Dopamine Functionalized S,N Co-doped Carbon Dots as a Fluorescent Sensor for the Selective Detection of Fe$^{3+}$ and Fe$^{2+}$ in Water

Siyu Lei,*,** Na Chang,*,** Jimei Zhang,*,**† and Haitao Wang,*,**†

*State Key Laboratory of Separation Membranes and Membrane Processes, Tiangong University, Tianjin, 300387, People’s Republic of China  
**School of Chemistry and Chemical Engineering, Tiangong University, Tianjin, 300387, People’s Republic of China  
***School of Environmental Science and Engineering, Tiangong University, Tianjin, 300387, People’s Republic of China

In current work, novel functionalized carbon dots have been designed and synthesized by covalently linking dopamine to the surface of S,N co-doped carbon dots (DA-S,N-CDs) for the selective detection of Fe$^{3+}$ and Fe$^{2+}$ in water. The as-synthesized DA-S,N-CDs emit blue fluorescence peaked at 470 nm and exhibit excitation-dependent tunable emissions. The tolerance towards pH, salt, and UV irradiation of synthesized carbon dots reveals excellent stability. Upon exposure to Fe$^{3+}$ or Fe$^{2+}$, the fluorescence of DA-S,N-CDs was selectively quenched, while other competitive cations did not change significantly. Under the optimal experimental conditions, the fluorescence intensity of DA-S,N-CDs showed a good linear relationship with the concentrations of Fe$^{3+}$ and Fe$^{2+}$ (5 - 200 μM for Fe$^{3+}$ and 5 - 300 μM for Fe$^{2+}$), and the limit of detection was 2.86 and 2.06 μM, respectively. Furthermore, considering the excellent stability and anti-interference, DA-S,N-CDs have been successfully used for the detection of Fe$^{3+}$ and Fe$^{2+}$ in environmental water.

Keywords Dopamine, S,N co-doped carbon dots, functionalized, Fe$^{3+}$ and Fe$^{2+}$, selective detection

(Received August 7, 2020; Accepted October 8, 2020; Advance Publication Released Online by J-STAGE October 16, 2020)
Guo et al. have developed a rhodamine-functionalized carbon dot for the detection of Fe\textsuperscript{3+} in tumor stem cells.\textsuperscript{20} Nitrogen-doped carbon dots and pillar[S]arenes were covalently functionalized for Fe\textsuperscript{3+} sensing.\textsuperscript{20} However, most of the currently reported fluorescent sensors for detecting iron ions can only detect Fe\textsuperscript{3+}, but not Fe\textsuperscript{2+}, which limits their practical applications.

In this work, a sensitive, reliable, and highly selective nanofluorescent probe: dopamine functionalized S,N co-doped carbon dots (DA-S,N-CDs) for simultaneous detection of Fe\textsuperscript{3+} and Fe\textsuperscript{2+}, showing high selectivity response was developed. The synthesis strategy is the hydrothermal synthesis of S,N co-doped carbon dots (S,N-CDs) with anhydrous citric acid and thiourea, and then the carbon dots are covalently combined with the dopamine monomer through the EDC/NHS coupling reaction. After the addition of Fe\textsuperscript{3+} or Fe\textsuperscript{2+}, the fluorescence of DA-S,N-CDs was quantitatively quenched, and the decrease in the fluorescence intensity was proportional to the ion concentration. In addition, the recovery of Fe\textsuperscript{3+} and Fe\textsuperscript{2+} was measured, and the results showed that the carbon dots have potential application value in the detection of Fe\textsuperscript{3+} and Fe\textsuperscript{2+} in water samples.

**Experimental**

**Materials and reagents**

An anhydrous citric acid (CA, 99.5%) and thiourea (99.0%) were purchased from Mreda Technology Co., Ltd. Dopamine hydrochloride (DA, 98.0%), N-hydroxysuccinimide (NHS, 98.0%), N-(3-dimethylamino)propyl)-N’-ethyl carbodiimide hydrochloride (EDC·HCl, 99.0%) were purchased from Bomei Biotechnology Co., Ltd. FeCl\textsubscript{2}·6H\textsubscript{2}O, FeCl\textsubscript{3}·4H\textsubscript{2}O, Cr(NO\textsubscript{3})\textsubscript{3}·9H\textsubscript{2}O, Al(NO\textsubscript{3})\textsubscript{3}·9H\textsubscript{2}O, Pb(NO\textsubscript{3})\textsubscript{2}, Cd(NO\textsubscript{3})\textsubscript{2}·4H\textsubscript{2}O, Ni(NO\textsubscript{3})\textsubscript{2}·6H\textsubscript{2}O, Mg(NO\textsubscript{3})\textsubscript{2}·6H\textsubscript{2}O, Zn(NO\textsubscript{3})\textsubscript{2}·6H\textsubscript{2}O, Ba(NO\textsubscript{3})\textsubscript{2}, Cu(NO\textsubscript{3})\textsubscript{2}·3H\textsubscript{2}O, MnCl\textsubscript{2}·4H\textsubscript{2}O, NaNO\textsubscript{3}, KCl, LiNO\textsubscript{3} were of analytical grade and used as received without further purification. All aqueous solutions were prepared with ultrapure water.

**Synthesis of S,N co-doped carbon dots (S,N-CDs)**

The S,N-CDs were prepared by a standard hydrothermal method by referring to previous work.\textsuperscript{21} Briefly, 1.1527 g (6 mmol) citric acid, 1.3701 g (18 mmol) thiourea were mixed with 20 mL ultrapure water, stirred until obtaining a homogeneous and transparent solution, and then transferred into a 50 mL autoclave and heated at 160°C for 5 h. The obtained suspension was filtered with a 0.22 μm membrane and dialyzed for 12 h. After evaporating the solvent at 60°C, the final product was collected by adding anhydrous ethanol and centrifuging at 8000 rpm for 10 min. The obtained solid can be easily dispersed into ultrapure water.

**Functionalization of S,N-CDs with dopamine (DA-S,N-CDs)**

Dopamine functionalized S,N co-doped carbon dots were synthesized by a classic EDC/NHS coupling reaction, where the carboxyl groups of the carbon dots were covalently combined with dopamine monomers to form an amide bond.\textsuperscript{32} A known amount of S,N-CDs (80 mg) was dissolved in 10 mL of ultrapure water, and the pH of the solution was adjusted to 6. Then, 2 mL of EDC and NHS (both 1 mol/L) were added into CDs solution to activate the carboxyl group for 30 min, and a 3 mL dopamine solution (1 mol/L) was added to the preceding solution incubated for 3 h; dissolved oxygen was removed by nitrogen bubbling. Finally, the prepared solution was purified by filtration through a 0.22 μm membrane and dialyzed for 4 h to remove excess dopamine, EDC/NHS, and possibly polydopamine. The final product was precipitated by adding ethanol and centrifuging at 8000 rpm for 10 min.

**Detection of Fe\textsuperscript{3+}/Fe\textsuperscript{2+} Using DA-S,N-CDs**

The detection of Fe\textsuperscript{3+}/Fe\textsuperscript{2+} by using DA-S,N-CDs (0.65 mg/mL) was performed at room temperature in the 10 mM phosphate buffer solutions (PB) at pH 7. The standard stock solution of Fe\textsuperscript{3+} and Fe\textsuperscript{2+} were prepared by dissolving the appropriate amount of FeCl\textsubscript{3}·6H\textsubscript{2}O and FeCl\textsubscript{2}·4H\textsubscript{2}O. To evaluate the sensitivity towards Fe\textsuperscript{3+}/Fe\textsuperscript{2+}, different concentrations of Fe\textsuperscript{3+}/Fe\textsuperscript{2+} were added into the aqueous solution of DA-S,N-CDs, and the mixed solution were incubated for 10 min before spectral measurements. The fluorescence spectra were recorded at an excitation wavelength of 380 nm. A similar procedure was performed for the detection of other metal ions.

**Determination of Fe\textsuperscript{3+}/Fe\textsuperscript{2+} in environmental water**

In order to evaluate the applicability of DA-S,N-CDs in environmental water, two samples, including tap water and lake water from Tiangong University, were collected. The samples were filtered through a 0.22 μm membrane and centrifuged at 8000 rpm for 10 min prior to testing, and then adjusted to pH 7. After pretreatment, the samples were spiked with Fe\textsuperscript{3+}/Fe\textsuperscript{2+} at different concentration levels (60, 120 μM), and then 0.65 mg/mL DA-S,N-CDs were added into the solutions for fluorescence intensity measurement to evaluate the recovery of Fe\textsuperscript{3+}/Fe\textsuperscript{2+} in environmental water samples.

**Results and Discussion**

**Characterization of dopamine functionalized S,N-CDs (DA-S,N-CDs)**

S,N-CDs are synthesized by a hydrothermal method and then functionalized through EDC/NHS amidation reaction to prepare DA-S,N-CDs as shown in Scheme 1. The fluorescence emission and UV-vis absorption spectra of S,N-CDs and DA-S,N-CDs are shown in Fig. 1. Upon coating with DA on the surface of CDs, the fluorescence of the DA-S,N-CDs was significantly reduced, and the fluorescence emission peak was red-shifted by about 15 to 470 nm. Two absorption peaks of S,N-CDs were
observed at 230 and 335 nm, in which the former may be assigned to the $\pi-\pi^*$ transition of the C=C bond and the latter was contributed from the n-$\pi^*$ transition of the C=O bond. After the functionalization of dopamine, the absorption peak at 230 nm disappeared. The typical absorption peak around 280 nm for DA-S,N-CDs was consistent with DA, which did not appear in the original S,N-CDs.

The successful functionalization of dopamine was also confirmed by FTIR spectroscopy. From the FTIR spectra of S,N-CDs (Fig. 2), the broad vibration band in the region of 2800 – 3440 cm$^{-1}$ was attributed to stretching vibrations of O–H and N–H, indicating the good hydrophilic nature of N,S-CDs which is contributed to the amino and carboxyl groups on the surface of the carbon dot. The characteristic peaks at 1700, 1541, and 1401 cm$^{-1}$ confirmed the presence of C=O, C=C, and C-N, respectively. The C-S stretching at 1180 cm$^{-1}$ and the peak of C-O stretching at 1311 cm$^{-1}$ were also observed. The other band at 1044 cm$^{-1}$ was attributed to the asymmetric vibration of C-O-C. After surface modification with dopamine, the shoulder peak at 1521 cm$^{-1}$ was observed for DA-S,N-CDs, which was attributed to the amide bond. Moreover, the characteristic peak at 1440 cm$^{-1}$ was ascribed to the breathing vibration of the benzene skeleton, which belongs to dopamine. Besides, three new peaks of DA-S,N-CDs at 1280, 1154, and 950 cm$^{-1}$, which are characteristic peaks belonging to dopamine, appeared with the disappearance of the peaks at 1180 and 1311 cm$^{-1}$. These results indicate that the dopamine monomer was successfully modified on the surface of S,N-CDs.

The elemental composition and the chemical state of S,N-CDs were confirmed by X-ray photoelectron spectroscopy (XPS).
An XPS survey spectrum reveals that the S,N-CDs mainly has four peaks located at 532.07, 400.41, 284.81, and 163.42 eV, which correspond to O1s, N1s, C1s, and S2p, respectively (Fig. 3a). In detail, the high-resolution C1s spectrum (Fig. 3b) shows peaks of C=C at 284.3 eV, C–C at 284.87 eV, C–N/C–S at 285.5 eV, and C=O at 288.7 eV. Moreover, three peaks can be seen in the high-resolution spectrum of N1s (Fig. 3c), which are associated with pyridinic N (399.6 eV), pyrrolic N (400.3 eV), and amidic N (401.7 eV).36,37 Two typical signals of 163.3 and 164.4 eV were observed in the high-resolution S2p spectrum (Fig. 3d), corresponding to S2p 3/2 and S2p 1/2 of thiophene,31 which confirmed the existence of C–S–C covalent bonds in the thiophene structure. Upon functionalizing with DA on the surface of CDs, the C/O atomic ratio for DA-S,N-CDs is about 2.201, which is higher than that of S,N-CDs (1.775), explaining that dopamine was successfully introduced into the S,N-CDs.

X-ray diffraction (XRD) has also been used to characterize the structure of S,N-CDs and DA-S,N-CDs (Fig. S1, Supporting Information). The as-prepared S,N-CDs exhibited a broad peak of around 23.5°, corresponding to the (002) plane of graphene.38 After the dopamine modification, the position of the XRD peak at 23.5° did not change, indicating that the introduction of dopamine was only attached to the edge of S,N-CDs.32

The transmission electron microscopy (TEM) images (Fig. 4a) shows that the obtained DA-S,N-CDs had an average diameter of ca. 18 nm. High-resolution TEM (HR-TEM) images disclosed that DA-S,N-CDs exhibited clear lattice structures with a fringe spacing of 0.242 nm (Fig. 4a inset), corresponding to the basal spacing of the (1120) lattice plane of graphene.39

Optical properties of DA-S,N-CDs

The optical properties of DA-S,N-CDs were investigated. DA-S,N-CDs exhibited an excitation wavelength-dependent feature with the excitation wavelength ranging from 350 to 420 nm (Fig. 4b). With a increase of the excitation wavelength, the fluorescence emission peak gradually red-shifted from 460 to 508 nm, and the fluorescence intensity increased firstly and then decreased. In addition, when the excitation wavelength was 380 nm, the fluorescence intensity of DA-S,N-CDs reached a maximum emission of around 470 nm. The DA-N,S-CDs emitted blue luminescence under 365 nm UV irradiation (Fig. 4b inset). Since the oxidation of dopamine is highly pH-dependent,40 the effects of different pH values on the fluorescence of DA-S,N-CDs were investigated (Fig. S2, Supporting Information). It can be seen that the fluorescence intensity of DA-S,N-CDs increases gradually when the pH increases from 3 to 8, and decreases slightly with a further increase of the pH, indicating that DA-S,N-CDs can maintain strong fluorescence over a large range. The stability of DA-S,N-CDs was also investigated. The prepared DA-S,N-CDs exhibited negligible photobleaching and sustained strong fluorescence when exposed to a 365 nm UV lamp for 3 h (Fig. S3, Supporting Information). Furthermore, the NaCl tolerance of DA-S,N-CDs was up to 2 mol/L (Fig. S4, Supporting Information), which indicated the stability of DA-S,N-CDs under high ionic strength. The above results indicate that the DA-S,N-CDs possess excellent fluorescence and stability under various complex environments, which make them suitable for further sensing applications.

The strategy towards fluorescence sensing of Fe\(^{3+}\) and Fe\(^{2+}\)

To test the potential utility of DA-S,N-CDs as a fluorescent probe, we explored the fluorescence response of DA-S,N-CDs to common metal ions (as shown in Fig. 5) in phosphoric acid buffer solution at pH 7, including Cr\(^{3+}\), Al\(^{3+}\), Fe\(^{3+}\), Ni\(^{2+}\), Ba\(^{2+}\), Pb\(^{2+}\), Mn\(^{2+}\), Fe\(^{2+}\), Cu\(^{2+}\), Mg\(^{2+}\), Zn\(^{2+}\), CO\(^{2-}\), Cd\(^{2+}\), Na\(^{+}\), K\(^{+}\), Li\(^{+}\). Under the same concentration (200 μM), the DA-S,N-CDs reveals specific recognition towards Fe\(^{3+}\) and Fe\(^{2+}\), while the fluorescence spectra of other competitive metal cations did not change significantly.
The possible mechanism of fluorescence quenching may be due to the presence of dopamine catechol residues on the surface of carbon dots that specifically interact with iron ions to form stable non-fluorescent complexes, resulting in a decrease in the fluorescence intensity of DA-S,N-CDs. The color change of the solution also illustrates the complex interaction between DA-S,N-CDs and iron ions (Fig. S5 inset). Meanwhile, the UV-Vis absorption spectra of CDs, Fe$^{3+}$, and CDs-Fe complex were investigated (Fig. S5). The change in the absorption spectrum of DA-S,N-CDs illustrates the formation of the ground-state complex.

The fluorescence quenching of DA-S,N-CDs by Fe$^{3+}$/Fe$^{2+}$ can be used to quantitatively detect Fe$^{3+}$/Fe$^{2+}$ in an aqueous solution. To further quantify the relationship between Fe$^{3+}$/Fe$^{2+}$ concentration and the fluorescence intensity of DA-S,N-CDs, the fluorescence spectra of DA-S,N-CDs were obtained by titration experiments of Fe$^{3+}$/Fe$^{2+}$. Figures 6a and 6b show the changes in the fluorescence intensity of DA-S,N-CDs in the presence of different concentrations of Fe$^{3+}$ and Fe$^{2+}$, respectively. With an increase of the ion concentration, the fluorescence of DA-S,N-CDs is regularly quenched, but the sensitivity of DA-S,N-CDs for Fe$^{2+}$ is lower than that of Fe$^{3+}$. According to Figs. 6c and 6d, there is a good linear correlation between the quenching efficiency and the concentration of Fe$^{3+}$ and Fe$^{2+}$, with linear ranges of 5 – 200 and 5 – 300 μM, respectively. The concentrations of Fe$^{3+}$ and Fe$^{2+}$ are calculated by the following equation, respectively:

$$\frac{F_0}{F} = 0.0051 \times [\text{Fe}^{3+}] + 0.9883$$

$$\left( R^2 = 0.9963, [\text{Fe}^{3+}] = 5 - 200 \mu\text{M}, \right)$$

$$\frac{F_0}{F} = 0.0068 \times [\text{Fe}^{2+}] + 0.9823$$

$$\left( R^2 = 0.9985, [\text{Fe}^{2+}] = 5 - 300 \mu\text{M}, \right)$$

where $F_0$ and $F$ are the fluorescence intensity at 380 nm in the absence and presence of Fe$^{3+}$ or Fe$^{2+}$, respectively. The limit of detection (LOD) was evaluated to be 2.86 μM for Fe$^{3+}$ and 2.06 μM for Fe$^{2+}$, which was calculated by $\text{LOD} = 3\sigma/k$, where $\sigma$ is the lowest signal standard deviation and $k$ is the slope of the linear calibration plot. The LOD is lower than the maximum allowable level (5.4 μM) for iron in drinking water permitted by the United States Environmental Protection Agency. It is worth mentioning that only a few articles have reported that carbon dots can detect two kinds of iron ions at the same time, which makes this work one of the few that can detect Fe$^{3+}$ and Fe$^{2+}$ simultaneously.

Besides, under the condition of coexisting with other metal ions, we have done the anti-interference test of Fe$^{3+}$ and Fe$^{2+}$, and the results are shown in Fig. 7. Compared with the blank control, the relative fluorescence intensity in the presence of Fe$^{3+}$ and Fe$^{2+}$ exhibit little change by the interfering ions, indicating that the interference of coexisting ions can be ignored. The above results indicate that DA-S,N-CDs have a reliable anti-interference ability and show high specificity toward Fe$^{3+}$ and Fe$^{2+}$.

Environmental water analysis

In order to evaluate the feasibility of DA-S,N-CDs in practical applications, different concentrations of Fe$^{3+}$ and Fe$^{2+}$ standard solutions were added into tap-water and lake-water samples, respectively, which were taken from Tiangong University. The detection results were summarized in Table 1. The floating range of spiked recoveries of Fe$^{3+}$ and Fe$^{2+}$ in actual water samples is 96.7 - 105.3%, and the relative standard deviation (RSD) is less than 2.64%, which confirms the accuracy of this method. Whether in tap water or lake water, the results obtained were satisfactory and reliable, which proves that the fluorescent...
material can be used for the determination of Fe³⁺ and Fe²⁺ in environmental water samples.

Conclusions

In the present work, dopamine functionalized carbon dots were successfully synthesized, which were covalently linked with S,N co-doped carbon dots through an EDC/NHS coupling reaction. The prepared carbon dots exhibited blue fluorescence under the excitation of a 365 nm UV lamp with good stability under harsh conditions. Under the conditions of coexistence with other interfering ions, DA-S,N-CDs exhibited high selectivity and sensitivity toward Fe³⁺ and Fe²⁺, which possess a wide linear correlation in the region of 5 – 200 μM for Fe³⁺ and 5 – 300 μM for Fe²⁺, as well as LOD of 2.86 μM (Fe³⁺) and 2.06 μM (Fe²⁺). Moreover, the practical feasibility of DA-S,N-CDs for simultaneously detecting Fe³⁺ and Fe²⁺ in aqueous media was verified and obtained satisfactory results. It also confirmed the potential application of the fluorescence analysis method based on DA-S,N-CD in the field of monitor the quality of environmental water.

Acknowledgements

The authors are grateful to Prof. Xihui Bian for help in revising this paper. This work was supported by Tianjin Key Science and Technology Program Foundation (19PTZWHZ00030, 19YFZCSF01110, 19YFSLQY00060).

Supporting Information

This material is available free of charge on the Web at http://www.jsac.or.jp/analsci/.

References

1. H. Nawaz, W. G. Tian, J. M. Zhang, R. Jia, Z. Y. Chen, and J. Zhang, ACS Appl. Mater. Interfaces, 2018, 10, 2114.
2. K. Saenwong, P. Nuengmatcha, P. Sricharoen, N. Limchoowong, and S. Chanthai, RSC Adv., 2018, 8, 10148.
3. M. W. Hentze, M. U. Muckenthaler, B. Galy, and C. Camachella, Cell, 2010, 142, 24.
4. S. H. K. Yap, K. K. Chan, G. Zhang, S. C. Tjin, and K. T. Yong, ACS Appl. Mater. Interfaces, 2019, 11, 28546.
5. S. X. Wang, X. M. Meng, and M. Z. Zhu, Tetrahedron Lett., 2011, 52, 302.
6. N. Narayanaswamy and T. Govindaraju, Sens. Actuators, B, 2012, 161, 304.
7. W. M. Xuan, R. Pan, Y. Y. Wei, Y. T. Cao, H. Q. Li, F. S. Liang, K. J. Liu, and W. Wang, Bioconjugate Chem., 2016, 27, 302.
8. C. J. Li, Y. Q. Wang, X. J. Zhang, X. L. Guo, X. X. Kang, L. B. Du, and Y. Liu, J. Colloid Interface Sci., 2018, 526, 487.
9. S. L. He, S. W. Qi, Z. C. Sun, G. S. Zhu, K. Zhang, and W. W. Chen, J. Mater. Sci., 2019, 54, 4297.
10. L. K. Mudashiru, A. C. Aplin, and B. R. Horrocks, Anal. Methods, 2011, 3, 927.
11. S. Lunvongs, M. Oshima, and S. Motomizu, Talanta, 2006, 68, 969.
12. J. Xu, P. Che, and Y. F. Ma, J. Chromatogr. A, 1996, 749, 287.
13. J. E. T. Andersen, Analyst, 2005, 130, 385.
14. X. P. Yan, M. J. Hendry, and R. Kerrich, Anal. Chem., 2000, 72, 1879.
15. Q. H. You, H. B. Huang, Z. X. Zhuang, X. R. Wang, and W. H. Chan, Bull. Korean Chem. Soc., 2016, 37, 1772.
16. F. J. Liu, Y. Jiang, C. Fan, L. Y. Zhang, Y. Hua, C. X. Zhang, N. Song, Y. J. Kong, and H. Wang, New J. Chem., 2018, 42, 9676.
17. J. Gao, M. M. Zhu, H. Huang, Y. Liu, and Z. H. Kang, Inorg. Chem. Front., 2017, 4, 1963.
18. K. Jiang, Y. H. Wang, C. Z. Cai, and H. W. Lin, Adv. Mater., 2018, 30, 1800783.
19. S. L. Hu, A. Trinchi, P. Atkin, and I. Cole, *Angew. Chem. Int. Ed.*, 2015, 54, 2970.
20. K. Jiang, Y. H. Wang, X. L. Gao, C. Z. Cai, and H. W. Lin, *Angew. Chem. Int. Ed.*, 2018, 57, 6216.
21. X. C. Sun and Y. Lei, *TrAC Trends Anal. Chem.*, 2017, 89, 163.
22. L. P. Lin, Y. X. Luo, P. Y. Tsai, J. J. Wang, and X. Chen, *TrAC Trends Anal. Chem.*, 2018, 103, 87.
23. S. F. Xu, S. Q. Ye, Y. H. Xu, F. F. Liu, Y. S. Zhou, Q. Yang, H. L. Peng, H. Xiong, and Z. Zhang, *Anal. Sci.*, 2020, 36, 353.
24. S. S. Wang, Y. Y. Wang, K. C. Yang, Y. Zhong, X. M. Yang, and Z. B. Chen, *Anal. Sci.*, 2017, 33, 1129.
25. Y. Park, J. Yoo, B. Lim, W. Kwon, and S. W. Rhee, *J. Mater. Chem. A*, 2016, 4, 11582.
26. S. J. Zhu, Y. B. Song, X. H. Zhao, J. R. Shao, J. H. Zhang, and B. Yang, *Nano Res.*, 2015, 8, 355.
27. S. J. Zhu, J. H. Zhang, S. J. Tang, C. Y. Qiao, L. Wang, H. Y. Wang, X. Liu, B. Li, Y. F. Li, W. L. Yu, X. F. Wang, H. C. Sun, and B. Yang, *Adv. Funct. Mater.*, 2012, 22, 4732.
28. Y. J. Ju, N. Li, S. G. Liu, Y. Z. Fan, Y. Ling, N. Xiao, H. Q. Luo, and N. B. Li, *Anal. Sci.*, 2019, 35, 147.
29. R. H. Guo, S. X. Zhou, Y. C. Li, X. H. Li, L. Z. Fan, and N. H. Voelcker, *ACS Appl. Mater. Interfaces*, 2015, 7, 23958.
30. J. Gao, M. X. Wu, D. H. Dai, Z. Cai, Y. Wang, W. H. Fang, Y. Wang, and Y. W. Yang, *Beilstein J. Org. Chem.*, 2019, 15, 1262.
31. N. T. N. Anh, A. D. Chowdury, and R. A. Doong, *Sens. Actuators, B*, 2017, 252, 1169.
32. A. D. Chowdury and R. A. Doong, *ACS Appl. Mater. Interfaces*, 2016, 8, 21002.
33. X. J. Xing, L. Huang, S. J. Zhao, J. F. Xiao, and M. H. Lan, *Microchem. J.*, 2020, 157, 105065.
34. S. Y. Liu, F. P. Shi, L. Chen, and X. G. Su, *Sens. Actuators, B*, 2014, 191, 246.
35. D. K. Dang, C. Sundaram, Y. L. T. Ngo, J. S. Chung, E. J. Kim, and S. H. Hur, *Sens. Actuators, B*, 2018, 255, 3284.
36. T. Liu, Z. W. Cui, J. Zhou, Y. Wang, and Z. G. Zou, *Nanoscale Res. Lett.*, 2017, 12, 375.
37. J. Zhang, J. B. Wang, J. P. Fu, X. C. Fu, W. Gan, and H. Q. Hao, *J. Nanopart. Res.*, 2018, 20, 41.
38. Z. Fu, M. H. Yao, X. Q. Niu, and F. L. Cui, *Sens. Actuators, B*, 2016, 226, 486.
39. X. Miao, X. L. Yan, D. Qu, D. B. Li, F. F. Tao, and Z. C. Sun, *ACS Appl. Mater. Interfaces*, 2017, 9, 18549.
40. J. J. Zhao, L. M. Zhao, C. Q. Lan, and S. L. Zhao, *Sens. Actuators, B*, 2016, 223, 246.
41. M. Lu and L. Zhou, *Mater. Sci. Eng., C*, 2019, 101, 352.
42. S. Arreguin, P. Nelson, S. Padway, M. Shirazi, and C. Pierpont, *J. Inorg. Biochem.*, 2009, 103, 87.
43. F. L. Zu, F. Y. Yan, Z. J. Bai, J. X. Xu, Y. Y. Wang, Y. C. Huang, and X. G. Zhou, *Microchim. Acta*, 2017, 184, 1899.
44. A. Shrivastava and V. Gupta, *Chron. Young Sci.*, 2011, 2, 21.
45. A. Iqbal, Y. J. Tian, X. D. Wang, D. Y. Gong, Y. L. Guo, K. Iqbal, Z. P. Wang, W. S. Liu, and W. W. Qin, *Sens. Actuators, B*, 2016, 237, 408.
46. L. J. Mohammed and K. M. Omer, *Sci. Rep.*, 2020, 10, 3028.
47. X. Gong, H. Y. Zhang, N. Jiang, L. Wang, and G. Wang, *Microchem. J.*, 2019, 145, 435.