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An aniline trimer-based multifunctional sensor for colorimetric Fe^{3+}, Cu^{2+} and Ag^{+} detection, and its complex for fluorescent sensing of L-tryptophan

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ABSTRACT

The detection of metal ions and amino acids by the aniline oligomer-based receptor has not been reported yet, to the best of our knowledge. In this study, an efficient multifunctional cation-amino acid sensor (CAS) with aniline moiety and chiral thiourea binding site was synthesized by the reaction of aniline trimer and (*S*)-(+)-1-phenyl ethyl isothiocyanate. CAS can sense Fe^{3+}, Cu^{2+}, Ag^{+} ions, and L-tryptophan. These results can be recognized by the naked eye. The appropriate pH range for the quantitative analysis of Fe^{3+}, Cu^{2+}, and Ag^{+} by CAS in DMSO/water (30 vol% water) was evaluated. The interaction between CCS and metal ions was analyzed by ^{1}H NMR titration. The detection limits of CAS for the Cu^{2+}, Ag^{+}, and Fe^{3+} were 0.214, 0.099, and 0.147 μM, respectively. Moreover, the CAS—Cu^{2+} complex can act as a turn-on fluorescence sensor for L-tryptophan. On the contrary, there is no response upon the addition of other amino acids, such as L-histidine, L-proline, *L*-phenylalanine, L-threonine, L-methionine, L-tyrosine, and L-cystine to CAS—Cu^{2+} complex.

1. Introduction

Colorimetric and fluorescent receptors for ion and amino acid detection have become a hot research topic because of its easy operation, low-cost, high sensitivity, good selectivity, and quick response. [1–5] Aniline based polymers and oligomers are very useful in the applications of sensors, photocatalysts, and anti-corrosive coatings. [6–11] Besides, thiourea derivatives were found to be very useful chemosensors for the selective sensing of cations, anions, and amino acids. [12–15] Kyne et al. [13] found that the acyclic thiourea derivatives containing chiral moieties exhibited good enantioselectivity towards amino acid derivatives. Yang et al. [15] found that a dumbbell-shaped probe, biscalix[4]-1,3-aza-crown 3, containing rigid thiourea-bridge exhibited high selectivity to Ag^{+}. The Ag^{+}/Hg^{2+} and Ag^{+}/Na^{+} extraction percentage reached 16.9 and 43.2, respectively. Therefore, aniline based derivatives with thiourea linkages have the potential for chemical sensor applications.

Some researchers have been devoted to the development of new chemical sensors that can achieve convenient, quick, and low-cost sensing of different amino acids and metal ions through sequential color change. [16–21] Kim et al. [16] reported an indazole-based chemosensor 1 for the sequential colorimetric detection Cu^{2+} and glutathione (GSH). The sensor can detect Cu^{2+} by color change. Then, the Cu^{2+}-sensor1 complex can be used for the colorimetric naked-eye recognition of GSH. Yoon et al. [17] reported a pyrene based probe 1, which showed distinct fluorescence quenching after the addition of Cu^{2+}. Then, the addition of three major biothiols (cysteine, glutathione, and homocysteine) to 1-Cu^{2+} leads to selective fluorescent turn-on response.

L-tryptophan is a crucial part of protein synthesis. It serves as the precursor for various biomolecule. The tryptophan content shows a strong influence on some neurobehavioral effects, HIV infections, cancers, Alzheimer's, and Parkinson's disease. [22–24] Thus, the development of effective recognition methods for the sensing of tryptophan has been of intense interest. Detection of trace amounts of amino acids is quite important for the disease diagnosis, food analysis, and biomedical study. Such kind of sensing is usually performed using liquid chromatography [25–27], capillary electrophoresis, and capillary electrochromatography [28–30]. However, these methods

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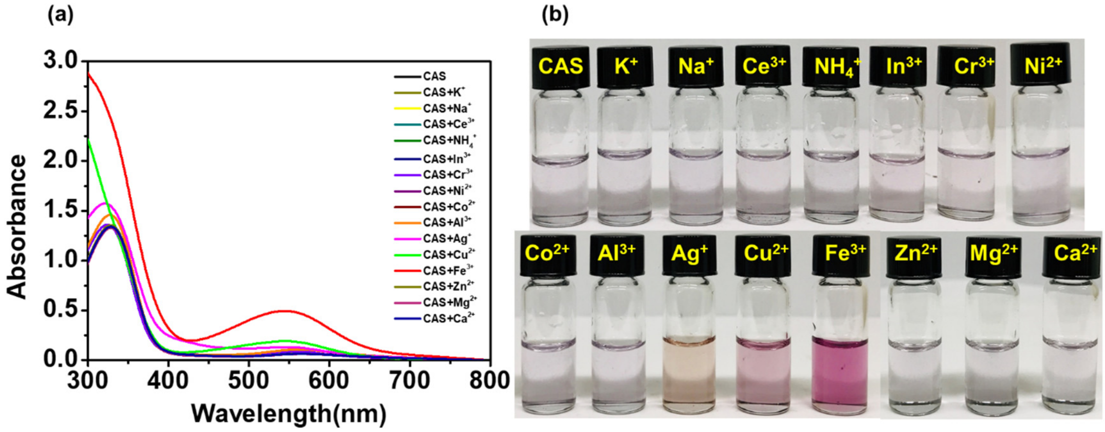


Fig. 1. (a) UV–Vis spectroscopic and (b) images of CAS (60 μM) solutions after the incorporation of different cations (10 eq.) as their nitrate in DMSO/H_2O (7:3 v/v) solution.

require relatively expensive instrumentation. Besides, they are time-consuming, labor-intensive, and are not adaptable to field determination. Fluorescence sensing of amino acids and biothiols by suitable probes has attracted much attention owing to their operational simplicity, fast response, low cost, and high sensitivity. [31–33] Some researchers have devoted to the fluorescence sensing of tryptophan by various sensors, such as 4,4-bipyridine-functionalized silver nanoparticles [34], functionalized Cu nanoparticles [35], and naphthalimide-benzothiazole hybrid-based chemosensor [36].

The development of sensors that are capable of sensitive and selective sensing of transition metal ions is critical for biological and environmental applications. To avoid an external infection during the common medical processes, Ag^+ complexes and nanomaterials are used as an antiseptic agent. [37,38] However, repetitive silver exposure may cause problems such as growth retardation, cardiac enlargement, and urine silver excretion. Cu^{2+} can act as a catalytic cofactor for some metalloenzymes, including superoxide dismutase and tyrosinase. Fe^{3+} is involved in some biological processes, including the oxygen-carrying capacity of heme, enzymatic reaction, and synthesis of DNA/RNA [39–41]. Overload of Cu^{2+} can lead to neurodegenerative diseases [42]. Excess intake of Fe^{3+} ions is deadly for promoting the oxidation of lipids and proteins [43], whereas the deficiency of Fe^{3+} results in anemia, diabetes, liver damage, and cancer [44]. Most of the chemosensors reported in the literature were designed to identify single metal ion. Recently, some new probes have been reported for the detection of two ions, such as polydentate ligand chromophore for Ag^+ and Fe^{3+} [45], cellulose-based probes for colorimetric sensing of Cu^{2+} and Ag^+ [46], pyrene-based chemosensor for Cu^{2+} and Fe^{3+} [47], and naphthalimide-based fluorescent probe for Hg^{2+} and Cu^{2+} [48]. Furthermore, the selective detection of three or four ions were also possible, such as the Schiff base fluorescent-colorimetric chemosensor for detecting Fe^{3+}, Zn^{2+}, Cu^{2+} [49], and Cr^{3+}, Cu^{2+}, Fe^{3+}, Al^{3+} ions [50].

Up to the present, there are few publications involved in the sequential detection of cations and amino acids. To achieve fast, efficient, and inexpensive sensing, it is quite important to design and synthesize new receptors that can detect multiple responses, such as amino acids, cations, and pH. Despite the extensive applications using aniline-based oligomers or polymers, the study of aniline-based oligomers for the recognition of cations and amino acids has not been reported yet, to the best of our knowledge. In this study, we develop an aniline trimer-based receptor CAS which can detect trace amounts of Fe^{3+}, Ag^+, and Cu^{2+} in DMSO/water samples and perform the selective fluorescent sensing of L-tryptophan.

2. Experimental

2.1. Materials

The metal ions, which are as their nitrate salts like Na^+, K^+, Ag^+, Cu^{2+}, Zn^{2+}, Mg^{2+}, Ce^{3+} were purchased from SHOWA chemicals (purity 99%), Ca^{2+}, Al^{3+}, Fe^{3+} (99.99%) were purchased from Aldrich and Cr^{3+}, Co^{2+}, Ni^{2+}, In^{3+}, NH^{4+} salts (98%) were brought from alfa-aesar. (*S*)-(+)-1-Phenylethyl isothiocyanate purity of (97%) was received from Alfa-Aesar.

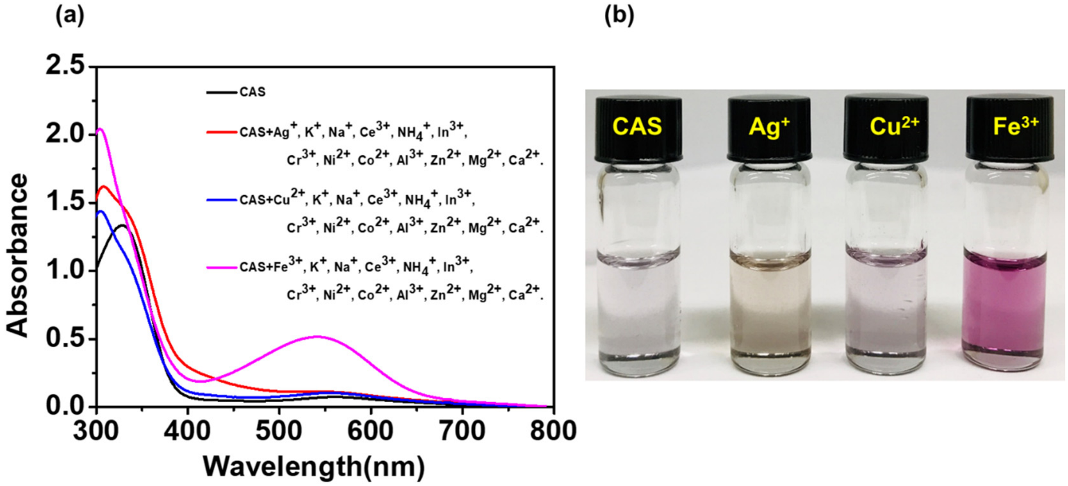


Fig. 2. UV–Vis spectroscopic (a) and images (b) of the CAS solution (60 μM) in DMSO/H2O (7:3 v/v) with competitive cations (10 eq. K^+, Na^+, Ce^{3+}, NH_4^+, In^{3+}, Cr^{3+}, Ni^{2+}, Co^{2+}, Al^{3+}, Zn^{2+}, Mg^{2+}, and Ca^{2+}) after the addition of Ag^+, Cu^{2+}, Fe^{3+} cations (10 eq.).

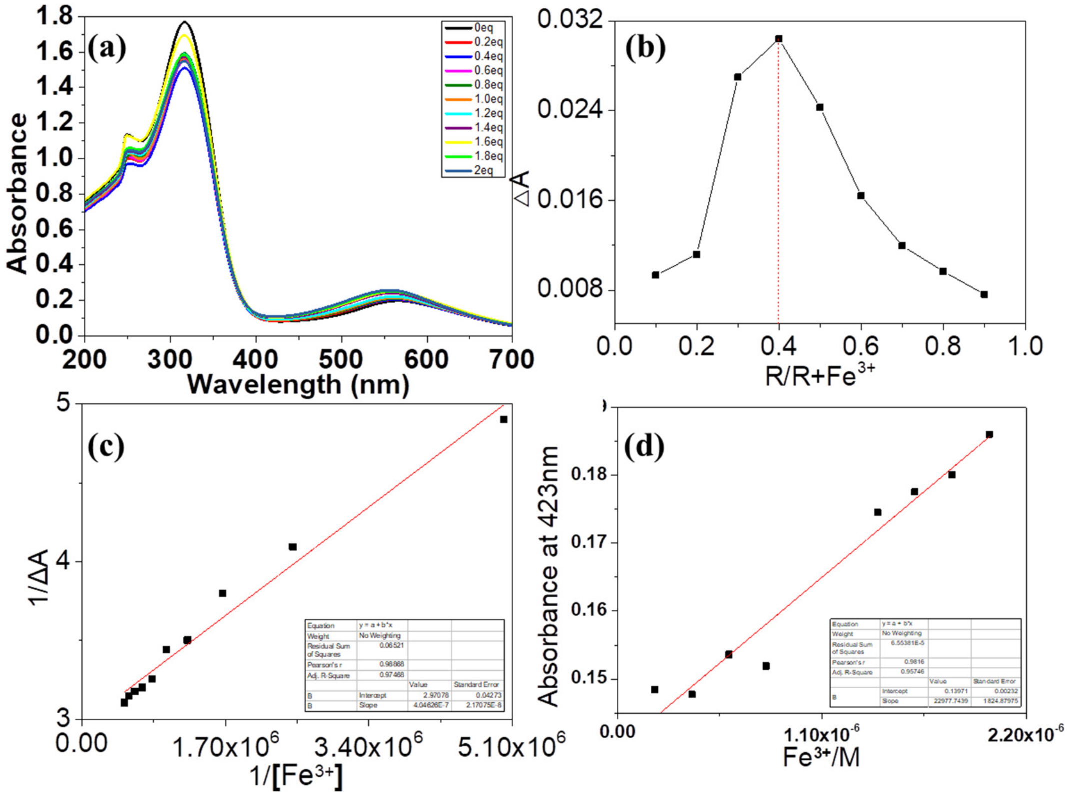


Fig. 3. (a) UV–vis spectra of CAS (60 μM) with Fe^{3+} (0–2 equivalents) (b) Job's plot analysis (c) Benesi–Hildebrand plot (d) detection limit of CAS for Fe^{3+} ion. All the tests were performed in DMSO/H_2O (7:3 v/v) solution.

2.2. Synthesis of CAS

CAS was synthesized in two steps.

Step (1). The synthesis of aniline trimer (AT) was performed according to the previously reported literature [51]. 4,4 -Diaminodiphenylamine sulfate (10.0 g, 0.336 mol) and aniline (3.12 g, 0.336 mol) were dissolved in an aqueous HCl solution (1.0 M, 400 mL) containing 38 g of NaCl. A solution of ammonium persulfate (9.00 g, 0.395 mol) in aqueous HCl (1.0 M, 100 mL) was added via a dropping funnel into the above solution at the rate of approximately 60 drops/min at 0–5 °C. The reaction mixture was stirred for 60 min at 0–5 °C. The resulting precipitate was filtered and washed with aqueous HCl solution (1.0 M, 200 mL) that was precooled to 0 °C. The solid product was washed with a 10% NH_4OH solution (100 mL) and a large amount of distilled water. The AT product (dark red solid) was obtained after being dried in a vacuum oven at 50 °C for 18 h.

Step (2). The synthesis was carried out according to the previously reported method [52]. 0.2 mol of (*S*)-(+)-1-phenyl ethyl isothiocyanate was added to a solution of 0.1 mol AT in anhydrous THF at mole ratios of 2:1. The reaction was performed for 2 h at room temperature under a nitrogen atmosphere (Fig. S1). Once the reaction was completed, the solvent was removed by using a rotary evaporator under reduced pressure. Then, the product was subjected to column chromatography using 10–20% ethyl acetate in hexane as eluents. The final product (purple solid) can be obtained.

^{1}H NMR (400 MHz, DMSO-d_6): $\delta = 9.22$ (s, 2H), 7.8–7.9(s, 2H), 7.44 (d, $J = 8.0$ Hz, 4H), 7.39–7.35 (m, 4H), 7.24 (d, $J = 4.2$ Hz, 4H), 7.15 (d, $J = 8.0$ Hz, 2H), 7.00 (t, 2H), 6.80–6.90 (dd, $J = 8.02$ Hz, 4H) 5.55 (s, 2H), 5.25 (d, $J = 7.6$ Hz, 2H), 1.61 (d, $J = 4.0$ Hz, 6H), (Fig. S2). ^{13}C NMR (100 MHz, D-Methanol): $\delta = 180.35$, 144.10, 143.66, 143.37, 128.30, 128.12, 126.73, 126.58, 125.89, 125.70, 125.57, 123.75, 120.24, 115.58, 53.60, 24.02 ppm (Fig. S3). ESI-MS (EI) *m*/*z*: [M^+] calcd for $C_{36}H_{34}N_6S_2$, 614.23; found, [M^{+1}] = 615.40 and [M^{+2}] = 616.50 (Fig. S4). Elemental analysis: Anal. Calc. for $C_{36}H_{34}N_6S_2$: C, 70.33; H, 5.57; N, 13.67%. Found: C, 70.72; H, 5.37; N, 12.70%.

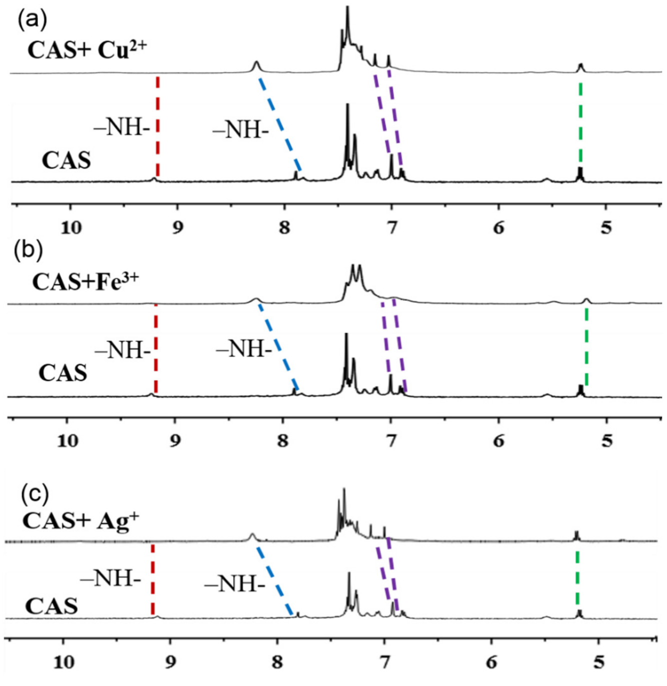


Fig. 4. The ^{1}H NMR spectra of CAS (60 μM) in DMSO-d_6/D_2O (7:3 v/v) upon the addition of 2 equivalents of (a) Cu $(NO_3)_2$ (b) Fe $(NO_3)_3$ (c) $AgNO_3$.

2.3. Characterization

UV–Visible absorption spectral study was carried out by Jasco V-700 spectrophotometer. Hitachi-7000 was used for Fluorescence spectral study. Santax micro digital pH meter is used for the pH tests. ^{1}H NMR spectra were measured by Agilent Technologies DD2 spectrometer (600 MHz) with chemical shifts reported in *d6*-DMSO/D_2O (v/v = 7/3).

2.4. ^{1}H NMR titration

NMR samples of the CAS receptor (60 µM) were dissolved in DMSO-d_6/D_2O (7:3 v/v). Two equivalents of $Fe(NO_3)_3$, $AgNO_3$, and $Cu(NO_3)_2$ were added in three CAS samples respectively. The solutions were blended for 5 min, and their ^{1}H NMR spectra were investigated.

3. Results and discussion

3.1. Spectroscopic and "naked eye" sensing of cations

Fig. 1a presents the changes in the images and the corresponding UV–vis spectra of CAS (60 µM) solutions after the incorporation of different cations (10 eq.) as their nitrate in DMSO/H_2O (7:3 v/v) solution. The peak maximum of CAS solution locates at 570 nm, which results from the π-π* transition of the benzenoid ring. In comparison with the peak of the pristine CAS solution, the maximum absorption peak showed a blue shift to a wavelength of 528, 550, and 548 nm after the incorporation of Ag^+, Cu^{2+}, and Fe^{3+} cations, respectively. The increase in the peak intensity and a blue shift was observed for these three samples. However, the addition of other tested cations (K^+, Na^+, Ce^{3+},

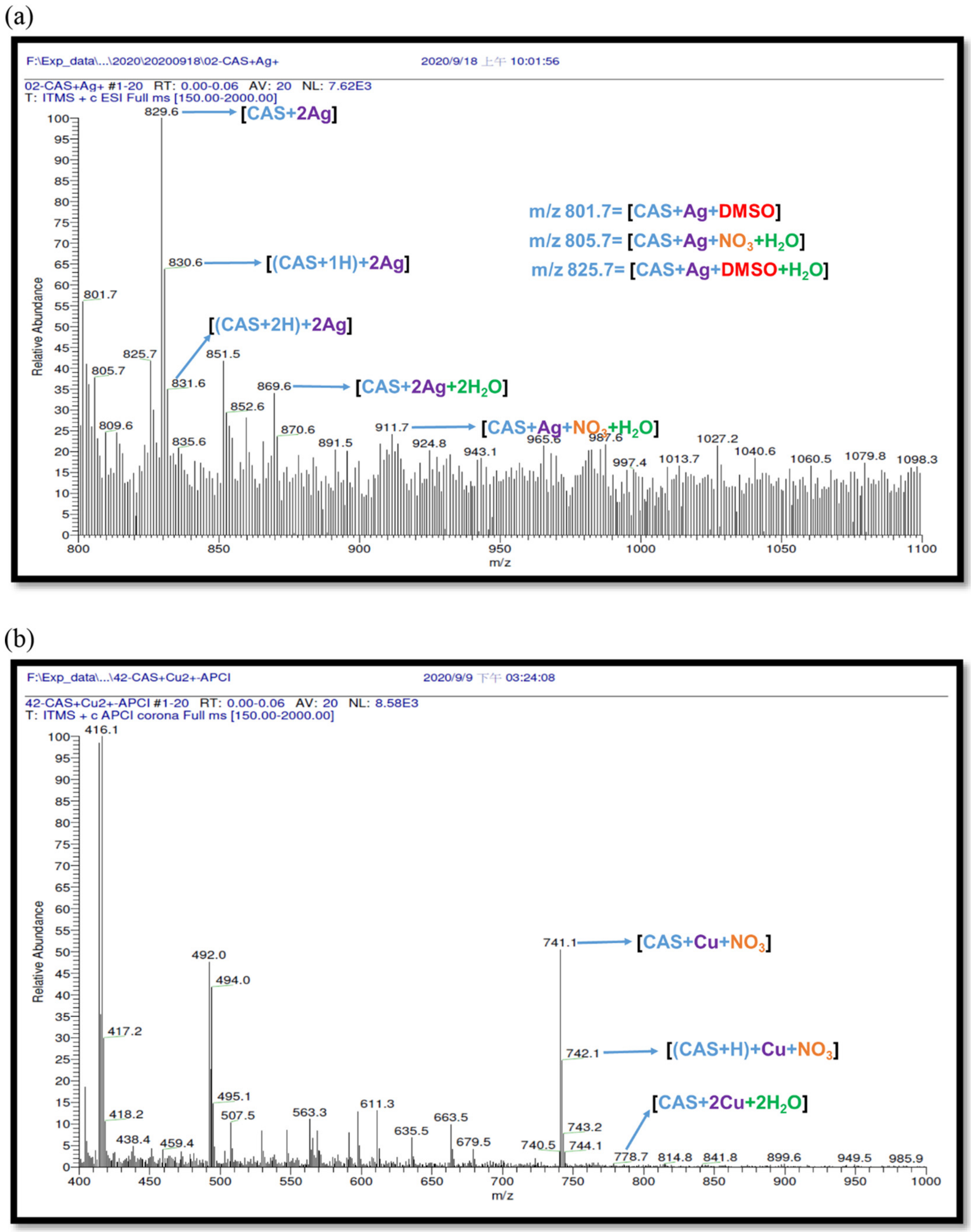


Fig. 5. ESI-MS results for (a) CAS—Ag^+ complex (b) CAS-Cu^{2+} complex (c) CAS-Fe^{3+} complex.

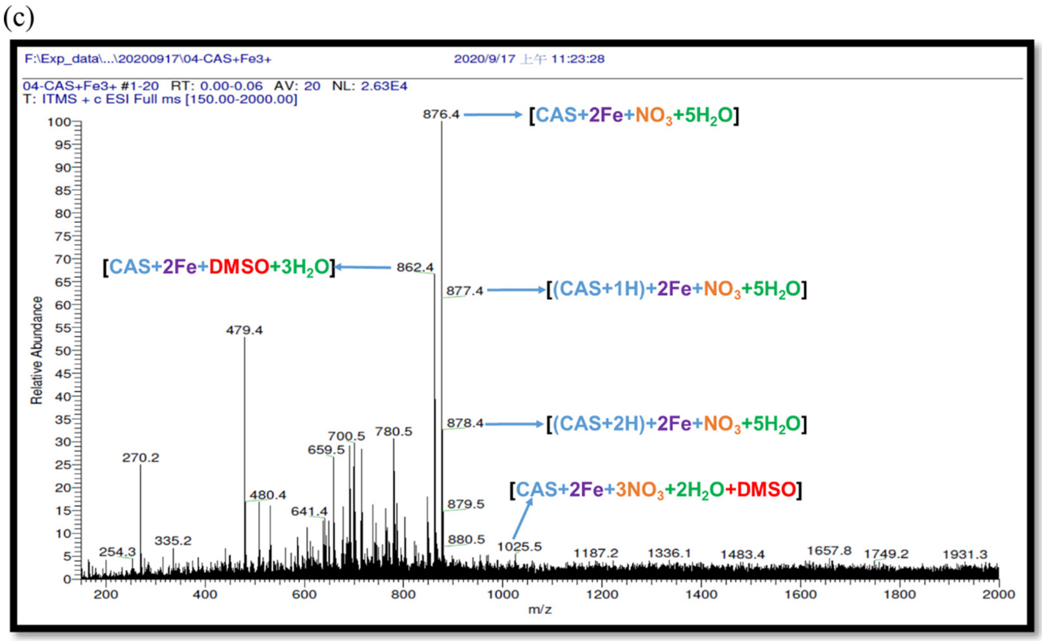


Fig. 5 (*continued*).

NH_4^+, In^{3+}, Cr^{3+}, Ni^{2+}, Co^{2+}, Al^{3+}, Zn^{2+}, Mg^{2+}, and Ca^{2+}) in the CAS solution showed no change on the characteristic absorption peak of CAS solution (Fig. 1a). The color is almost unchanged. The color changes of CAS solution upon the addition of Fe^{3+}, Ag^+, and Cu^{2+} ions can be observed as shown in Fig. 1(b). The solution of CAS ($DMSO/H_2O = 7:3$ v/v) exhibited a light purple color. The solution turned immediately into the brown, lighter reddish-purple, and fuchsia color after the incorporation of Ag^+, Cu^{2+}, and Fe^{3+} ions, respectively. However, other tested cations (K^+, Na^+, Ce^{3+}, NH_4^+, In^{3+}, Cr^{3+}, Ni^{2+}, Co^{2+}, Al^{3+}, Zn^{2+}, Mg^{2+}, and Ca^{2+}) did not change the light purple color of the CAS solution.

3.2. Selectivity of CAS to Cu^{2+}, Fe^{3+}, and Ag^+ ions

The major challenges for the recognition of Ag^+, $Cu^{2+,}$ and Fe^{3+} are the possible interferences caused by competitive cations. To investigate the influences of interference metal ions on Cu^{2+}-CAS complexation, the competition experiments were performed in the $DMSO/H_2O$ (7:3 v/v) solution with Cu^{2+} (10 equiv) in the presence of other interfering cations, including K^+, Na^+, Ce^{3+}, NH_4^+, In^{3+}, Cr^{3+}, Ni^{2+}, Co^{2+}, Al^{3+}, Zn^{2+}, Mg^{2+}, and Ca^{2+} (each cation concentration is 10 eq.). As shown in Fig. 2a, Upon the incorporation of Ag^+, Cu^{2+}, and Fe^{3+} to the CAS solution containing different cations, the absorption peak of CAS shifted (Hypsochromic shift) from 570 nm to the shorter wavelength of 528, 570, and 550 nm. The colors of the solutions change from light purple to brown, purple, and fuchsia (Fig. 2b). The addition of Ag^+ and Fe^{3+} ions lead to changes in the UV–vis spectra and color of the CAS solution containing different cations. The response of CAS to Fe^{3+} is almost identical to that obtained without other ions (Fig. 1b). The results revealed that these competitive ions did not interfere with the sensing performance of CAS for Ag^+ and Fe^{3+}. However, the response of CAS to Cu^{2+} deteriorates after the incorporation of other competitive cations.

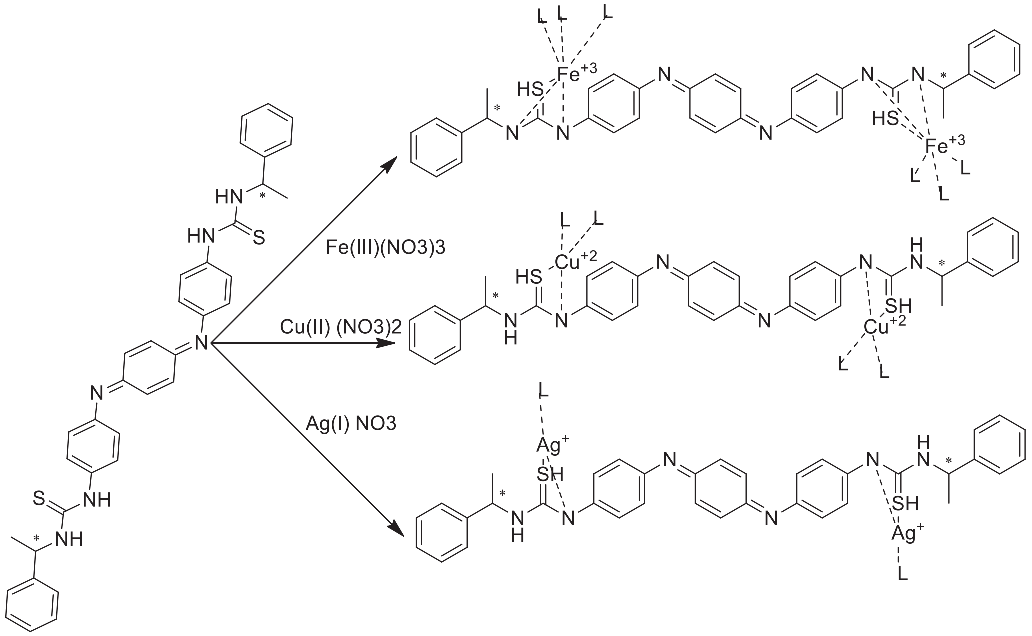
3.3. Binding stoichiometry

Fig. 3a presents the UV–vis spectra of CAS solution (60 μM) with the addition of Cu^{2+} ions (0–2 equivalents). There is an absorption band at 570 nm for CAS receptor. It shifted gradually to a lower wavelength during the incorporation of Fe^{3+} (0 to 2 eq.), revealing the interaction between CAS and Fe^{3+} ion. Fig. 3b demonstrates the Job's plot analysis for the binding stoichiometry of Fe^{3+} to CAS. The absorption reaches a maximum when the molar fraction of CAS was 0.4, indicating that the binding between CAS and Fe^{3+} followed a 1:2 stoichiometry. The binding constant between CAS and Fe^{3+} was $7.34 \times 10^6\ M^{-1}$ ($K_{CAS\text{- }Fe3+}$) based on the Benesi–Hildebrand method (Fig. 3c). A calibration curve was established for the quantitative analysis of Fe^{3+} by the CAS receptor (Fig. 3d)., the detection limit of CAS for the sensing of metal ions was obtained from the plot of the absorbance changes vs. the metal ions concentration. Based on the 3σ/slope, the detection limit of CAS for Fe^{3+} sensing was 0.147 μM.

The absorption reached a maximum when the molar fraction of CAS was 0.4, indicating that the binding of CAS—Ag^+ and CAS—Cu^{2+} followed a 1:2 stoichiometry. The binding constants of CAS—Ag^+ complex and CAS—Cu^{2+} complex were $4.93 \times 10^6\ M^{-1}$ ($K_{CAS\text{-}Ag+}$) and $5.93{\times}10^6\ M^{-1}$, ($K_{CAS\text{-}Cu2+}$), respectively (Fig. S3 and S4). The binding affinities of CAS-cations (in 50% aq. DMSO solution) were $Fe^{3+} > Cu^{2+}$- $> Ag^+$. The detection limit of Ag^+ by CAS is 0.099 μM (Fig. S5). The detection limit of Cu^{2+} by CAS is 0.214 μM (Fig. S6), which is much lower than the guideline value (31.5 mM) in drinking water announced by the World Health Organization (WHO). [53]

3.4. ^1H NMR experiments

^1H NMR titrations were monitored to investigate the interactions between the CAS receptor and metal ions. Fig. 4 presents the changes in the ^1H NMR spectra of CAS (60 μM) in DMSO-d_6/D_2O (7:3 v/v) upon the addition of 2 equivalents of (a) Cu $(NO_3)_2$ (b) Fe $(NO_3)_3$ (c) $AgNO_3$. Because of the paramagnetic property of Cu^{2+} ion, Cu^{2+} can affect the NMR resonance frequency of protons near the thiourea binding site. After the addition of 2 equivalents of copper (II) nitrate ($Cu(NO_3)_2$) to CAS, the singlet -NH- peak of the intramolecular hydrogen bond at 9.2 ppm disappeared completely. Another –NH- peak at 7.8 ppm shifted to higher δ values of 8.4 ppm. In addition to the downfield shift, we observed a change in the peak with broadening. All these results revealed the coordination of CAS with Cu^{2+} ion. Besides, the peaks between 7.4 and 6.8 moved towards downfield, suggesting that the Cu^{2+} has a binding ability towards CAS. Similarly, after the addition of 2 equivalents of iron (III) nitrate ($Fe(NO_3)_3$) to CAS, the singlet –NH- peak at 9.2 ppm disappeared, and another –NH- peak at 7.8 ppm shifted (downfield) to 8.2 ppm. The peaks ranging between 7.4 and 6.8 shifted



Scheme 1. Proposed binding possibilities between CAS and metal ions.

towards downfield with decreased intensity, suggesting the coordination of CAS with Fe^{3+} ion. After adding 2 equivalents of silver nitrate ($AgNO_3$) to CAS, the singlet –NH- peak at 9.2 ppm disappeared. Another –NH- peak at 7.8 ppm shifted to higher δ values 8.4 ppm (downfield). Besides, the peaks between 7.4 and 6.8 moved towards downfield, revealing that the Ag^+ has a strong binding ability towards CAS. Protons on the benzene ring display downfield shifts. Such a shift is due to the decrease in electron density of the benzene ring, indicating that part of the Fe^{3+} or Ag^+ or Cu^{2+} ions coordinate to the thiourea groups of CCS.

3.5. ESI-MS and proposed binding mechanism

The binding mechanism and stoichiometric ratios were confirmed by ESI-MS spectra. Fig. 5 presents the ESI-MS results for (a) CAS—Ag^+ complex (b) CAS-Cu $^{2+}$ complex (c) CAS-Fe $^{3+}$ complex. Upon the addition of $Ag(NO_3)$, Cu $(NO_3)_2$, and $Fe(NO_3)_3$ to CAS, the following peaks were observed. The corresponding peaks in Fig. 5a at m/z = 801.7, 829.6, 830.6, and 869.6 represent (CAS + Ag^++ C_2H_6SO (DMSO)), (CAS + $2Ag^+$), (CAS—H^+ + $2Ag^+$), and (CAS + $2Ag^+$ + $2H_2O$). It indicates the binding of Ag^+ with CAS. The peaks at m/z = 741.1, 742.1, and 778.7 correspond to (CAS + Cu^{2+} + NO_3), ((CAS + H^+) + Cu^{2+} + NO_3), and (CAS + $2Cu^{2+}$ + $2H_2O$), indicating the binding of Cu^{2+} with CAS (Fig. 5b). The peaks at m/z = 862.4, 876.4, and 877.4 corresponding to (CAS + $2Fe^{3+}$+ C_2H_6SO (DMSO) + $3H_2O$), (CAS + $2Fe^{3+}$+ NO_3 + $5H_2O$), and (CAS—H^+ + $2Fe^{3+}$+ NO_3 + $5H_2O$) were observed for CAS—Fe^{3+} complex (Fig. 5c). These ESI mass spectra provide the evidences for the formation of a CAS—Ag^+ complex and CAS—Cu^{2+} complex in (1:1) and (1:2) binding ratios. For CAS—Fe^{3+} complex, a binding stoichiometric ratio of 1:2 was observed.

Possible bindings between CAS and metal ions were proposed in Scheme 1.

3.6. pH effect

Fig. 6 presents the color of CAS solution at different pH values (pH = 3–11, DMSO/H_2O = 7:3 v/v). The pH of the testing solution was tuned by adding an appropriate amount of NaOH (0.1 M) and HCl (0.1 M). These CAS solutions all exhibit the same light purple color. The pH dependence of Cu^{2+}-CAS, Fe^{3+}-CAS, Ag^+-CAS complex was monitored in the pH range of 3–11. An appropriate pH environment is important for colorimetric sensors to detect metal cations [54]. Since the samples may be generated from various industries, the pH of these samples may be different. Therefore, scientists have tried to prepare a novel chemical sensor that can recognize specific cations at different pH environments. The ion sensing properties of the CAS probe at various pH was observed to explore the appropriate pH range for the detection of Cu^{2+}, Fe^{3+}, and Ag^+ cations. The results shown in Fig. 1 were measured at pH = 9. The optical color change and corresponding UV–vis spectral responses of CAS solution to cations were performed at pH 3, 5, 7, and 11 (Fig. 7). The responses of CAS to three metal cations in these solutions with various pH are different. As shown in Fig. 6a-6c, the solution

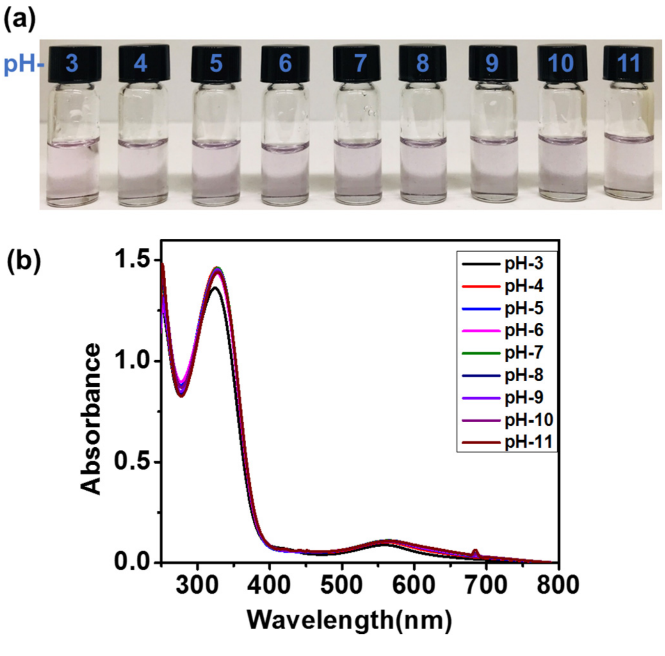


Fig. 6. The (a) images and (b) UV–Vis spectra of CAS solution at different pH values. (pH = 3–11, DMSO/H_2O = 7:3 v/v).

turned immediately into a darker purple color after adding Fe^{3+} at pH 5, 7, and 11. The color of the CAS solution became reddish-purple upon the addition of Cu^{2+} at pH 7 and 11. The solution turned into brown color after the addition of Ag^{+} at pH 9 (Fig. 1) and 11. There is no color change upon the incorporation of Cu^{2+}, Fe^{3+}, and Ag^{+} ions to the CAS solution at pH 3 (Fig. 6d). CAS solution shows an absorption peak at 570 nm. In comparison with the absorption peak of the pristine CAS solution, the maximum absorption peak showed a blue shift to 550 nm after the addition of Fe^{3+} ion to the CAS solution (pH 5, 7, 9, 11, Fig. 7 and Fig. 1). The absorption peak maximum shifted to 499 nm after adding Cu^{2+} at pH 7, 9, and 11. Upon the addition of Ag^{+} to the CAS solution at pH 9 and 11, the maximum absorption peak appeared at 537 nm. The appropriate pH ranges for the detection of Fe^{3+}, Cu^{2+}, and Ag^{+} cations by CAS are pH 5–11, 7–11, and 9–11, respectively.

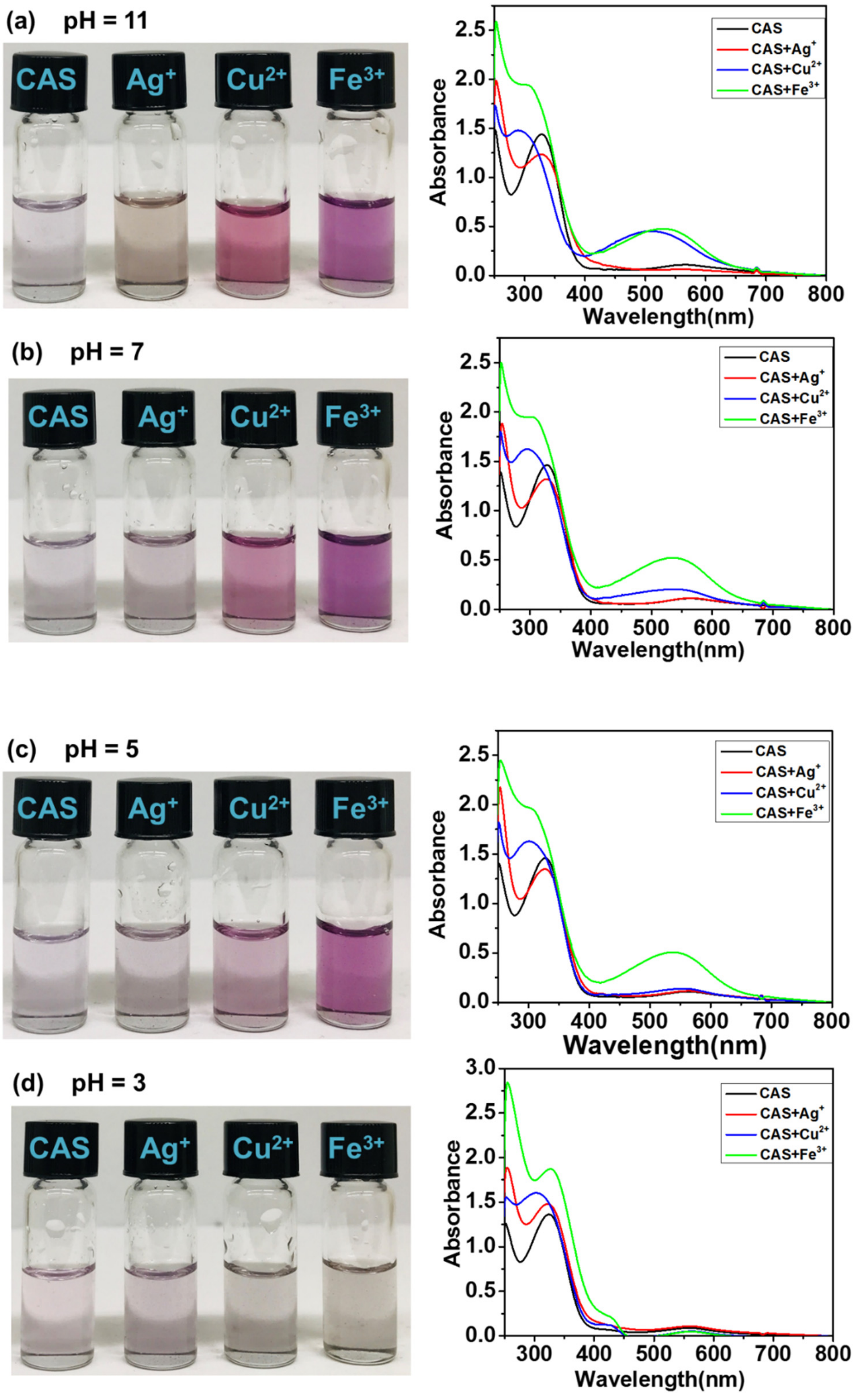


Fig. 7. Images and UV–Vis spectra of CAS with and without cations in DMSO/H_2O solution (7:3 v/v) at different pH values. (a) pH = 11 (b) pH = 7 (c) pH = 5 (d) pH = 3.

3.7. Sensing of L-tryptophan by CAS—Cu^{2+} based complex

To expand the potential application, the CAS—Cu^{2+} complex based sensor was explored to detect amino acids. Fig. 8 shows the PL spectra and the fluorescent images of CAS (60 μM)-Cu^{2+}(10 eq.) complex solutions with the addition of different amino acids (15 eq.) in DMSO/H_2O (9:1 v/v) solution. The CAS solution in the presence of Cu^{2+} cation shows no peak at the PL spectrum (Fig. 8a), which can be attributed to the formation of CAS—Cu^{2+} complexes. By the addition of L- Tryptophan to the CAS—Cu^{2+} complex, the fluorescence was 'switched on'. It may result from the formation of ternary complexes, by displacement of L-tryptophan from the weakest binding site of copper (II) [55]. There is a fluorescent peak with a peak maximum at 366 nm and a shoulder extends to 485 nm. On the contrary, the addition of other tested amino acids (including L-histidine, L-proline, *L*-phenylalanine, L-threonine, L-methionine, L-tyrosine, L-cystine) showed no effect on the PL response of CAS—Cu^{2+} solution (Fig. 8a). As shown in Fig. 8b, the turn-on fluorescence of CAS—Cu^{2+} solution caused by the addition of L- tryptophan can be detected by naked eyes. The solution of the CAS—Cu^{2+} complex in DMSO/H_2O exhibited no fluorescence. However, the blue fluorescence appears immediately upon the addition of L-tryptophan to the solution. Meanwhile, other tested amino acids (L-histidine, L-proline, *L*-phenylalanine, L-threonine, L-methionine, L-tyrosine, L-cystine) showed no effect on CAS—Cu^{2+} solution. These findings illustrated that the CAS—Cu^{2+} complex displayed selective turn-on fluorescence sensing properties to L-tryptophan.

4. Conclusion

There is an urgent need to develop chemosensors for the sequential sensing of metal ions and amino acids. In this study, an efficient multifunctional cation-amino acid sensor (CAS) containing aniline trimer moiety and chiral thiourea binding site was designed and synthesized for selective recognition of L-tryptophan, Fe^{3+}, Cu^{2+}, and Ag^{+} ions. In comparison with single-response probes, multifunctional probes that can respond to multiple responses (amino acids, cations, and pH) exhibit some advantages such as fast response, efficient, and inexpensive sensing. CAS can detect Fe^{3+}, Ag^{+}, and Cu^{2+} ions in DMSO/H_2O solution (7:3 v/v). The detection limits of CAS for the Cu^{2+}, Ag$^{+,}$ and Fe^{3+} reached 0.214, 0.099, and 0.147 μM, respectively. Job's plot confirmed that the sensing mechanism for CAS—Ag^{+}, CAS—Cu^{2+}, and CAS—Fe^{3+} is the formation of a 1:2 complex. The interaction between CCS and metal ions was analyzed by ^{1}H NMR titration. The appropriate pH ranges for the detection of Fe^{3+}, Cu^{2+}, and Ag^{+} cations by CAS are pH 5–11, 7–11, and 9–11, respectively. Moreover, the nonfluorescent Cu^{2+}-CAS complex and its L-tryptophan-facilitated fluorescence enhancement make CAS a turn-on fluorescence sensor for L-tryptophan. No response was detected upon the incorporation of other amino acids, such as L-histidine, L-proline, *L*-phenylalanine, L-threonine, L-methionine, L-tyrosine, and L-cystine to the Cu^{2+}-CAS complex.

CRediT authorship contribution statement

Arul Pundi: Methodology, Validation, Formal analysis, Writing - original draft. **Chi-Jung Chang:** Conceptualization, Investigation, Writing - review & editing. **Yi-Shao Chen:** Validation, Formal analysis. **Jem-Kun Chen:** Investigation. **Jui-Ming Yeh:** Investigation, Resources. **Cai-Shan Zhuang:** Validation. **Ming-Ching Lee:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

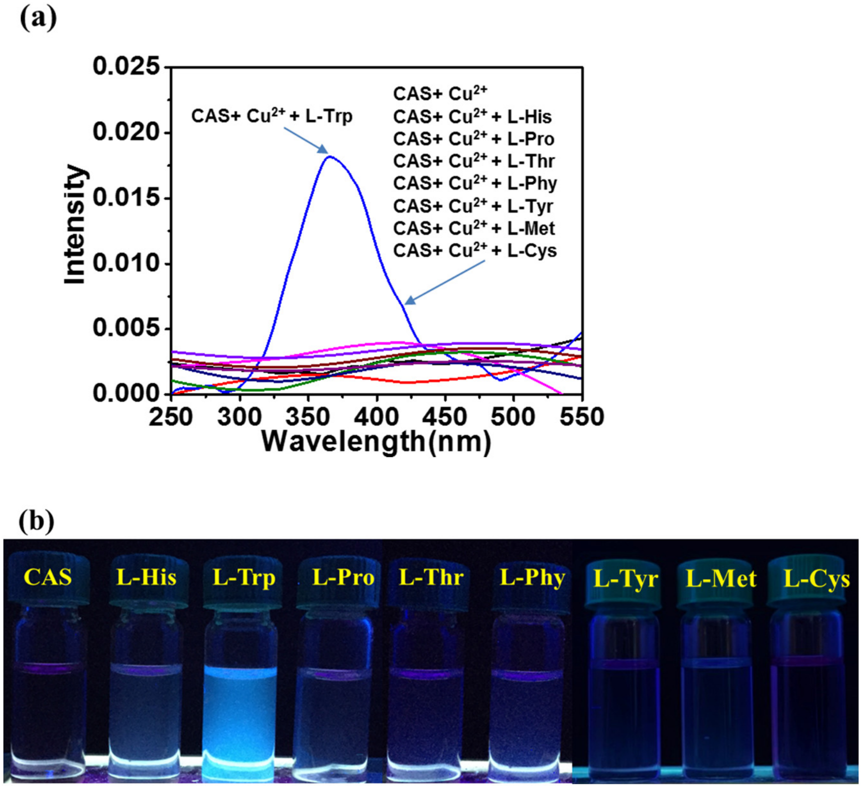


Fig. 8. (a) PL spectroscopic and (b) naked-eye recognition of copper (10 eq.) and amino acids (15 eq.) by CAS sensor (60 μM) in DMSO/H_2O (9:1 v/v). From left to right: CAS+ Cu^{2+}, CAS+ Cu^{2+} +L-Histidine, CAS + Cu^{2+} +L-tryptophan, CAS + Cu^{2+} +L-Proline, CAS + Cu^{2+} +L-Threonine, CAS + Cu^{2+} +L-Phenylalanine, CAS + Cu^{2+} +L-Tyrosine, CAS + Cu^{2+} +L-Methionine, CAS + Cu^{2+} +L-Cystine.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.saa.2020.119075.

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