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Magnetic nanoprobe for rapid detection of copper ion in aqueous environment by surface-enhanced Raman spectroscopy†

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Excessive copper ions in drinking water could cause serious health issues, such as gastrointestinal disorders and cirrhosis, and they are associated with Alzheimer's disease. ICP-OES, ICP-MS, and AAS are the most common methods of copper ion determination. However, the high cost of sample preparation and labor limit the possibility of on-site detection. In this study, rapid monitoring of copper ion through the SERS technique was evaluated. Fe₃O₄@SiO₂-Ag-4MBA nanoparticles were investigated as SERS-activated magnetic nanoprobe. These magnetic nanoprobe underwent superparamagnetism for rapid aggregation in seconds and provided selectivity in sensing copper ions. According to the dose-response curve of the SERS spectra, the limit of detection (LOD) was 0.421 ppm and the dynamic range was from 0.5 to 20 ppm in the presence of other metal ions. Copper ion detection through SERS was highly correlated with ICP-OES ($R^2 = 0.95$, slope = 0.974). These results demonstrate that magnetic nanoprobe may ultimately be used in a platform for on-site detection.

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1. Introduction

Copper is a required trace element in organisms, especially for the regulation of many cellular enzymes. For instance, hemato-poiesis in humans relies on ceruloplasmin, a copper ion-containing protein, for the oxidation of Fe²⁺.^{1,2} Although copper ion plays an important role in organisms, uptake of excessive copper ion can induce acute toxicities, resulting in diarrhea, nausea, and vomiting.³ Moreover, chronic toxicities of copper ion significantly impact the viscera and the central nervous system, especially the brain, leading to Alzheimer's disease⁴ and Parkinson's disease.⁵ For example, Abbaoui *et al.* reported that Cu²⁺ damages the neuron system and the decreased locomotor performance once the uptake dose of Cu²⁺ is over 10 mg kg⁻¹ BW.⁶ The Taiwan Environmental Protection Agency (EPA) has set health advisory levels for copper ion in drinking water at 1 ppm.⁷ Therefore, the development of a rapid and sensitive method for copper ion detection has attracted considerable attention.

Traditional techniques for Cu²⁺ detection from wastewater are not suitable for on-site detection, such as inductively coupled plasma optical emission spectroscopy (ICP-OES), mass spectroscopy, and atomic absorbance spectroscopy (AA). In practice, ICP-OES and AA are used for Cu²⁺ concentrations within the ppm level. Mass spectroscopy has a lower detection limit, approaching ppb level.⁸⁻¹⁰ Researchers are currently

investigating alternative detection platforms, including electrochemical, fluorescence, and colorimetric methods. Although electrochemical^{11,12} and fluorescence methods¹³ provide high sensitivity for Cu²⁺ in water samples, these two approaches require a complex operation process and high-cost equipment.^{14,15} In addition, most colorimetric probes for Cu²⁺ are processed under organic solvent because of the organic dyes employed as probes. Recently, silver or gold nanoparticles were reported to display distance-dependent optical properties for rapid detection of Cu²⁺. For example, Lou *et al.* designed S₂O₃²⁻ decorated Ag/Au nanoprobe to detect Cu²⁺ based on color change.¹⁶ Xiang *et al.* presented NTBL as a colorimetric chemosensor, showing high selectivity for Cu²⁺ in aqueous solution.¹⁷ However, the salt present in aqueous solutions could interrupt the aggregation of nanoprobe, affecting copper ion concentration detection.¹⁸ There is a need to develop a detection platform with rapid detection, high selectivity, and low interference for Cu²⁺ detection.

Raman spectroscopy is a convenient technique for molecular detection through inelastic light scattering in an aqueous sample. However, the intensity of Raman scattering is extremely low because little inelastic light scattering occurs naturally. To improve the Raman signal, metallic nanoparticles, such as silver or gold nanoparticles, create plasmonic 'hotspots' through aggregation.¹⁹ Other heavy metals, such as As³⁺,²⁰ Hg²⁺,^{21,22} Pb²⁺,²² and Cr⁶⁺,²³ in aqueous solution are detected using the SERS technique. The use of chelator and organic linkers are common strategies to induce the aggregation of nanoparticles through chelation. Li *et al.* designed stimuli-response Raman reporters for simultaneous detection of Cu²⁺

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and HClO through covalent bonding.²⁴ Inspired by the above report, we developed functional magnetic nanoparticles, Fe₃O₄@SiO₂-Ag-4MBA, which were designed as probes for copper ion detection by surface-enhanced Raman spectroscopy (SERS). This approach monitors the signal increases through the formation of 'hotspots' with simultaneous magnetic field application and copper ion chelation. Magnetic nanoprobe exhibit superparamagnetism to achieve rapid aggregation, and 4-MBA composes the carboxylic acid group, which can react with copper ion through chelation. On the other hand, 4-MBA contributes to the selective molecular aggregation with copper ions, leading to the enhanced Raman signal of 4-MBA. As a result, the quantitative results are investigated by a significant change in Raman spectra accomplished by increasing the signal intensity of 4-MBA after Cu²⁺ induction. This demonstrates that the described SERS magnetic nanoprobe are able to capture and sense Cu²⁺ for this magnetic assay development.

2. Experimental

2.1 Reagents and materials

Silver nitrate reagent plus (AgNO₃, 99.85%), sodium borohydride (NaBH₄, 99%), and copper(II) nitrate trihydrate (99%) were purchased from Acros Organics. Thiosalicylic acid (C₇H₆O₂S, 98%) and iron(II) chloride tetrahydrate (FeCl₂·4H₂O, 98%) were purchased from Alfa Aesar. Silver nitrate solution 0.01 N and hydrochloric (HCl) were purchased from Honeywell Fluka. Tin(II) chloride dihydrate (SnCl₂·2H₂O, 98%) was purchased from Scharlau. Copper sulfate (CuSO₄·5H₂O, 98%) was purchased from Choneye pure chemicals. Cupric chloride dihydrate (CuCl₂·2H₂O, 99%) was purchased from HSE pure chemicals. 4-Mercaptobenzoic acid (4-MBA, >95%) was purchased from TCI. Tetraethyl orthosilicate (TEOS, 98%) was purchased from Aldrich. Ammonium hydroxide (NH₄OH, 28–30%) was purchased from MTEDIA. Iron(III) chloride hexahydrate (FeCl₃·6H₂O, >98%) was purchased from Sigma Aldrich. All solutions were prepared using high-purity water with a resistance of 18 MΩ cm. All chemicals used were analytical grade or of the highest purity available.

2.2 Synthesis of 4MBA-Ag nanoparticle probe (4MBA-AgNPs)

First, 200 mL of 10⁻⁴ M AgNO₃ solution was prepared and then 0.02 g NaBH₄ was added into the solution. Next, the solution was stirred vigorously for 5 minutes, and the solution color turned light-yellow. Then, 600 μL of 10⁻³ M 4-MBA solution was added into the AgNP solution. The solution was adjusted to pH 7.4 and stirred continuously for 1 h 4-MBA will self-assemble onto the AgNP surface. All the above procedures were prepared in an ice bath.

2.3 Synthesis of Fe₃O₄@SiO₂-Ag nanoparticle probe (Fe₃O₄@SiO₂-AgNPs)

FeCl₂·H₂O (1.8 g) and FeCl₃·6H₂O (4.8 g) were mixed in 100 mL DI water. Next, the mixture was stirred vigorously under a N₂ atmosphere until the salt dissolved completely. Then, 28%

NH₄OH was added slowly into the reaction mixture at room temperature and stirred for 1 h. After the reaction was completed, the black precipitate, Fe₃O₄, was separated using a magnetic field. The isolated Fe₃O₄ nanoparticles were washed with DI water several times and redispersed in a 100 mL ethanol solution containing 10 mL of 28% NH₄OH and 6 mL TEOS. The polymerization of SiO₂ was spontaneously processed onto the surface of magnetic nanoparticles under 2 hours of sonication. The residue was cleaned with anhydrous ethanol three times. The third step was to deposit Ag onto the Fe₃O₄@SiO₂ NPs through reduction. SnCl₂ and HCl were added to the solution containing Fe₃O₄@SiO₂ NPs for activation. Then, silver ammonia solution was mixed with Fe₃O₄@SiO₂ NP solution, forming Fe₃O₄@SiO₂-AgNPs. The final step was to introduce SERS-activated molecules, 4-MBA, onto the Fe₃O₄@SiO₂-AgNPs as a magnetic probe. Fe₃O₄@SiO₂-AgNPs were resuspended in anhydrous ethanol and mixed with 50 mL of 10⁻³ M 4-MBA solution under 2 hours self-assembly reaction. The reacted NPs were collected as Fe₃O₄@SiO₂-AgNPs probe for further sensing purposes.

2.4 Characterization of Fe₃O₄@SiO₂-AgNP probe

The chemical structure of Fe₃O₄@SiO₂-AgNPs was characterized by Fourier transform infrared spectroscopy (FT-IR, Nicolet iS5), X-ray diffraction (XRD, Bruker D8), and X-ray photoelectron spectroscopy (XPS, VG Scientific ESCALAB 250). The morphology of NPs was observed by transmission electron microscopy (TEM, JEOL-2100F). The magnetic properties were measured using a superconducting quantum interference device (SQUID, MPMS-XL7, QUANTUM DESIGN, America). Particle size and distribution were determined by Nano-ZS.

2.5 Copper ion detection

This study aimed at developing 4-MBA-activated nanoprobe for copper ion detection. 4-MBA not only contributes to the selectivity toward copper ion but also plays the role of Raman reporter. The wavelength of the laser was 532 nm for launching surface plasma around the surface of silver nanoparticles. Then, the generated surface plasma is delivered to 4-MBA. The characteristic peaks of 4-MBA are present in the Raman spectrum because of loss of Laser energy. In addition, the intensity of 4-MBA peaks corresponds to the level of aggregation of nanoprobe, which is caused by various concentrations of copper ions. The transmission grating beam splitter had 1800 grooves per mm. The scan range was from 1000 to 2000 cm⁻¹. All experimental results were recorded under 100 seconds of exposure time within one scan, and these recorded results were analyzed by LabSpec5 software. To validate the concentration of copper ions determined using SERS, the prepared copper ion sample was confirmed by inductively coupled plasma optical emission spectrum (ICP-OES, Perkin-Optima 7000 DV).



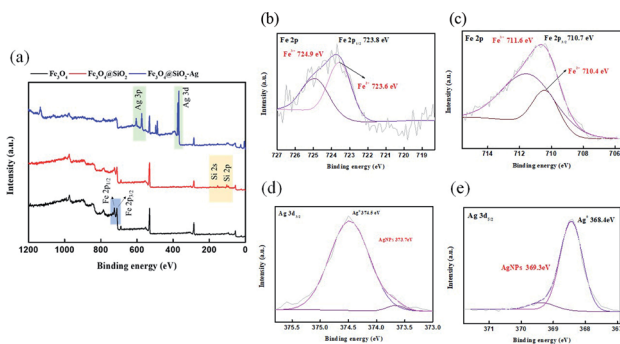


Fig. 1 XPS spectra of the $\text{Fe}_3\text{O}_4@SiO_2\text{-Ag}$ composite nanoparticles. (a) Survey spectrum; (b) Fe $2p_{1/2}$; (c) Fe $2p_{3/2}$; (d) Ag $3d_{5/2}$; (e) Ag $3d_{3/2}$.

3. Results and discussion

3.1 Characterization of $\text{Fe}_3\text{O}_4@SiO_2\text{-AgNP}$ probe

Fig. 1 shows the XPS results for the $\text{Fe}_3\text{O}_4@SiO_2\text{-AgNP}$ composite. The survey spectrum of Fe_3O_4 (Fig. 1a) showed two photoelectron peaks at 710.7 and 723.8 eV corresponding to Fe $2p_{3/2}$ and Fe $2p_{1/2}$, respectively.^{25,26} The newly added peaks in $\text{Fe}_3\text{O}_4@SiO_2$ at 103.5 eV were assigned as SiO_2 . In addition, the binding energies at 368 and 374 eV observed in the survey spectrum of $\text{Fe}_3\text{O}_4@SiO_2\text{-AgNPs}$ were demonstrated as Ag $3d_{5/2}$ and Ag $3d_{3/2}$. Fig. 1b and c present the Fe 2p spectrum of $\text{Fe}_3\text{O}_4@SiO_2\text{-AgNPs}$. The peaks at 710.4 and 723.6 eV were contributed by Fe^{2+} , and the peaks at 711.6 and 724.9 eV were assigned as Fe^{3+} .²⁷ The ratio of the respective areas under Fe^{2+} and Fe^{3+} peaks was 1 to 1.6, which is ascribed to Fe_3O_4 . Fig. 1d shows the high-resolution Ag 3d spectrum. Binding energy at 368.4 and 374.5 eV is ascribed to metallic silver (Ag^0) on $\text{Fe}_3\text{O}_4@SiO_2\text{-AgNPs}$.²⁸ In addition, shoulder peaks located at 369.3 and 373.4 eV were related to AgNPs.²⁹

Fig. 2a presents the XRD patterns of Fe_3O_4 , $\text{Fe}_3\text{O}_4@SiO_2$, and $\text{Fe}_3\text{O}_4@SiO_2\text{-AgNPs}$. The main peaks of Fe_3O_4 within the inverse spinel phase presented at 30.4° , 35.7° , 43.4° , 53.8° , 57.3° and 62.9° , which correspond to (2 0 0), (3 1 1), (4 0 0), (4 2 2), (5 1 1) and (4 4 0).^{30,31} In the case of $\text{Fe}_3\text{O}_4@SiO_2$, a newly broadened peak was observed between 20 and 30° , which was contributed by amorphous SiO_2 .^{32,33} The diffraction pattern of Ag can be characterized in the XRD spectrum of $\text{Fe}_3\text{O}_4@SiO_2\text{-AgNPs}$. The additional angles of 38.3° , 44.5° , 64.6° , and 77.5°

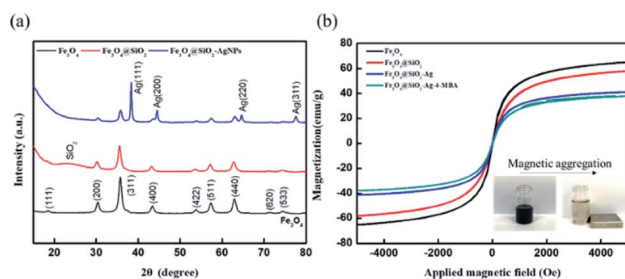


Fig. 2 Characterization of $\text{Fe}_3\text{O}_4@SiO_2\text{-Ag}$ composite nanoparticles. (a) XRD spectrum; (b) SQUID analysis (inset shows magnetic aggregation of probes).

correspond to AgNPs within FCC structure, marked as (1 1 1), (2 0 0), (2 2 0) and (3 1 1).^{34,35} The results, in line with previous research, reflected that AgNPs were successfully modified onto the $\text{Fe}_3\text{O}_4@SiO_2$ surface. Fig. 2b demonstrates the magnetic properties of $\text{Fe}_3\text{O}_4@SiO_2\text{-AgNPs}$ in each modification. Even though magnetization saturation (M_s) of Fe_3O_4 decreased after multiple modifications, there is no observation of magnetic hysteresis loop (the coercivity and remanence are zero). This indicated that the synthesized Fe_3O_4 , after multiple steps of modifications, still exhibited superparamagnetism, and aggregations of magnetic nanoprobe easily formed in a few seconds (inset photo in Fig. 2b).

Fig. 3a and b present DLS results for particle size and distribution of AgNPs and Fe_3O_4 NPs. 4-MBA-AgNPs showed slightly larger average particle size (14.63 ± 2.14 nm, PDI = 0.210) than the bare Ag spherical NPs, as shown in Fig. 3c (12.95 ± 1.58 , PDI = 0.179), because of self-assembled 4-MBA molecules. Meanwhile, the average size of Fe_3O_4 particles also increased from 24.79 ± 1.58 nm (PDI = 0.138) to 31.84 ± 2.78 nm (PDI = 0.254) due to the formation of the 7 nm-thick SiO_2 layer. Based on the TEM image, the appearance of bare Fe_3O_4 NPs (Fig. 3d) was spherical, and their particle size ranged from 13 to 15 nm. Superparamagnetic property is attributed to the critical size range of magnetic nanoparticles between 10 to 15 nm,³⁶ proving the superparamagnetism of $\text{Fe}_3\text{O}_4@SiO_2\text{-AgNPs}$. $\text{Fe}_3\text{O}_4@SiO_2\text{-AgNPs}$ were synthesized by the Stöber method, resulting in the formation of core-shell structures, as shown in Fig. 3e. The dark region in the core-shell is Fe_3O_4 , and the gray region is SiO_2 ; small particles on the SiO_2 surface are silver nanoparticles.³⁷⁻³⁹ The EDS results also indicated that the central area has Si and Fe elements, and the outer layer of the core-shell structure reflects Ag and Si elements. Based on these analytic results from XRD, XPS, DLS, and TEM, SERS-activated $\text{Fe}_3\text{O}_4@SiO_2\text{-AgNP}$ probes were successfully synthesized.

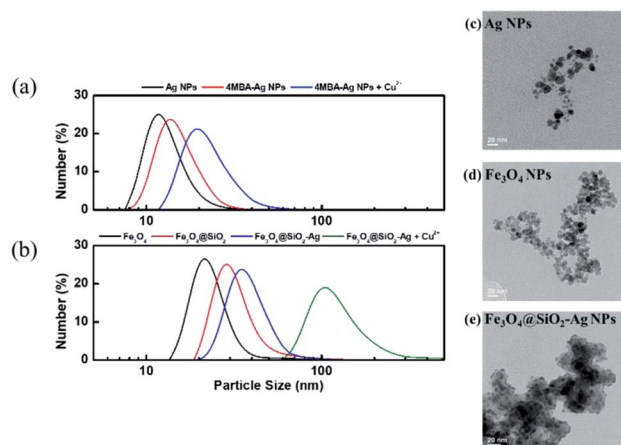


Fig. 3 Particle size and morphology of AgNPs and $\text{Fe}_3\text{O}_4@SiO_2\text{-Ag}$ composite nanoparticles before/after copper ion-induced aggregation. Size distribution of (a) AgNPs, 4 MBA-AgNPs, and 4 MBA-AgNPs + Cu^{2+} ; (b) Fe_3O_4 NPs, $\text{Fe}_3\text{O}_4@SiO_2$ NPs, $\text{Fe}_3\text{O}_4@SiO_2\text{-Ag}$, and $\text{Fe}_3\text{O}_4@SiO_2\text{-Ag} + Cu^{2+}$; TEM images of (c) AgNPs; (d) Fe_3O_4 NPs; and (e) $\text{Fe}_3\text{O}_4@SiO_2\text{-AgNPs}$ (scale bar: 20 nm).

3.2 Copper ion detection using SERS

4-MBA was the Raman reporter, which emitted surface-enhanced Raman signal (SERS) after $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-AgNP}$ probes aggregated, called a hot spot. The generation of hot spots can be determined by magnetic field application and copper ion introduction. Fig. 4a presents the Raman spectrum of 4-MBA with or without copper ion introduction. There were two specific peaks, 1080 cm^{-1} and 1584 cm^{-1} , corresponding to C-H in-plane bending and C-C stretching vibrational modes of 4-MBA, respectively.^{40,41} Once the magnetic field was applied for aggregation, the SERS peak intensities of the vibrational mode at 1080 and 1584 cm^{-1} increased compared to a plain solution without magnetic field. Further, the introduction of 30 ppm copper ion would additionally enhance the intensity of SERS peaks. This indicated that a magnetic field would physically generate a hot spot, resulting in improved Raman peak intensities. Then, copper ion was chelated with a carboxylic acid of 4-MBA for additional aggregation between magnetic nanoprobe. Fig. 3a and b prove that the average particle size of 4-MBA-AgNPs and $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-Ag-MBA}$ NPs became larger after adding copper ion, from $14.63 \pm 2.14\text{ nm}$ (PDI = 0.210) to $21.57 \pm 1.97\text{ nm}$ (PDI = 0.48) and from $37.08 \pm 1.33\text{ nm}$ (PDI = 0.191) to $124.37 \pm 8.75\text{ nm}$ (PDI = 0.364), respectively. Therefore, $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-Ag-MBA}$ NPs can be used as a probe for sensing copper ions in an aqueous environment.

To optimize the sensitivity of copper ion detection, we relied on the SERS peak at 1584 cm^{-1} because of its high intensity after copper-induced aggregation. According to the strategy of copper ion detection, the concentration of the modifier (4-MBA) and the magnetic probe/copper ion ratio play essential roles. Fig. 4b illustrates the concentration of 4-MBA for copper ion detection. The concentration of 4-MBA was set as $5 \times 10^{-4}\text{ M}$, $5 \times 10^{-3}\text{ M}$, 10^{-3} M , and 10^{-2} M , respectively. A low amount of 4-MBA was unable to generate sufficient chelation between magnetic nanoprobe, resulting in less aggregation and low SERS signal intensity, while a higher concentration of 4-MBA

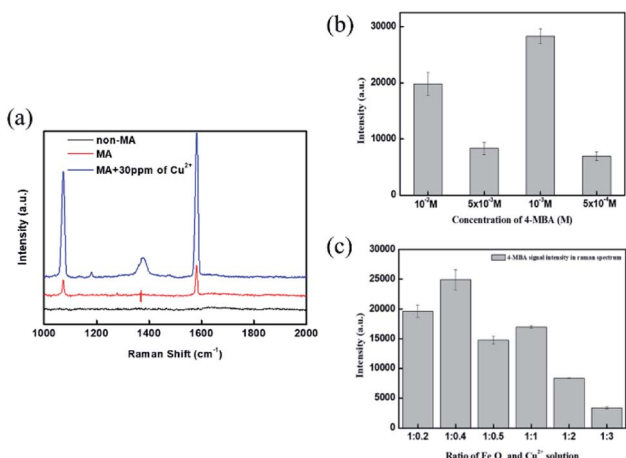


Fig. 4 Copper ion detection using $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-AgNP}$ probe. (a) Raman spectrum of 4-MBA before/after copper ion induction using 10^{-3} M 4-MBA as a modifier (MA is magnetic aggregation); (b) concentration effect of 4-MBA; (c) ratio of $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-AgNPs}$ and copper ion solution (total volume: 5 mL).

caused molecular overlapping. Consequently, the copper ion was hard to chelate with 4-MBA and even reduced the SERS peak signal.⁴² The optimized concentration of the modifier was 10^{-3} M for further preparation. Fig. 4c presents the Raman signal intensity under different volume ratios between magnetic nanoprobe and copper ion. The best performance was the ratio of 1 : 0.4 (magnetic nanoprobe/copper ion).

The stock magnetic nanoprobe prepared from the optimized condition was mixed with different concentrations of copper ions from 0 to 30 ppm. The SERS peak intensities of the vibrational mode at 1080 and 1584 cm^{-1} as a function of concentration are shown in Fig. 5a. The trend of copper ion concentration and SERS signal intensity at 1584 cm^{-1} followed a dose-response curve, where the MBA intensity can be distinguished over 1 ppm and saturated around 30 ppm. A better linear correlation result was observed for concentrations ranging from 0.5 to 20 ppm ($R^2 = 0.99$), meaning 30 ppm would be close to the copper ion detection upper limit.

To confirm the SERS signal was launched by copper-induced aggregation, 2TSA, the isomer of 4-MBA, was selected as an alternative modifier decorating $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-AgNPs}$. Fig. 6 demonstrated the Raman spectrum under different SERS modifiers. The SERS peaks for $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-Ag-4-MBA}$ NPs were more obvious than for $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-Ag-2TSA}$ NPs. The carboxyl acid group in 4-MBA is positioned toward the outer region, resulting in an effective triggering of copper-induced aggregation. Meanwhile, the carboxyl acid group of 2TSA is at the *ortho* position, which indicated this activated site is positioned toward the inside. The steric hindrance of the chemical structure usually reduces the reaction speed, and the degree of influence of the *ortho* position would be greater than the *para* position.⁴³ This explanation was further proved through the colorimetric method using 4MBA@Ag and 2TSA@Ag, as shown in Fig. S1.† 4MBA@Ag successfully induced aggregation because of the color change from bright yellow to red, while 2TSA@Ag did not effectively trigger aggregation. In the UV spectrum, 4MBA@Ag showed a distinct red-shift with increasing concentration of copper ion, compared with 2TSA@Ag probes. Consequently, $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-Ag-2TSA}$ NPs have no response for copper ion detection through the Raman signal. It was demonstrated that the steric effect of modifiers could significantly affect copper ion detection.

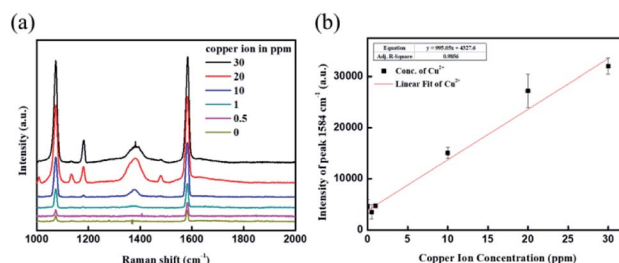


Fig. 5 Detection of different concentrations of copper ions using $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-AgNPs}$ probe. (a) Raman spectrum of 4-MBA under different concentrations of copper ions; (b) linear calibration curve of copper ion based on the intensity of the peak at 1584 cm^{-1} .



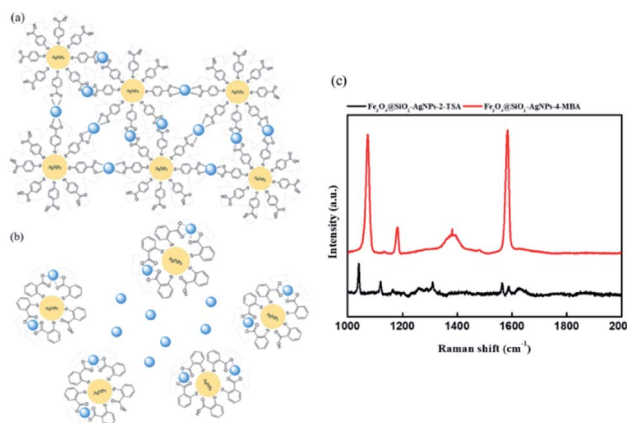


Fig. 6 The steric effect of modifier (4-MBA and 2-TSA) on $\text{Fe}_3\text{O}_4\text{-SiO}_2\text{-AgNP}$ probe for copper ion response. Scheme of (a) 4-MBA-induced aggregation and (b) 2-TSA-induced aggregation; (c) Raman spectrum of $\text{Fe}_3\text{O}_4\text{-SiO}_2\text{-AgNPs-4MBA}$ and $\text{Fe}_3\text{O}_4\text{-SiO}_2\text{-AgNPs-2TSA}$ after copper ion-induced aggregation (copper ion concentration: 30 ppm).

3.3 Interference of copper ion detection through $\text{Fe}_3\text{O}_4\text{-SiO}_2\text{-Ag-4MBA}$ NPs

The strategy of $\text{Fe}_3\text{O}_4\text{-SiO}_2\text{-Ag-4MBA}$ NPs for copper ion detection follows chelation of the carboxyl acid group on 4MBA. Therefore, other transition metals that exist in wastewater would potentially interfere with the detection. Fig. 7 presents the intensity of the SERS peak at 1584 cm^{-1} after introducing different types of metal ions. Copper ion exhibited a more sensitive response to $\text{Fe}_3\text{O}_4\text{-SiO}_2\text{-Ag-4MBA}$ NPs, and second was lead ion. Other metal ions introduced, like Fe^{2+} , Ni^{2+} , and Zn^{2+} , performed similar SERS response as the control groups, which are DI water without any metal ion. The results indicated that $\text{Fe}_3\text{O}_4\text{-SiO}_2\text{-Ag-4MBA}$ NPs can selectively detect copper and lead ions. Further, the response of $\text{Fe}_3\text{O}_4\text{-SiO}_2\text{-Ag-4MBA}$

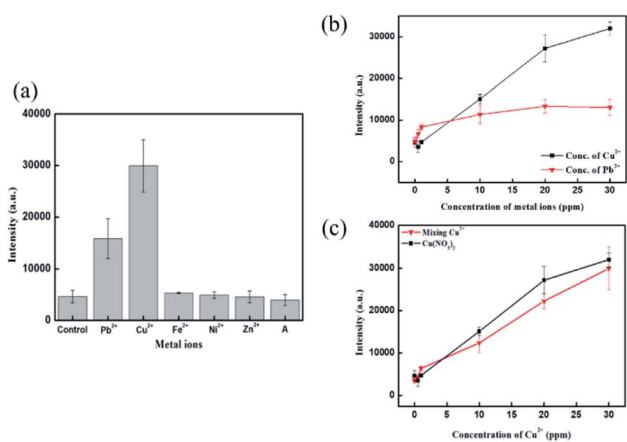


Fig. 7 Environmental effect of copper ion detection using $\text{Fe}_3\text{O}_4\text{-SiO}_2\text{-AgNPs}$ probe. (a) SERS response in different metal ions (copper ion concentration: 30 ppm); (b) SERS response of copper and lead ion in different concentrations; (c) anion effect in different concentrations of copper ions.

NPs toward copper ion and lead ion was investigated, and the concentration ranges of these two metal ions were from 0 to 30 ppm, as shown in Fig. 7b. The detection range for lead ion was narrower than for copper ion because lead ion-induced Raman signal achieved saturation soon after 1 ppm. This obvious difference was caused by chelating types. The chelation between the metal ion and the chelating agent could achieve equilibrium. Therefore, the stability of the chelating complexes determined the level of aggregation of magnetic nanoprobe and the stimulation of SERS signals. Copper ions and carboxylic acid prefer to form bidentate chelates,⁴⁴ which illustrates that copper ion requires two carboxyl acid groups to stabilize the chelating complex. Copper ions could process spontaneous aggregation of magnetic nanoprobe due to maintenance of the stability for copper-based chelation complexes. In contrast, lead ion belongs to monodentate chelation,⁴⁴ and lead ion only induced partial aggregation of magnetic nanoprobe. Therefore, the SERS peak intensity was reflected in a slightly increasing manner by added lead ions compared to the bare magnetic aggregation. Consequently, $\text{Fe}_3\text{O}_4\text{-SiO}_2\text{-Ag-4MBA}$ NPs have selectivity for copper ion, with the highest sensitivity.

Apart from metallic ions, the SERS signal was also influenced by anions. Fig. S2† presents copper ion detection under different anions using 4MBA@Ag. The results show different dose-response curves, indicating different sensitivities and linear detection ranges for copper ion with different salts. Copper ion detection in the presence of chloride had higher sensitivity than with sulfate. In addition, the linear range of copper ion detection in the presence of sulfate was wider than with chloride. The possible reason is the Hofmeister series, which influences the hydration ability of copper ion compounds.¹⁸ In addition, sulfate (SO_4^{2-}) exhibit strong hydration ability and greater hydrogen bonding toward water molecules, resulting in reduced solubility of copper sulfate.^{45,46} It was demonstrated that free copper ion determines the sensitivity and linear detection range using 4MBA@Ag nanoprobe. Fig. 7c shows the anion effect for copper ion using $\text{Fe}_3\text{O}_4\text{-SiO}_2\text{-Ag-4MBA}$ NPs. The Raman results demonstrated that the trend of sensitivity and linear detection range were similar

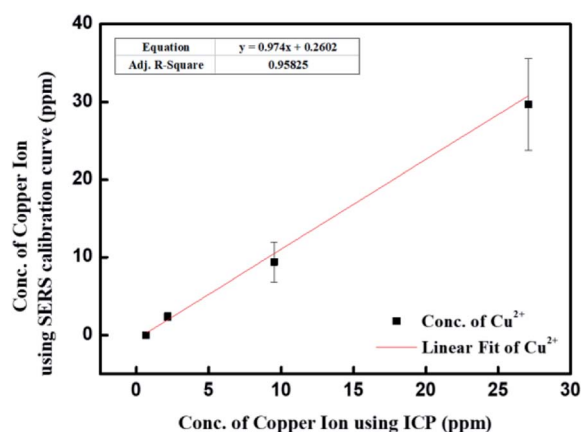


Fig. 8 Comparison of copper ion detection through ICP and SERS analysis.



Table 1 Comparison of colorimetric sensors for the detection of Cu²⁺

Methods	Analytical range (μM)	Limit of detection (μM)	Reaction time	Ref.
Colorimetric	0.1–100	25×10^{-3}	30 min	47
Colorimetric	1–1000	1	30 min	48
Fluorescent	0.25–10	29.5×10^{-3}	3 s	13
Fluorescent	0.01–1.1	6×10^{-3}	1 min	49
Electrochemical	1–10	N/A	5 min	11
Electrochemical	0.001–100	0.3×10^{-3}	1 h	12
SERS	3.7–148.7	3.13	10 s	This study

either in copper nitrate or the mixed copper salts. It was illustrated that the application of magnetic field would effectively aggregate Fe₃O₄@SiO₂-Ag-4MBA NPs, and then magnetic nanoprobe clusters would be additionally become dense through copper ion introduction. Consequently, the Hofmeister series would be minimized using Fe₃O₄@SiO₂-Ag-4MBA NPs in copper ion detection.

To validate the copper ion concentration using SERS detection, ICP-OES is a reliable tool for the quantification of metal ion. The prepared copper ion concentrations were 0.5, 2, 10, and 30 ppm, respectively. Fig. 8 shows the plot of copper ion concentration through ICP analysis and SERS detection. The slope of linear fitting was close to 1, indicating the precision of copper ion detection through SERS detection in this study. When comparing the results of this study with the other favourable methods shown in Table 1, it can be suggested that the Fe₃O₄@SiO₂-Ag-4MBA-based detection assay approaches the rapid detection of copper ion under a similar analytical range.

4. Conclusion

This study aimed to develop a platform for rapid detection of copper ions in wastewater through Raman spectra without any further pretreatment. Sensitive detection through SERS required generating the detection area, called hot spot, in a wastewater sample. Fe₃O₄@SiO₂-Ag-4MBA NPs can activate the hot spot through magnetic aggregation and copper ion-induced aggregation. Magnetic aggregation was processed by superparamagnetic material-Fe₃O₄, and copper ion-induced aggregation was launched by carboxylic acid chelation. 4-MBA not only provides carboxylic acid chelation with copper ion but also emits the Raman signal after aggregation. The Raman signal increased as a function of copper ion increase. The linearity of detection range was from 0.5 to 20 ppm within a high coordination, and the limit of detection was 0.421 ppm. In addition, it is noted that the error bar at higher concentrations of copper ion is larger than at the lower concentration due to the non-homogeneous nature of the aggregation. On the other hand, the uniform distribution of AgNPs does influence reproducibility. The limit of detection and reproducibility can be improved by other chelators modified on silver nanoparticles. 4-MBA only contributes carboxylic acid for chelating copper ions. Modifiers containing more amines and carboxylic

acid in their molecular structure, like polyethyleneimine (PEI) and peptide-containing cysteine, would effectively contribute stronger interaction toward copper ions, leading to higher sensitivity. Magnetic aggregation belongs to active aggregation, which can effectively minimize the anion effect (Hofmeister series) in wastewater. In addition, the carboxylic acid on magnetic nanoprobe determined the selectivity for metal ions through chelation affinity. Copper and lead ion gave significant SERS responses compared with other transition metal ions. Based on bidentate chelation, Fe₃O₄@SiO₂-Ag-4MBA NPs were more sensitive for copper ion in a wide range. Copper ion detection using the SERS method was as precise as ICP-OES. All of the measurements can be done in a couple of seconds, achieving rapid detection. In the near future, these magnetic probes can be integrated with a microfluidic device and a portable Raman spectrometer as a portable device for on-site detection of wastewater.

Author contributions

Po-Jung Huang conceived, planned and supervised the project. Min-Ying Hsieh performed the experiments and interpreted the data. Po-Jung Huang and Min-Ying Hsieh wrote the manuscript.

Conflicts of interest

There are no conflicts to declare.

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