metal nanostructures such as gold and silver adsorb the molecules to be measured, under the excitation condition of a laser with a specific wavelength, the free electrons on the metal surface undergo collective oscillation, producing a localized surface plasmon resonance effect (LSPR). The nanoparticle tips or interparticle gap regions, commonly known as "hotspots", see their local electromagnetic field intensity improved by several orders of magnitude, and the Raman scattering signals of the molecules adsorbed there are significantly amplified [5]. Existing related studies have proven that under the combined action of surface enhancement and resonance enhancement effects, the enhancement factor of the system can reach 10^{14}-10^{15} at the highest, which can fully achieve single-molecule detection [4].

The chemical enhancement mechanism (CM) is a secondary enhancement pathway; this mechanism originates from the charge transfer resonance phenomenon occurring between the molecules to be measured and the metal interface, and the signal enhancement amplitude it brings is usually only on the order of 10^2 [5]. In the actual design work of magnetic SERS substrates, constructing "hotspots" with high density, uniform distribution and strong controllability is the core means of obtaining high-sensitivity detection signals [3, 5].

2.2. Principles and advantages of separation and enrichment of magnetic nanomaterials

Magnetic nanomaterials such as Fe_3O_4 have superparamagnetic properties: when an external magnetic field is applied, the material can respond to the magnetic field rapidly and achieve directional enrichment; when the magnetic field is removed, the material has almost no remanence and can be redispersed into the solution, making it very suitable as a separation and enrichment carrier [7]. An ideal magnetic core should have a suitable particle size, a narrow particle size distribution range, a high saturation magnetization intensity, and excellent biocompatibility. The material particle size, microscopic morphology and surface chemical properties directly change the magnetic properties of magnetic nanoparticles as well as the colloidal dispersion stability [7].

Compared with traditional separation methods such as centrifugation and filtration, the advantages of magnetic separation technology are relatively prominent: first, the operation threshold is low, and solid-liquid two-phase separation can be completed with the help of an external magnet alone; second, the separation efficiency is high, and trace target substances in a large sample system can be concentrated into a small-volume solution; third, the anti-interference ability is strong, and during the magnetic separation process washing operations are carried out simultaneously, which can remove a large number of non-specific adsorption impurities originating from food matrices [3].

2.3. Coupling sensing mechanism of magnetic enrichment and SERS detection

The combination of magnetic enrichment and SERS detection is not a simple physical superposition of the two technologies; there is an obvious synergistic effect between the two. The existing coupling modes are mainly divided into two types, as shown in Table 1.

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Table 1. Comparison of two coupling modes of magnetic enrichment and SERS detection

Coupling mode	Operating process	Technical characteristics	Applicable scenarios
Capture-separation-detection three-step mode	the functionalized magnetic SERS substrate captures pathogens → an external magnetic field separates the "magnetic bead-target bacterium" complex → a SERS signal probe label is introduced and the spectrum is then collected	capture and signal labeling are completed step by step, probe selection is flexible, and the operating process is slightly longer	sample detection of complex food matrices where background interference needs to be reduced
One-step capture-simultaneous detection mode	composite probes with both magnetic separation and SERS enhancement activity are used to directly collect SERS spectra while capturing pathogens	the detection process is simplified and takes less time; the requirements for the comprehensive performance of composite probes are high	field rapid screening and POCT detection scenarios

The synergistic effect of the two is reflected in multiple levels: magnetic enrichment can improve the local concentration of pathogens in the SERS "hotspot" regions and amplify the originally weak detection signals; an external magnetic field induces nanoparticle aggregation, generating more uniformly distributed plasmonic coupling hotspots, that is, magnetic-field-mediated hotspot engineering, further strengthening the SERS response signals [3, 6]. The physical separation effect brought by magnetic separation can also eliminate the scattering interference of the solution body and suspended impurities on the excitation light path, ultimately obtaining detection results with a high signal-to-noise ratio [3].

3. Construction and material design of magnetic SERS composite substrates

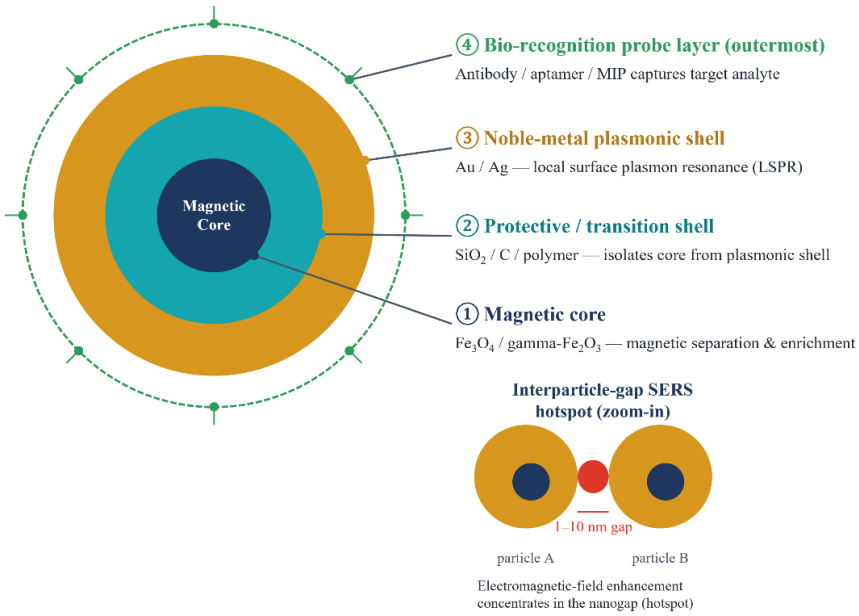


Figure 1. Layered structure of magnetic SERS composite substrate

High-performance magnetic SERS substrates are the foundation of the entire sensing system, and the design work needs to be carried out in coordination around the three parts of the magnetic core, the

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plasmonic shell and the biorecognition layer [3]. Figure 1 shows the structural schematic diagram of the magnetic SERS composite substrate.

3.1. Selection and synthesis of magnetic core materials

Magnetic core materials with excellent performance need to have a high saturation magnetization intensity, good biocompatibility and chemical stability. Iron tetroxide (Fe_3O_4) nanoparticles have a mature preparation process, excellent magnetic response performance, and are the most widely used in related research. Common synthesis methods include the co-precipitation method, the hydrothermal/solvothermal method, and the thermal decomposition (high-temperature organic phase) method. The co-precipitation method is simple to operate and suitable for large-scale preparation, but the particle size distribution of the synthesized product is relatively wide; the hydrothermal/solvothermal method facilitates the control of particle size and morphology, and the products have better crystallinity; the thermal decomposition method yields products with good monodispersity and narrow particle size distribution, but the reaction conditions are harsh [7]. When the co-precipitation method is used for preparation, the particle size distribution is affected by crystal nucleation and growth kinetics, and parameters such as the reaction pH, ionic strength, Fe^{2+}/Fe^{3+} molar ratio and reaction temperature need to be regulated to complete performance optimization [7].

Bare Fe_3O_4 particles are easily oxidized by air, and the particles are highly prone to agglomeration under the influence of magnetic dipole interactions; generally, the particle surface needs to be coated with SiO_2, gold or polymer shells such as dextran and polydopamine. The SiO_2 coating layer can weaken magnetic dipole interactions, improve the chemical stability and colloidal dispersion performance of the material, and can also provide a large number of active groups, facilitating the subsequent loading of precious metals and the coupling of biorecognition molecules [3, 7].

3.2. Construction of plasmonic resonance (SERS hotspots)

The construction of the plasmonic resonance layer directly determines the SERS activity of the substrate. Gold (Au) and silver (Ag) are the most widely used precious metal materials in this field; the signal enhancement effect of silver is stronger, while the chemical stability and biocompatibility of gold are more advantageous; the particle sizes at which spherical gold and silver nanoparticles exert their optimal enhancement effect are mostly in the range of 30-100 nm [5].

The mainstream methods for assembling precious metal nanostructures on the surface of magnetic cores are divided into the seed growth method and the in-situ reduction method. The seed growth method first reduces gold or silver seed particles on the surface of the magnetic core, and then adds a growth solution to regulate the particle size; the in-situ reduction method relies on the active groups on the material surface to complex metal ions, directly completing the reduction reaction. The core-shell structure Fe_3O_4@SiO_2@Au/Ag is a classic configuration and can protect the internal magnetic core; satellite structures and core-satellite heterostructures rely on the nanogaps between particles to construct a large number of high-density SERS hotspots, achieving an order-of-magnitude improvement in detection signals [5].

The unique advantage of magnetic composite substrates is reflected in the ability to regulate the arrangement of nanoparticles and the interparticle gaps by means of a magnetic field, obtaining magnetically regulated hotspots with better reproducibility and stronger enhancement effects [3, 6]. Existing studies have proven that introducing ferromagnetic media such as nickel-phosphorus (Ni-P) thin films between permanent magnets and nanoparticles can promote the aggregation of magnetic nanoparticles driven by the magnetic field, generating extra SERS hotspots and significantly improving the detection sensitivity [6].

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3.3. Functional modification of biorecognition probes

To achieve the specific recognition of pathogens, corresponding biorecognition elements need to be coupled on the surface of magnetic SERS substrates. Combining the target pathogen types and detection mode differences, the recognition molecules commonly used are mainly of three types. The first type is antibodies, which have excellent specificity and affinity, but the material cost is relatively high, and performance fluctuates between different batches [1, 3]. The second type is nucleic acid aptamers, which are prepared with the help of the SELEX in-vitro screening technique; chemical synthesis is simple, chemical stability is good, chemical modification is easy, the cost is controllable, and they are recognition components that are very widely used at the present stage [1]. The third type includes phages, antimicrobial peptides and vancomycin-type antibiotics, which naturally possess bacterial binding ability and can withstand relatively harsh environmental conditions, and the attention of related research continues to rise [1, 3].

Covalent coupling is the main modification method; generally, EDC/NHS is used to activate the carboxyl groups on the substrate surface, which then bind with the amino groups of the recognition molecules, ensuring the oriented arrangement of recognition probes and retaining their biological activity to the greatest extent [5]. When carrying out surface functionalization modification, it is necessary to take into account both the capture efficiency and the anti-non-specific adsorption ability, and bovine serum albumin (BSA) is usually introduced to block the active sites of the substrate where probes are not bound [1, 5].

4. Application examples of magnetic SERS sensing in the detection of typical foodborne pathogens

4.1. Detection of Gram-negative bacteria (taking Salmonella and Escherichia coli as examples)

Lipopolysaccharide (LPS) exists in the outer membrane of the cell wall of Gram-negative bacteria and can serve as an antigen site for specific recognition. Label-free SERS can obtain strain- or even serovar-specific bacterial fingerprint spectra; compared with ordinary Raman spectra, the spectral bands obtained by this method are clearer, the strain differentiation effect is good, and the fluorescence background interference is low; under low laser power conditions, single-cell observation can also be completed, laying an experimental foundation for the direct identification of pathogens inside food samples [8].

For Salmonella typhimurium, many studies have chosen LPS-targeted aptamer-modified magnetic SERS probes, combined with high-enhancement substrates such as silver nanorod arrays, to complete the capture and detection of pathogens, achieving culture-free rapid screening [1, 3]. For the detection of Escherichia coli (including the O157:H7 serotype), a sandwich dual-function detection system is mostly adopted: Fe_3O_4@Au and Fe_3O_4@SiO_2-Au magnetic nanomaterials are selected, with antibodies or aptamers coupled as capture probes; high-SERS-activity nanostructures such as gold nanostars are modified with Raman reporter molecules as signal probes. Under the condition of an external magnetic field, a "capture probe-target bacterium-SERS tag" sandwich composite structure is formed [3, 9]. Plasmonic coupling occurs between the capture probes and the SERS tags, and superimposed on the hotspot density improvement brought by magnetic enrichment, the dual signal amplification strategy can realize the simultaneous detection of multiple bacteria. Literature reports that the detection limit of this system for Escherichia coli and Staphylococcus aureus is as low as 10 CFU/mL, and it has been successfully verified in real milk samples [9]. It should be noted that the LPS layer has a steric hindrance effect, which reduces the capture efficiency of recognition molecules; generally, a flexible linker needs to be added to the aptamer to optimize the binding site [1].

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4.2. Detection of Gram-positive bacteria (taking Staphylococcus aureus and Listeria as examples)

Gram-positive bacteria do not have an outer membrane structure; the cell wall is a relatively thick peptidoglycan layer. Protein A specific to the surface of Staphylococcus aureus and various membrane proteins on the surface of Listeria can both serve as capture targets.

For the detection of Staphylococcus aureus, many studies have constructed aptamer-modified core-shell magnetic SERS platforms: aptamer-functionalized magnetic gold-shell composites serve as the capture and enrichment unit, high-activity SERS tags coupled with reporter molecules serve as the signal unit, and an aptamer-vancomycin dual-recognition mode or sandwich detection structure is adopted to achieve specific capture and signal amplification [3, 9]. The detection limit of this type of aptamer-magnetic SERS system can reach 10 CFU/mL, and it has been used for the detection of food samples with complex matrices such as milk [9].

For Listeria monocytogenes, an immunomagnetic separation (IMS) combined with SERS integrated scheme is often adopted, and literature reports that the detection limit of this system is about 12 CFU/mL [1]. This pathogen has strong survivability in food processing environments, and some studies have also attempted label-free detection: positively charged magnetic nanoparticles rely on electrostatic action to adsorb negatively charged bacteria, and combined with microdroplet concentration means, the target bacteria are enriched into a very small volume for SERS spectrum collection, relying on the bacteria own fingerprint characteristic peaks to differentiate strains, saving the complicated steps of antibody modification [1, 8].

For spore-forming Gram-positive pathogens such as Bacillus anthracis, detection can be completed by identifying spore characteristic markers. Dipicolinic acid (DPA, mostly existing in the form of the calcium salt CaDPA) accounts for about 10% of the dry weight of spores and is an ideal detection target for spores. Zhang et al. extracted CaDPA inside spores by nitric acid ultrasonication on a silver film-over-nanosphere (AgFON) substrate, carried out SERS detection, and obtained a detection limit of about 2.6×10^3 spores, lower than the anthrax infectious dose of 10^4 spores; combined with a portable Raman instrument, field detection of 10^4 spores can be completed in only 5 s [10].

4.3. Complex matrix interference in actual food samples and its elimination

Promoting magnetic SERS technology from the laboratory to the detection of real food samples such as meat homogenate, milk and egg liquid, the interference brought by complex matrices is an unavoidable problem. The interference sources are divided into two types: one is physical-level interference, where proteins and fat particles scatter and absorb the excitation light, causing spectral baseline drift; the second is non-specific adsorption, where matrix macromolecules compete for the active sites on the probe surface. The current mainstream interference elimination methods are as follows: preliminary removal of large-particle impurities by means of pretreatment methods such as dilution, centrifugation and filtration [1]; specific extraction and enrichment of the target by relying on immunomagnetic separation, stripping most of the matrix components before SERS testing [3]; optimization of the magnetic separation washing process, using buffer solutions supplemented with the Tween-20 surfactant to wash the magnetic bead complexes multiple times, eluting physically adsorbed proteins and lipids [1]. In addition, ratiometric and internal-standard SERS detection strategies introduce built-in reference molecules to correct signal fluctuations, which can improve the accuracy of quantitative results [5].

Table 2 summarizes the representative studies of magnetic SERS sensing technology in the detection of typical foodborne pathogens in recent years. As can be seen from Table 2, magnetic SERS sensing technology has shown good application potential in complex food matrices such as milk, but

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different studies still differ in substrate materials, recognition elements and signal collection conditions; subsequently, the unification of performance evaluation standards needs to be further strengthened, and the capability of multi-target simultaneous detection and field rapid detection needs to be strengthened.

Table 2. Representative studies on magnetic SERS sensing in the detection of typical foodborne pathogens

Target pathogen/target	Recognition/capture element	Magnetic SERS substrate/probe	Detection mode	Analytical performance	Sample/validation	Reference
Salmonella typhimurium	LPS-targeted aptamer	magnetic SERS probe + silver nanorod array	culture-free capture detection	not explicitly listed	rapid screening of food samples	[1, 3]
Escherichia coli O157:H7	antibody or aptamer	Fe3O4@Au, Fe3O4@SiO2-Au capture probes; gold nanostar SERS tags	sandwich detection	as low as 10 CFU/mL	milk	[9]
Staphylococcus aureus	aptamer, aptamer-vancomycin dual recognition	aptamer-functionalized magnetic gold-shell composite + high-activity SERS tag	dual recognition/sandwich detection	as low as 10 CFU/mL	milk	[3, 9]
Listeria monocytogenes	antibody	immunomagnetic separation + SERS integrated system	IMS-SERS	about 12 CFU/mL	food matrix	[1]
Listeria	electrostatic adsorption by positively charged magnetic nanoparticles	microdroplet concentration + label-free SERS	label-free detection	not explicitly listed	bacterial fingerprint differentiation	[1]
Bacillus anthracis spores (extended case)	CaDPA target	AgFON silver-film-over-nanosphere substrate	label-free SERS	about 2.6×10^3 spores	portable Raman detection of 10^4 spores in 5 s	[10]

5. Existing technical bottlenecks and optimization strategies of the technology

5.1. Technical problems existing in current magnetic SERS detection systems

Although related research has achieved many results, the large-scale industrialization of magnetic SERS sensing technology still faces multiple technical obstacles. Precious metal nanoparticles are prone to agglomeration in solution environments, and also undergo oxidation after contact with air, resulting in uneven hotspot distribution and obvious differences in substrate performance between different batches; most of the reported substrates have a short storage validity period, and the long-term stability of substrates and signal reproducibility remain to be improved [3, 5].

In real food matrix environments, specific recognition also faces challenges. When antibodies and aptamers come into contact with actual samples, non-specific adsorption of matrix macromolecules and interference from matrix components may both cause the failure of recognition elements. Label-

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free detection relies heavily on the bacteria own fingerprint peaks and is easily disturbed by environmental conditions; some substances to be measured have weak Raman scattering signals themselves, and the specificity of characteristic peaks is insufficient [3, 5]. The SERS signal intensity is affected by multiple factors such as laser optical path deviation and substrate batch differences, and achieving stable and reliable absolute quantification is relatively difficult [5]. The industry has not yet established a unified standardized evaluation system; the performance indicators of substrates prepared by different laboratories are not unified, and the horizontal comparison of experimental results is difficult to carry out [1, 3].

5.2. Strategies for material optimization, algorithm correction and detection system improvement

Researchers have carried out optimization work from multiple dimensions of materials, algorithms and detection systems. In terms of material modification, metal-organic frameworks (MOFs) can serve as templates and carriers for precious metal growth, improving the thermal stability and specific surface area of substrates, while strengthening the molecular enrichment capability. For example, the Fe_3O_4@NH_2-MIL-101 (Fe)@Ag magnetic MOF-SERS sensor has good detection signal uniformity, an RSD of about 7.73% under the 4-NBT system, and stable material performance after storage for 30 d; the large number of amino groups and porous structures inside the material strengthen the adsorption and enrichment of target molecules by means of hydrogen bonding [11].

Some studies have used defect engineering to prepare small-size UiO-66 and electrostatically self-assembled it with spiky magnetic gold substrates, obtaining a "berries-on-hedgehog" DU-W type magnetic SERS substrate. The MOF outer shell layer isolates air and protects the easily oxidized gold spikes; under 4 °C storage conditions, the shelf life of the material is extended from 30 d to 50 d, and the binding specificity of target molecules is also improved [12]. The Au/MIL-101 magnetic MOF substrate combined with the external-magnetic-field-induced hotspot aggregation effect can also improve the sensitivity and reproducibility [13]. Graphene and its two-dimensional oxidation products can support and disperse precious metal nanoparticles, suppress fluorescence backgrounds by means of charge transfer, and enrich aromatic molecules to be measured by means of π-π interactions, which is also conducive to improving the stability and capture capability of substrates [3, 9].

At the algorithm level, machine learning and deep learning models such as support vector machines (SVM) and random forests are introduced to automatically deduct background noise, correct the spectral drift brought by fluorescence, extract target characteristic signals from complex raw spectra, and improve the accuracy of qualitative discrimination and quantitative analysis [1, 14].

5.3. Multi-technology integration (microfluidics, AI recognition, portable equipment)

The cross-integration of multiple technologies is an important development direction in the future. ① Microfluidic chip integration: integrating the complete set of steps of magnetic SERS probe mixing, magnetic separation, washing and spectral detection into a microfluidic chip, achieving sample-in-result-out fully automatic detection, reducing errors introduced by manual operations and improving detection throughput [3]. Magnetic-field-driven magnetic nanochain microfluidic chips and digital microfluidic-MagSERS immunoassays have already verified the feasibility of automated biological separation detection [3]. ② AI-assisted spectral analysis: building a standard SERS spectral database of pathogens, with SVM machine learning algorithms completing automatic spectrum comparison and discrimination. Literature reports that magnetic SERS biosensors combined with SVM algorithms can achieve a classification accuracy of 100% for bacterial and viral samples [14]. ③ Portable Raman equipment: the volume and weight of handheld portable Raman instruments continue to decline, and a

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785 nm near-infrared excitation light source can be selected, allowing SERS technology to move out of the laboratory. Existing studies have used battery-powered portable Raman equipment, using SERS substrates stored for 1 month, to complete the detection of 10^4 anthrax spore simulants in 5 s [10]. Fe_3O_4-Au magnetic composites combined with gold nano-needle arrays construct magnetic SERS sensors, and field detection of swab samples can be completed in about 15 min [14]. The above studies prove that magnetic SERS technology has good application potential in the field of POCT detection at farmers markets and canteens [3].

6. Conclusion and prospects

Overall, magnetic SERS substrate sensing technology combines the two major advantages of efficient magnetic separation enrichment and ultra-sensitive SERS fingerprint detection, and has very considerable application prospects in the field of rapid detection of foodborne pathogens [3]. This paper reviews the basic theory of this technology, introduces the substrate construction approach of the magnetic core, plasmonic hotspots and biorecognition layer, and summarizes the research progress in the detection of pathogens such as Salmonella and Staphylococcus aureus.

Follow-up research can be advanced around the three directions of standardization, intelligentization and portability. First, continue to develop new composite nanomaterials, improve the environmental tolerance and long-term storage stability of substrates, refer to MOF-coated precious metals to extend shelf life related ideas [11, 12], and further improve the capability of multi-target simultaneous detection [3]. Second, establishing a unified magnetic SERS operating process and performance evaluation standard is a necessary condition for the industrialization of this technology [3, 5]. Third, combine 5G networks, cloud artificial intelligence analysis modules and portable Raman instruments to create an integrated field detection terminal of microfluidic automatic pretreatment-spectral collection-machine learning intelligent interpretation [3, 14]. With the continuous deepening of multidisciplinary cross research, magnetic SERS technology has the opportunity to become an important technical means of food safety intelligent supervision.

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