



Ionic-liquid-stabilized fluorescent probe based on S-doped carbon dot-embedded covalent-organic frameworks for determination of histamine

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Abstract

An ionic-liquid-stabilized fluorescent probe for histamine is described. Sulfur-doped carbon dots (S-CDs) were incorporated into a covalent organic framework (COF) that was prepared from 1,3,5-triformylphloroglucinol and 2,5-dimethyl-*p*-phenylenediamine by one-pot hydrothermal polymerization in the dark. The blue fluorescence of the S-CDs (with excitation/emission maxima at 350/440 nm) is enhanced (compared to undoped CDs) due to element doping by ionic-liquid modification. The COF is resistant to acids, bases, and boiling water. The fluorescence of the probe is statically quenched by histamine, and quenching follows the Stern-Volmer equation. The normalized fluorescence of the probe drops in the 10 to 1000 $\mu\text{g kg}^{-1}$ histamine concentration range, and the limit of detection is 5.3 $\mu\text{g kg}^{-1}$. The probe was successfully applied to the analysis of wine and fermented meat products. The recoveries from spiked samples range between 84.6 and 115.3%. The method is selective, sensitive, stable and repeatable. The mechanisms of the fluorometric response and molecular recognition were explored.

Keywords Fluorescence · Quenching · 3-Methacryloxypropyltrimethoxysilane · One-pot · 1-Vinyl-3-butyylimidazole tetrafluoroborate · Ketoenamine · COFs · Schiff base reaction

Introduction

Carbon-based nanomaterials such as carbon nanotubes, graphene, and carbon quantum dots/carbon dots (CDs) have attracted attention because they are benign, inexpensive, and non-toxic materials with excellent physical and chemical properties [1, 2]. CDs are excellent candidates for use as

optosensors or probes. They have good chemical stability, low toxicity, and good biocompatibility, and have special optical and electronic properties compared with other fluorescent dyes. The fluorescence can be enhanced by doping CDs with various dopants, e.g., B, S, Gd, or N. This introduces localized states that change the electron transfer properties [3].

Highly porous solid metal-organic frameworks (MOFs), which consist of assemblies of metal ions with inorganic ligands, have been widely reported [4, 5]. Lin's and Chowdhuri's groups [6, 7] embedded CDs in MOFs to obtain probes with enhanced sensitivity and chemical sensing properties. Covalent organic frameworks (COFs), which are organic analogs of MOFs, are constructed from organic units through strong covalent bonds [8]. COFs have many useful properties, e.g., they are highly ordered and flexible, and have good chemical and thermal stabilities, low densities, uniform and tunable pore sizes, and high porosities and surface areas [9–11]. These advantages enable COFs to be tailored for use in gas adsorption and storage, catalysis extraction and separations, energy storage, and proton conduction. We previously constructed an optosensor based on CD-embedded COFs for rapid detection of tryptamine and 4-ethylguaiacol [12, 13].

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To improve the properties of CDs for biosensing applications, signal amplification, and conjugation with biomolecules, an ionic-liquid-stabilized fluorescent probe based on a S-doped CD-embedded COF was prepared. Element doping enhanced the fluorescence intensity, quantum yield (QY), and lifetime compared with those of undoped CDs, the ionic liquid enhanced the fluorescence stability and sensitivity, and the COF increased the specific surface area and mass transfer of the probe.

In this study, we used the fluorescent probe for highly sensitive and selective determination of histamine (HIS), which is a neurohormone that triggers a variety of allergic reactions [14]. Abnormal HIS concentrations in the body can lead to dysfunction-related diseases such as mastocytosis, gastric disorders, or chronic myelogenous leukemia [15]. HIS detection methods have been reported by fluorescence chemosensor, electrochemical sensor, quartz crystal microbalance sensor, etc. [16–27]. Although these sensor-based methods are operational and convenient, the stability, sensitivity, and reproducibility are needed to go further promote in HIS detection. The fluorescence signal response and molecular recognition mechanisms of the fluorescent probe were investigated experimentally and fitted by Stern-Volmer theory.

Experimental

Materials

All the standards used in the experiments were obtained from J&K Scientific Ltd. (<https://www.jk-scientific.com>), and other chemicals were obtained from the Sinopharm Chemical Reagent Beijing Co., Ltd., Beijing, China (<http://www.crcbj.com>).

Synthesis of S-doped carbon dots (CDs)

Sodium thiosulfate (10 mL, 0.1 M) and sodium citrate solutions (10 mL, 0.3 M) were used as the precursors for the synthesis of S-doped CDs by a one-step hydrothermal method. The sodium thiosulfate and sodium citrate solutions (1:3, v/v) were added to a 50 mL autoclave heating for 6 h at 200 °C. The S-doped CDs were obtained by filtering the mixture through a 0.22 µm cylindrical filtration membrane.

Preparation of 3-methacryloxypropyltrimethoxysilane (MPTS)-modified S-doped CDs

3-Methacryloxypropyltrimethoxysilane (MPTS) was used to modify the S-doped CDs by reverse microemulsion polymerization. The reverse microemulsion system, which consisted of TritonX-100 (1.8 mL) and cyclohexane (7.5 mL), was stirred for 15 min. The S-doped CDs (1 mL) and MPTS

(0.5 mL) were added to the reverse microemulsion system with ammonia (1 mL) and stirred for 20 h. Acetone (10 mL) was used to stop the reaction, and then the mixture was centrifuged at 3000×g for 10 min. Water was used to purify the MPTS-modified S-doped CDs.

Covalent organic framework (COF) synthesis

A two-dimensional crystalline ketoenamine COF was prepared by a Schiff base reaction of 1,3,5-triformylphloroglucinol (Tp, 0.3 mmol) with 2,5-dimethyl-*p*-phenylenediamine (Pa, 0.45 mmol) in 3 mL of mesitylene/dioxane (1:1, v/v). The mixture was sonicated for 10 min and then 3 M acetic acid (0.5 mL) was added. The mixture was reacted at 120 °C for 3 days under N₂. The COF was separated by centrifugation and dried at 180 °C under vacuum for 24 h.

Preparation of ionic-liquid-stabilized fluorescent probe based on S-doped CD-embedded COF

An ionic-liquid-stabilized fluorescent probe based on an S-doped CD-embedded COF (IL-stabilized S-doped CDs@COF) was prepared by one-pot hydrothermal polymerization under dark conditions. The TpPa COF (1 mg) was dispersed in ethanol (5 mL) in a 25 mL round-bottomed flask, and then MPTS-modified S-doped CDs (2 mL) were added. The mixture was stirred at 60 °C for 30 min after addition of HIS/1-vinyl-3-butylimidazole tetrafluoroborate ([VBIm][BF₄])/acrylamide (AM)/ethylene glycol dimethyl acrylate (EGDMA) (1:2:2:5, mol/mol). Azobisisobutyronitrile (AIBN, 45 mg) was added, the flask was sealed, and the mixture was stirred at 60 °C for 24 h. The HIS molecules were removed by Soxhlet extraction with methanol (200 mL) and the IL-stabilized S-doped CDs@COF was obtained by drying at 60 °C under vacuum for 24 h.

Instrumentation

All fluorescence detection was performed with a multifunctional microplate (Biotek, USA, <https://www.biotek.com>). Transmission electron microscopy (TEM; JEM-2012, JEOL, Japan, <https://www.jeol.co.jp>) and scanning electron microscopy (SEM; S-4800, Hitachi, Japan, <http://www.hitachi.com>) were used to examine the morphologies of the S-doped CDs, MPTS-modified S-doped CDs, COF, and the probe. Fourier-transform infrared (FT-IR) spectroscopy (Bruker, Germany, <https://www.bruker.com>) was performed in the wavenumber range 4000–400 cm^{−1} to identify the chemical groups. Thermogravimetric analysis (TGA; PTC-10A analyzer, Rigaku, Japan, <https://www.rigaku.com/en>) was used to investigate thermal stabilities and thermal decomposition. X-ray diffraction (XRD; D/max-2500 diffractometer, Rigaku, Japan, <https://www.rigaku.com/en>) was used to identify crystal

structures. The probe size was determined by dynamic light scattering (DLS; Zetasizer Nano ZS90, Malvern Instruments Ltd., Malvern, UK, <https://www.malvernpanalytical.com/en>). The fluorescence lifetimes of the probe were determined with a Jobin Yvon time-correlated single-photon-counting system.

Fluorometric assay

The fluorescent probe was dissolved in standard ethanol solutions of analytes at various concentrations. The solutions were added to a Lab systems 96-well plate, and the plate was scanned at excitation and emission wavelengths of 350 and 440 nm, respectively. Fluorescence quenching arises from the interactions between the fluorescent probe and the target molecules. Quenching is a phenomenon in which the excited state achieves optical stability through non-radiative recombination. Fluorescence quenching can be divided into static quenching and dynamic quenching. Static quenching can be described by the Stern-Volmer equation:

$$F_0/F = 1 + k_{sv}[Q] \quad (1)$$

Dynamic quenching is described by another Stern-Volmer equation:

$$F_0/F = \tau_0/\tau = 1 + k_{sv}\tau_0 [Q] \quad (2)$$

In the equations, F_0 and F are the fluorescence intensities before and after addition, respectively, of the quencher; K_{sv} is the rate constant for static/dynamic quenching; τ_0 is the lifetime of the fluoroprobe in the absence of a quencher; τ is the lifetime in the presence of a quencher; and $[Q]$ is the quencher concentration in solution.

Calculation of fluorescence quantum yield (QY)

The QY of the probe was determined from the fluorescence intensity and ultraviolet absorption by using Eq. 1. The reference was a 0.1 M quinine sulfate solution in sulfuric acid [28, 29] and the QY was 54%.

$$\Phi_x/\Phi_q = (F_x/F_q)(A_x/A_q)(\eta_q/\eta_x) \quad (3)$$

where Φ is the QY, F is the integral of the fluorescence intensity, A is the ultraviolet absorbance at the excitation wavelength, and η is the refractive index of the solvent; x and q indicate the sample and quinine sulfate, respectively.

Selectivity

The selectivity of the fluorescent probe for HIS was determined from.

$$SF = K_{sv, \text{HIS}}/K_{sv, \text{analogs}} \quad (4)$$

where SF is a selectivity factor and is used to evaluate the selectivity of the fluorescent probe and K_{sv} is the rate constant in the Stern-Volmer equation.

Determination of histamine in real samples

We chose three types of liquid food, namely red wine, yellow rice wine, and baijiu, and three types of meat product, namely canned fish, fermented pork, and chicken sausage, as real samples. The specific pretreatment process was as follows.

For the liquid foods, the sample (1 g) was diluted ten times with doubly deionized water. The samples (100 μL) were added to a 96-well plate and mixed with the fluorescent probe (1 mg mL^{-1}) in ethanol (200 μL). The fluorescence intensity, with excitation/emission maxima set at 350/440 nm, was recorded after shaking for 10 min.

For the meat products, minced meat samples (10 g) were homogenized with ethanol (20 mL) in a homogenizer for 2 min. The meat samples were then centrifuged at 12000 $\times g$ for 20 min at 4 $^{\circ}\text{C}$. The detection procedures were the same as those used for liquid foods.

Results and discussion

Preparation of ionic-liquid-stabilized fluorescent probe

Figure 1a shows a schematic diagram of the ionic-liquid-stabilized fluorescent probe that was prepared for HIS detection. The MPTS-modified S-doped CDs provided the fluorescence signal for target recognition and a COF was used as a support for the CDs to enhance the fluorescence. Because of the irreversible nature of the overall reaction and the absence of an imine bond in the COF system, it showed strong resistance to acids, bases, and boiling water [30]. The ionic liquid [VBIm][BF₄] reacted with MPTS via covalent bonding to form a stable structure. Ionic liquids are considered to be green reaction media because they are non-volatile, non-flammable, and have high ionic densities and ionic conductivities [31]. We previously introduced an ionic liquid on the surfaces of quantum dots to enhance the fluorescence [32]. Here, the introduction of a doping element and an ionic liquid enhanced the fluorescence intensity of the probe, as shown in Fig. 1b.

Sensing mechanisms based on fluorescence quenching include inner filter effects, non-radiative recombination pathways, electron transfer processes, and ion-binding interactions. The fluorescent probe is an excellent HIS detector because the fluorescence is effectively quenched (Fig. 1b) by electron transfer from the S-doped CDs to HIS. This is confirmed by Fig. 1c, which shows the fluorescence of the S-doped CDs before and after addition of the HIS target. Charge transfer can occur from the conduction bands of the

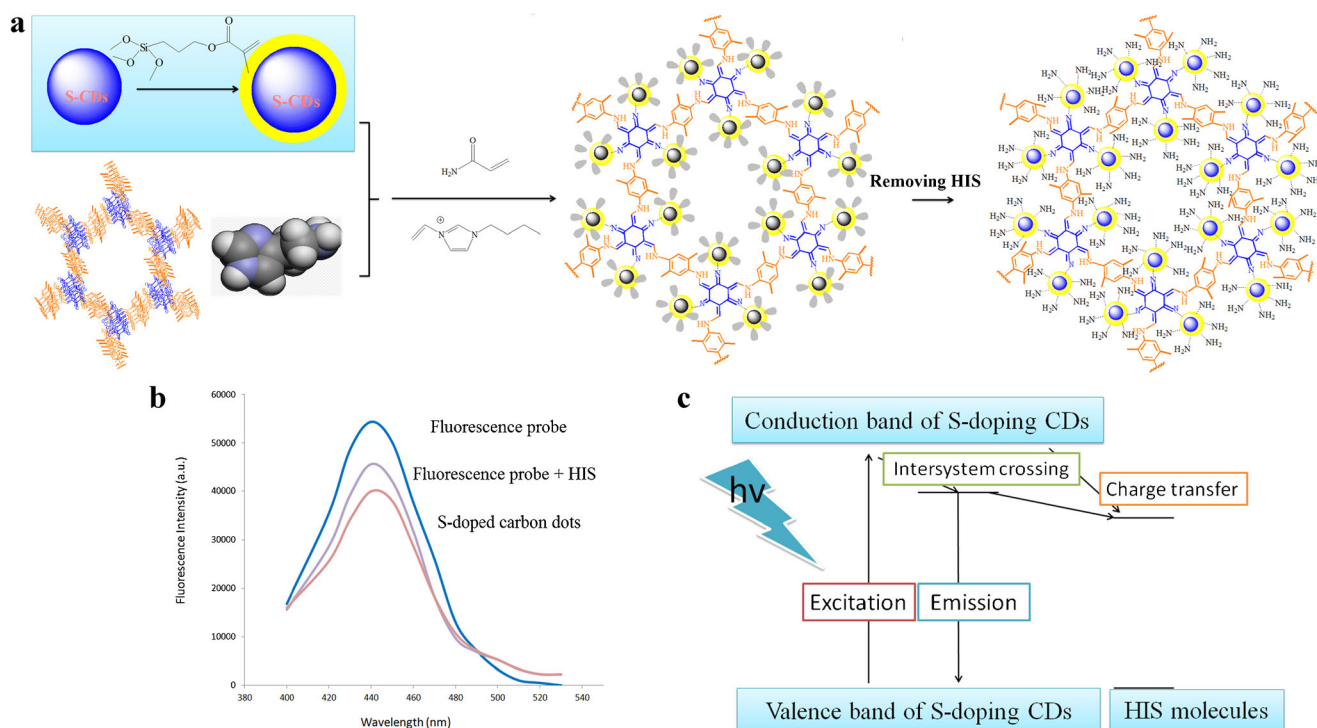


Fig. 1 **a** Schematic diagram of synthesis of ionic-liquid-stabilized fluorescent probe based on S-doped carbon dot-embedded covalent organic framework. **b** Fluorescence intensities of ionic-liquid-stabilized

fluorescent probe, ionic-liquid-stabilized fluorescent probe with $300 \mu\text{g kg}^{-1}$ of histamine, and S-doped carbon dots. **c** Mechanism of electron transfer between probe and histamine

S-doped CDs to the lowest unoccupied molecular orbital of the ultraviolet band of the HIS molecules.

Characterization of ionic-liquid-stabilized fluorescent probe

The morphology, crystal structure, stability, and fluorescence properties of the ionic-liquid-stabilized fluorescent probe based on a S-doped CD-embedded COF were investigated.

TEM and SEM were used to determine the sizes and morphologies of the S-doped CDs (Fig. 2a) and the fluorescent probe (Fig. 2b). Figure 2a shows that the S-doped CDs were spherical, uniformly distributed, and of particle size ~ 5 nm. The average particle diameter of the probe was clearly larger than that of the S-doped CDs, and was calculated by DLS to be 244 nm (Fig. S1). Figure 1b shows that the probe had a uniform spherical distribution, like the CDs, because the probe was coated on the CD surfaces of the branched COF supported the probe. The surface of the probe was rough because some molecular cavities were left on the surface during Soxhlet extraction, which enabled specific recognition of the target molecules.

The FT-IR spectra of the S-doped CDs and the probe are shown in Fig. 2c and d, respectively. The peak at $1000\text{--}1200 \text{ cm}^{-1}$ is ascribed to --SO_3^- , C--O--C , and C--O bonds in the S-doped CDs³³. The peaks at around 3300 , 2900 , and 1700 cm^{-1} correspond to the stretching vibrations of O--H ,

C--H , and C=O , respectively. The peak between 1300 and 1500 cm^{-1} can be attributed to C--N , N--H , and COO^- groups. The FT-IR spectrum of the probe is different from that of the S-doped CDs because the S-doped CDs were embedded in the probe. Figure 2d shows the presence of various peaks at around 2900 cm^{-1} , which correspond to saturated C--H , and a strong broad peak at around 1725 cm^{-1} from C=O double bonds; this indicates that EGDMA was successfully incorporated into the probe. The clear peaks at 1651 and 1453 cm^{-1} correspond to the stretching vibrations of C=C and aromatic C=C , respectively; this indicates that preparation of the probe with $[\text{VBIIm}][\text{BF}_4]$ and MPTS was successful.

The XRD pattern of the probe (Fig. 2e) shows a strong and broad peak at $2\theta = 24.6^\circ$; this is consistent with the patterns for N- or S-doped CDs, which show peaks at $2\theta = 23.4^\circ\text{--}24.6^\circ$.³⁶ The pattern indicates that the carbon phase is amorphous, which is attributed to the introduction of S- and O-containing groups.

TGA was used to evaluate the thermal stability of the probe (Fig. 2f). The TGA curve shows that no significant weight loss occurred with increasing temperature from 0 to 100°C , and only a 1.63% weight loss occurred at 100°C . The first significant weight loss, i.e., 13.37% , occurred at about 150°C and corresponds to elimination of organic reagents. The second decrease, i.e., 84.24% of the total weight, occurred at about 400°C and indicates disintegration of the COF structure. The stability of the probe was further investigated by studying the

Fig. 2 **a** TEM image of S-doped carbon dots. **b** SEM image of ionic-liquid-stabilized fluorescent probe. **c** FT-IR spectrum of S-doped carbon dots. **d** FT-IR spectrum of ionic-liquid-stabilized fluorescent probe. **e** XRD pattern of ionic-liquid-stabilized fluorescent probe. **f** TGA curve for ionic-liquid-stabilized fluorescent probe

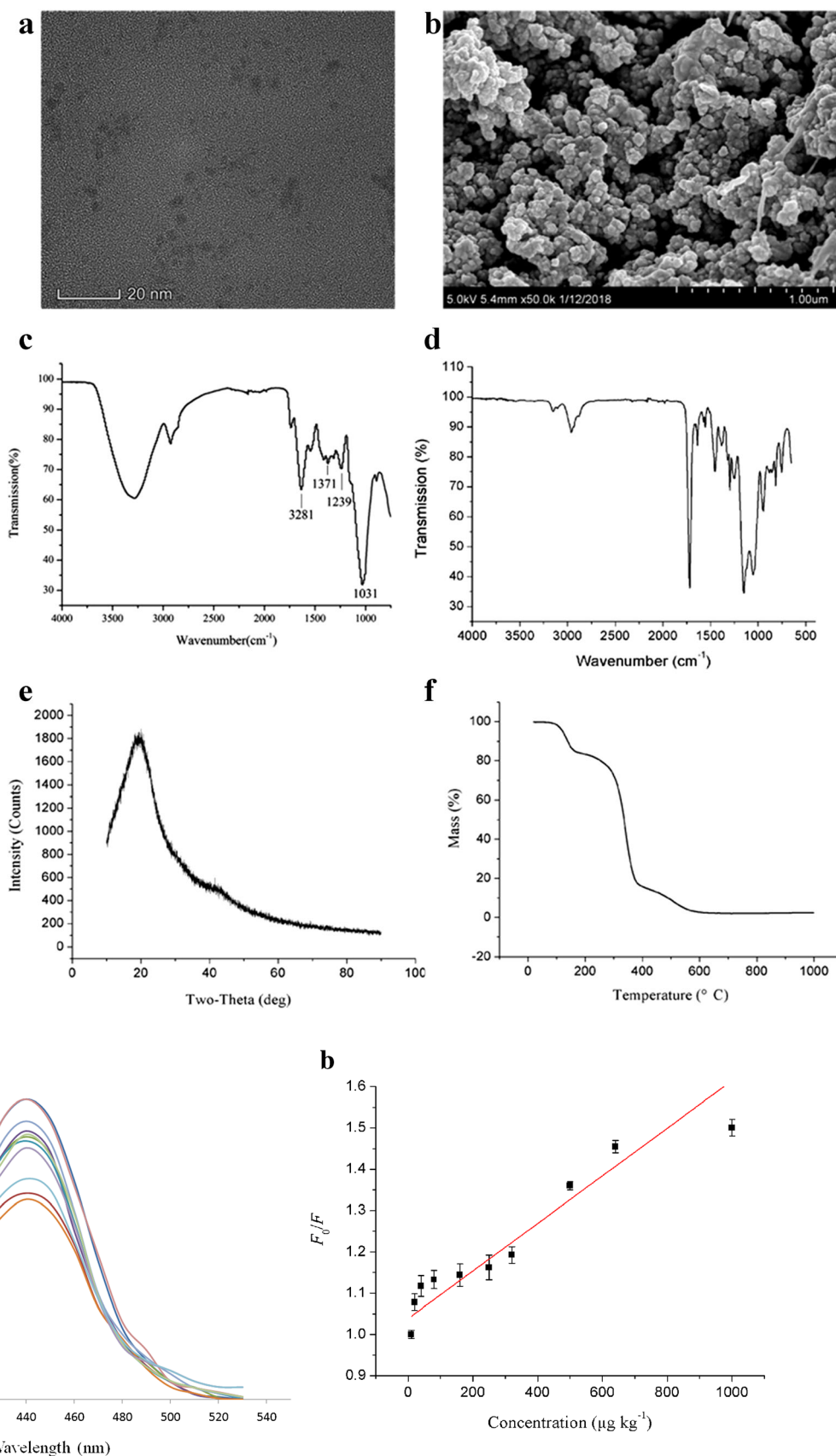


Fig. 3 **a** Fluorescence spectra of ionic-liquid-stabilized fluorescent probe in presence of increasing concentrations of histamine. **b** Stern–Volmer plot of histamine concentration against fluorescence intensity of ionic-liquid-stabilized fluorescent probe

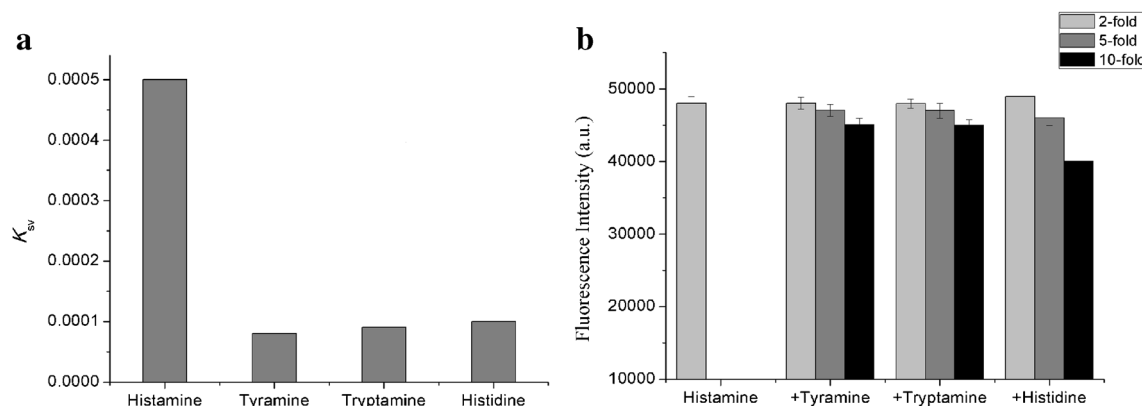


Fig. 4 **a** Specificities of ionic-liquid-stabilized fluorescent probe for histamine and analogs. **b** Interference by two-, five-, and ten-fold concentrations of histamine analogs with ionic-liquid-stabilized fluorescent probe

optical properties of the probe from 5 to 30 days at room temperature. Fig. S2 shows that the fluorescence intensity was almost unchanged after 1 month. This shows that the probe has good thermal, chemical, and optical stabilities for the detection of target molecules. The good stability is mainly attributed to the S-doped CDs, and the ionic liquid [VBIm][BF₄] gives good luminescence stability.

The optimum excitation and emission wavelengths are 350 nm and 440 nm, respectively. The probe decay was recorded at the optimum excitation and emission wavelengths at room temperature by using a time-correlated single-photon-counting technique. The average fluorescence lifetime of the probe was 5.04 ns (Fig. S3), therefore it is potentially an excellent fluorescent probe. The QY, which was calculated to be 38.7% at room temperature, was used to further evaluate the optical properties of the probe. The probe QY measurements were reliable, and the precision for three replicate detections was 2.73% [relative standard deviation (RSD)]. The probe gave a good fluorescence QY because of the use of element-doped CDs and [VBIm][BF₄]. Many researchers have reported that element doping enhances the fluorescence intensity and QY of CDs [3, 33].

Fluorescence properties of probe

The adsorption time is an important parameter in practical applications of a fluorescent probe. The adsorption kinetics of the probe were investigated at 100 $\mu\text{g kg}^{-1}$ HIS by shaking for 1 to 30 min at room temperature (Fig. S4). The results show that equilibrium was reached in 10 min, which indicates fast adsorption or detection ability. The imprinted cavities on the probe surface enable fast detection and the COF support provides a large specific surface area for good mass transport. The Brunauer-Emmett-Teller (BET) surface area was determined and used to further evaluate the adsorption properties of the probe powder. The results show a high BET surface area, i.e., 102 $\text{m}^2 \text{g}^{-1}$.

Stern-Volmer plots were constructed by plotting the static quenching of the fluorescence intensity against HIS concentration (Fig. 3). The lifetime of the fluorophore is not affected by static quenching, therefore lifetime measurements provide a definitive method for distinguishing between static and dynamic quenching. Figure 3a shows that the fluorescence intensity was clearly quenched with increasing HIS concentration. Figure 3b shows a linear relationship between F_0/F and

Table 1 HIS detection in real samples by fluorescent probe

Samples	Detection (mean $\pm$ SD, $n = 3$, $\mu\text{g kg}^{-1}$)	RSD (%)
Red Wine 1	557 $\pm$ 25	4.4
Red Wine 2	643 $\pm$ 26	4.0
Yellow Rice Wine 1	404 $\pm$ 11	2.6
Yellow Rice Wine 2	369 $\pm$ 12	3.2
Baijiu 1	ND	—
Baijiu 2	ND	—
Fermented Pork Sausage 1	262 $\pm$ 8	3.2
Fermented Pork Sausage 2	212 $\pm$ 6	2.9
Fermented Chicken Sausage 1	25.4 $\pm$ 1.7	6.8
Fermented Chicken Sausage 2	54.7 $\pm$ 1.8	3.3
Canned Fish 1	84.2 $\pm$ 4.3	5.1
Canned Fish 2	103 $\pm$ 5	4.5

Table 2 Summary of literature reports on histamine determination of various foods by different methods

Methods	Detection Limit	Linear Range	Reproducibility (RSD%)	Stability	Samples recovery values	Samples	References
An electrophoretic method (on-line coupled capillary isotachopheresis with capillary zone electrophore-sis) with conductometric detection (GTP-CZE-COND)	4 ng/mL (4 µg/L)	22–222 ng/mL (22–222 µg/L)	3.4%	–	91 ± 9%	food stuffs and feed stuffs	[16]
Fluorescence based on molecularly imprinted polymer	1.80 µmol L ⁻¹ (2.00 × 10 ² µg/L)	1.80–44.98 µM (2.00 × 10 ² –4.99 × 10 ³ µg/L)	–	–	87.95–101.01%	milk	[17]
A electrochemical method using nafioncoated copper phosphate electrodes	3.0 ppm (3.0 × 10 ³ µg/kg)	5–500 ppm (5 × 10 ³ –5 × 10 ⁵ µg/kg)	–	–	–	fish	[18]
A blue fluorescence chemosensor and surfacecharge selector based on FC-modified silica nanoporous	8.55 µmol L ⁻¹ (9.49 × 10 ² µg/L)	29.12–166.67 µM (3.23 × 10 ³ –1.85 × 10 ⁴ µg/L)	–	–	96.4–110.3%	salmon and tuna	[19]
A electrochemical method using Cu@Pd core-shell nanostructures	3.2 ± 0.1 nmol L ⁻¹ (0.355 µg/L)	0.1–100 µM (11.1–1.11 × 10 ⁴ µg/L)	–	–	98.3–100.4%	tuna fish	[20]
A electrochemical method using surface oxide regeneration behavior of copper electrode	0.33 µmol L ⁻¹ (36.63 µg/L)	1–750 µM (1.11 × 10 ² –8.33 × 10 ⁴ µg/L)	–	28 days.	–	seafood	[21]
A electrochemical method using Silver nanoparticles decorated graphene nanoribbon modifiedpyrolytic graphite sensor	0.049 µmol L ⁻¹ (5.439 µg/L)	1–50 µM (60–500 µM) (1.11 × 10 ² –5.55 × 10 ³ µg/L) (6.66 × 10 ³ –5.55 × 10 ⁴ µg/L)	± 2.48%.	24 days	98.83–100.3%	red wine	[22]
A electrochemical method using Prussian blue-chitosan-gold nanoparticle nanocomposite films	1.25 pg/mL (1.25 × 10 ⁻³ µg/L)	0.01–100 µg/mL (10–1 × 10 ⁵ µg/L)	<3.61%	2 weeks	97.25%–105%.	fish	[23]
Quartz crystal microbalance sensor based on molecularly imprinted sol-gel polymer	7.49 × 10 ⁻⁴ mg kg ⁻¹ (0.749 µg/kg)	0.11 × 10 ⁻² –4.45 × 10 ⁻² mg L ⁻¹ (1.1–44.5 µg/L)	4.8%	6 months	93.2–100.4%	canned sardines, saury, and mackerel	[24]
Fluorescence based on molecularly imprinted polymers (MIPs) doped with silver nanoparticles (AgNPs) on the surface of upconversion particles (UCNPs).	0.04 mg L ⁻¹ (40 µg/L)	0.1–100 mg L ⁻¹ (1 × 10 ² –1 × 10 ⁵ µg/L)	–	–	86.89–117.36%	red wine, rice wine and canned tuna	[25]
A electrochemical method using molecularly-imprinted polymer-based voltammetric Sensor	7.4 × 10 ⁻¹¹ mol L ⁻¹ (8.21 × 10 ⁻³ µg/L)	1 × 10 ⁻¹⁰ –7 × 10 ⁻⁹ M (7 × 10 ⁻⁹ –4 × 10 ⁻⁷ M) (1.11 × 10 ⁻² –0.78 µg/L) (0.78–44.4 µg/L)	–	–	95–105%	human serum	[26]
Ionic liquid stabilized fluorescent probe based on S-doped carbon dot-embedded covalent-organic frameworks	5.27 µg kg ⁻¹	10–1000 µg kg ⁻¹	2.77%	30 days	84.6–115.3%	red wine, yellow rice wine, baijiu, canned fish, fermented pork, and chicken sausage	This article

the HIS concentration in the range 10–1000 $\mu\text{g kg}^{-1}$. The limit of detection, calculated as the HIS concentration that quenched three times the standard deviation of the blank signal in the standard curve, was 5.27 $\mu\text{g kg}^{-1}$. This value is significantly lower than 100 mg kg^{-1} , which is the allowable limit for HIS in Scombridae fish specified in the European Union, and lower than the guideline limit of 50 mg kg^{-1} specified by the United States Food and Drug Administration [34].

The reproducibility of the fluorescent probe results was investigated by performing ten repeated measurements with a HIS concentration of 100 $\mu\text{g kg}^{-1}$. After each measurement, the probe was washed with methanol by Soxhlet extraction to remove any residual HIS molecules. The fluorescence detection method gave a RSD of 2.77%.

The selectivity and sensitivity of the fluorescent probe for HIS are important for practical applications. Structural analogs of biogenic amines, namely tyramine, tryptamine, and histidine, were used in the study. The fluorescence responses of the probe to HIS and its analogs were investigated to evaluate the selectivity. Figure 4a shows that the Stern-Volmer constant K_{sv} was considerably higher for HIS than for the other amines, which indicates strong fluorescence quenching of the probe with HIS. This is because cavities specifically for HIS were formed on the fluorescent probe surface during preparation. The SF factors were 6.04, 5.83, and 4.91 for tyramine, tryptamine, and histidine, respectively. This indicates good detection. The effects of the copresence of HIS analogs were further investigated by using two-, five-, and ten-fold concentrations of the analogs to evaluate the selectivity and sensitivity (Fig. 4b). When the analog concentration was less than five-fold that of HIS, the probe fluorescence intensity was not significantly affected. When the concentration was more than ten-fold that of HIS, the probe fluorescence intensity decreased significantly, which indicates that the copresence of analogs affected the sensitivity.

Histamine-sensing capability of fluorescent probe for real samples

HIS is one of the most important biogenic amines in clinical and food chemistry [35]. Red wine, yellow rice wine, baijiu, canned fish, fermented pork, and chicken sausage were used as real samples for HIS detection by the fluorescent probe; the results are shown in Table 1. The accuracy of the method was further shown by performing spiked recovery experiments at spiked concentrations of 10, 20, and 50 $\mu\text{g kg}^{-1}$ in red wine 1 (Table S1). The recovery was 84.6%–115.3% ($n = 3$, average of three replicate measurements), which indicates that the method gives good accuracy. The probe is therefore suitable for rapid determination of HIS in complex samples. We also compared the HIS detection results with those achieved with other sensing methods, in terms of the detection limit, linear range, reproducibility, stability, recovery, and sample type

(Table 2). The ionic-liquid-stabilized fluorescent probe provides good sensitivity, a wide linear range, and good reproducibility and stability in HIS detection.

Conclusions

An ionic-liquid-stabilized fluorescent probe based on a S-doped CD-embedded COF was prepared by one-pot hydrothermal polymerization. The probe was suitable for the rapid detection of HIS in wine and meat products, and gave good accuracy, selectivity, sensitivity, stability, and repeatability. This is a promising method for enhancing the performances of fluorescent probes for the sensing and detection of small molecules and hazardous substances in food, agricultural, and environmental samples. However, the need for UV working condition in the excitation at 350 nm, it makes the probe prone to interferences by biomatter. The UV light used for fluorescence excitation will be screened off by UV absorbers and this will weaken the signal. In addition, this method can only detect a single target of histamine specifically, and the simultaneous detection of multiple targets of biogenic amines by optosensing needs further study.

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Compliance with ethical standards

Conflict of interest The authors declare no competing interest.

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Electronic Supporting Material

Ionic-liquid-stabilized fluorescent probe based on S-doped carbon dot-embedded covalent-organic frameworks for determination of histamine

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Supporting Information Index:

Fig. S1 Particle diameter of ionic-liquid-stabilized fluorescent probe; results were obtained by dynamic light scattering analysis.

Fig. S2 Stability of ionic-liquid-stabilized fluorescent probe.

Fig. S3 Fluorescence lifetimes of ionic-liquid-stabilized fluorescent probe.

Fig. S4 Time evolution of histamine adsorption ($100\ \mu\text{g kg}^{-1}$) by ionic-liquid-stabilized fluorescent probe.

Table S1 Spiked recovery results for HIS determination in Red Wine 1.

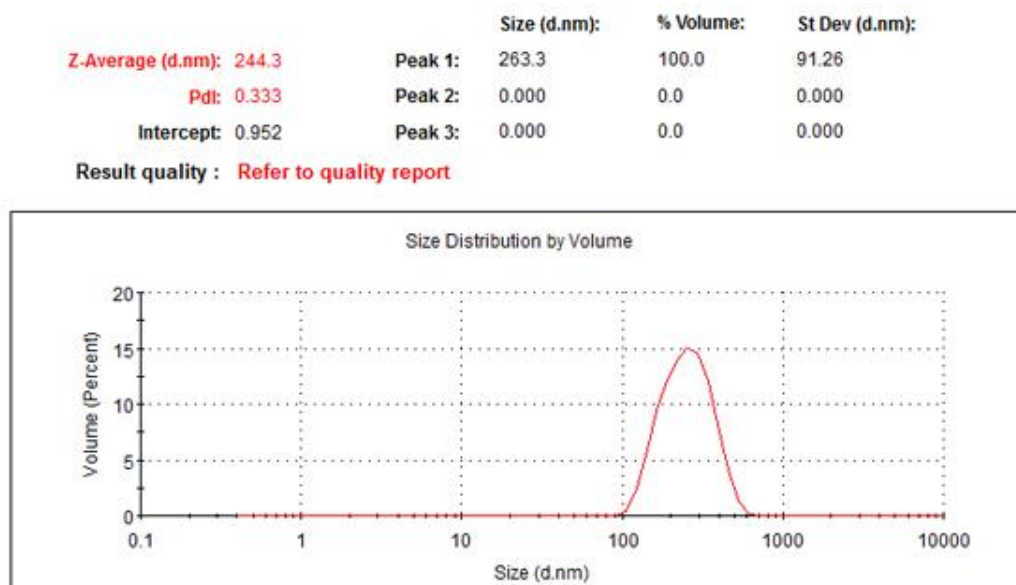


Fig. S1 Particle diameter of ionic-liquid-stabilized fluorescent probe; results were obtained by dynamic light scattering analysis.

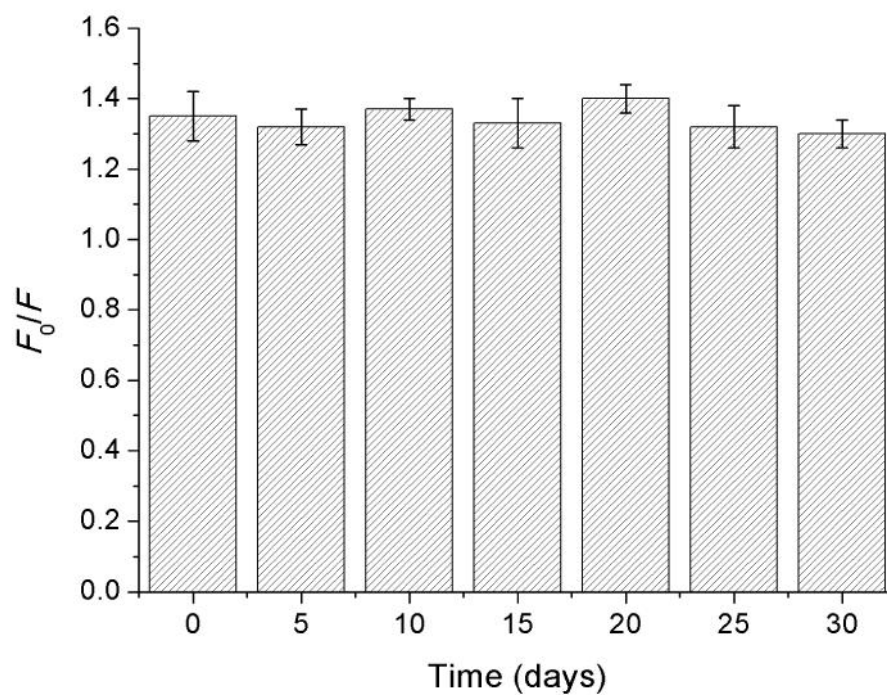


Fig. S2 Stability of ionic-liquid-stabilized fluorescent probe.

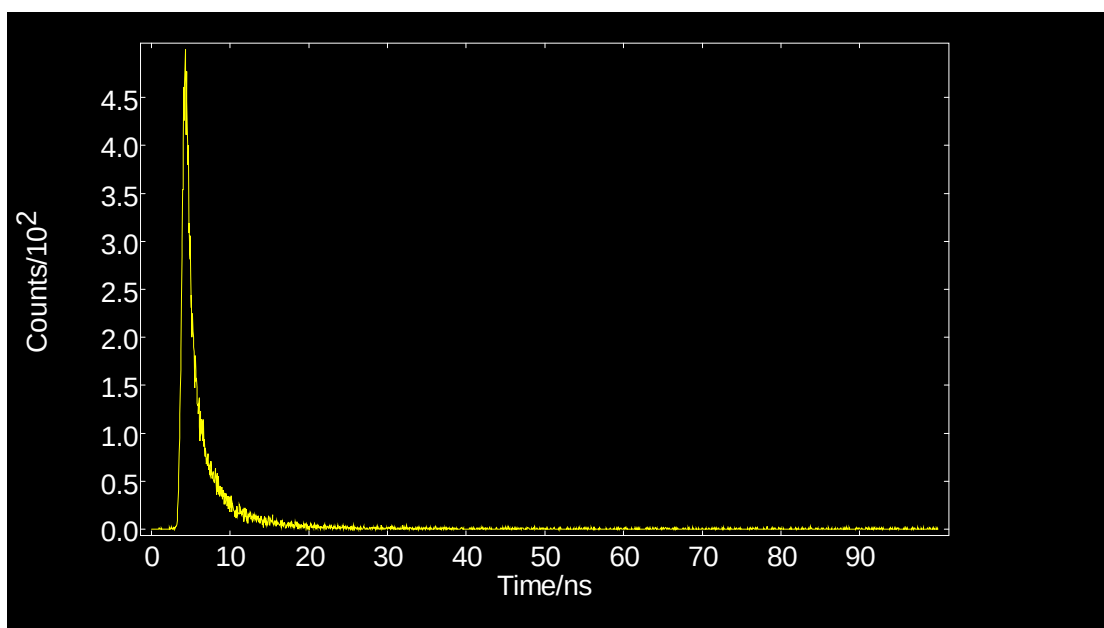


Fig. S3 Fluorescence lifetimes of ionic-liquid-stabilized fluorescent probe.

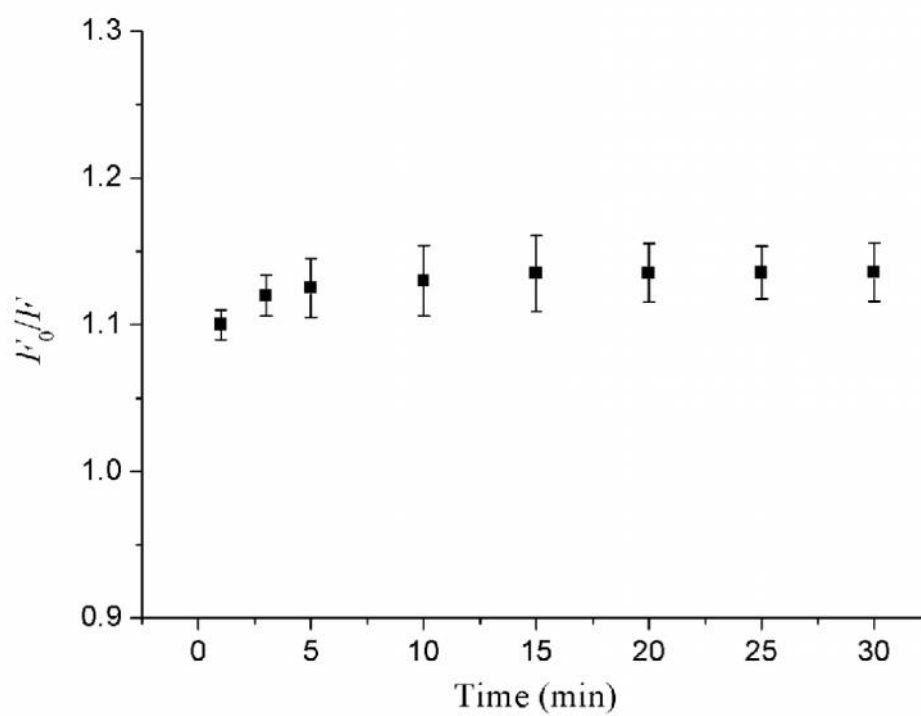


Fig. S4 Time evolution of histamine adsorption ($100 \mu\text{g kg}^{-1}$) by ionic-liquid-stabilized fluorescent probe.

Table S1 Spiked recovery results for HIS determination in Red Wine 1.

Samples	Added	Determined TRY	Recovery
	($\mu\text{g kg}^{-1}$)	(mean $\pm$ SD; n=3, $\mu\text{g kg}^{-1}$)	(%)
Red Wine 1	10	568.37 $\pm$ 25.14	115.30
	20	573.76 $\pm$ 29.63	84.60
	50	611.41 $\pm$ 33.07	109.14