Organic & Biomolecular Chemistry

PAPER

View Article Online
View Journal | View Issue

Cite this: *Org. Biomol. Chem.*, 2019, **17**, 9251

Thiophenol detection using an AIE fluorescent probe through self-assembly with TPE-based glycoclusters†

Lei Dong,[a] Guo-Rong Chen,[b] Xiao-Peng He*[b] and Sébastien Vidal*[a]

Received 3rd September 2019,
Accepted 25th September 2019

DOI: 10.1039/c9ob01937e

rsc.li/obc

We describe a novel green-emitting tetraphenylethylene-dicyanomethylene-4*H*-pyran (TPE-DCM) based fluorescent probe (**TD-1**). Conjugating TPE and DCM moieties allowed **TD-1** to display high selectivity for thiophenol with excellent AIE properties in aqueous solution. Nevertheless, the poor water solubility of the hydrophobic structure resulted in a weak and unstable emission intensity. The non-covalent self-assembly of **TD-1** with a TPE glycocluster (TPE2S) led to a largely improved water solubility producing a reliable and stable sensing system. The corresponding glyco-probe could sensitively detect exogenous thiophenol concentrations in PBS buffer or environmental water samples.

Introduction

Thiophenol (PhSH), as an important organosulfur compound, is the simplest aromatic thiol and an essential starting material extensively applied in the organic synthesis of agrochemicals, pharmaceuticals and dyes.[1–3] Different from aliphatic thiols including cysteine (Cys), homocysteine (Hcy) and glutathione (GSH), which play important roles in biological systems,[4] thiophenol and its derivatives are pollutants with high toxicity to the environment. The toxicity of thiophenol is high in fish and mice with a median lethal dose (LC50) from 0.01 to 0.04 mM or as low as 46.2 mg kg^{-1}.[5,6] Long-term exposure to thiophenol liquid or vapor in water or soil is detrimental to human health due to the triggering of a series of severe systemic injuries, such as damage to the central nervous system, muscle weakness and even death.[7] Therefore, a convenient, rapid, accurate, sensitive and selective method is necessary for the detection of thiophenol pollution in the environment.

Compared with traditional methods such as HPLC, UV-vis and chromatography-mass analysis,[8,9] fluorescence spectroscopy is widely applied for thiophenol detection due to its high sensitivity, simple processing and low detection limits. A reactive moiety is typically introduced into a fluorophore scaffold to quench its fluorescence, and then a reaction with thiophenol triggers a cascade that would release the moiety enhancing the fluorescence. 2,4-Dinitrobenzene was extensively used as the reactive group since when this group is conjugated through sulfonyl ether,[4,10–12] sulphonamide[13–16] and sulfonate[17–19] bonds to a fluorophore, it could lead to the production of fluorogenic probes for the selective detection of thiophenol over other aliphatic thiols.[20] The electron-deficient 2,4-dinitrobenzene suppresses the fluorescence emission of organic dyes by an intramolecular charge transfer (ICT)[21,22] or a photo-induced electron transfer (PET) mechanism.[13,18,23] Recently, fluorescent probes for thiophenol detection have been developed with high sensitivity, selectivity and a short response time. For example, a squaraine-based NIR probe for the detection of thiophenol through colorimetric and "off–on" fluorometric response with high water solubility was developed through conjugation with glucose.[19] A dicyanomethylene-4*H*-pyran (DCM) based probe with a large Stokes shift (159 nm) and low detection limit (8.3 nM) was also constructed.[24] However, most fluorescent probes exhibited low reactivity and fluorescence intensity due to their poor water solubility and the notorious ACQ (aggregation-induced quenching) effect.

Aggregation induced emission (AIE) is widely used in the design of organic fluorescent probes to overcome ACQ in aqueous solutions[25–27] based on the pioneering studies of Prof. Ben Zhong Tang who coined the concept of AIE in 2001.[28] Tetraphenylethene (TPE) has attracted much attention due to its readily available structural modification and functionalization as well as its AIE properties and photostability.[29–31] However, the wavelength of blue emission largely overlaps the autoluminescence of biomolecules. As a

[a]*Institut de Chimie et Biochimie Moléculaires et Supramoléculaires, Laboratoire de Chimie Organique 2-Glycochimie, UMR 5246, CNRS and Université Claude Bernard Lyon 1, Université de Lyon, 1 Rue Victor Grignard, F-69622 Villeurbanne, France. E-mail: sebastien.vidal@univ-lyon1.fr*

[b]*Key Laboratory for Advanced Materials and Joint International Research Laboratory of Precision Chemistry and Molecular Engineering, Feringa Nobel Prize Scientist Joint Research Center, School of Chemistry and Molecular Engineering, East China University of Science and Technology, 130 Meilong Rd., Shanghai 200237, PR China. E-mail: xphe@ecust.edu.cn*

†Electronic supplementary information (ESI) available. See DOI: 10.1039/c9ob01937e

consequence, fluorophores with a longer emission wavelength, such as dicyanomethylene-4*H*-pyran (DCM), have been applied for the design of fluorescent probes.[32–34]

We described herein the conjugation through a C=C double bond between the DCM and TPE fluorophores to obtain a novel TPE-DCM fluorophore with yellow fluorescence emission as well as AIE properties for the detection of thiophenol. After functionalizing the electron-poor 2,4-dinitrobenzene on the fluorophore, the restricted AIE effect and blocked ICT effect were observed to "turn-off" the fluorescence in aqueous solution. However, the poor water solubility of the hydrophobic structure of **TD-1** led to a weak and unstable fluorescence emission in aqueous solution, due to the precipitation of probes from the solution. Tetraphenylethene (TPE) based glycoclusters (TPE2S) have an outstanding ability to improve the water solubility, fluorescence stability and sensitivity of **TD-1** for thiophenol detection after self-assembly (Scheme 1). Therefore, the self-assembled glyco-probe was explored to quantify the concentration of thiophenol in real water samples (Rhône River and Saône River, Lyon).

Results and discussion

Chemical synthesis

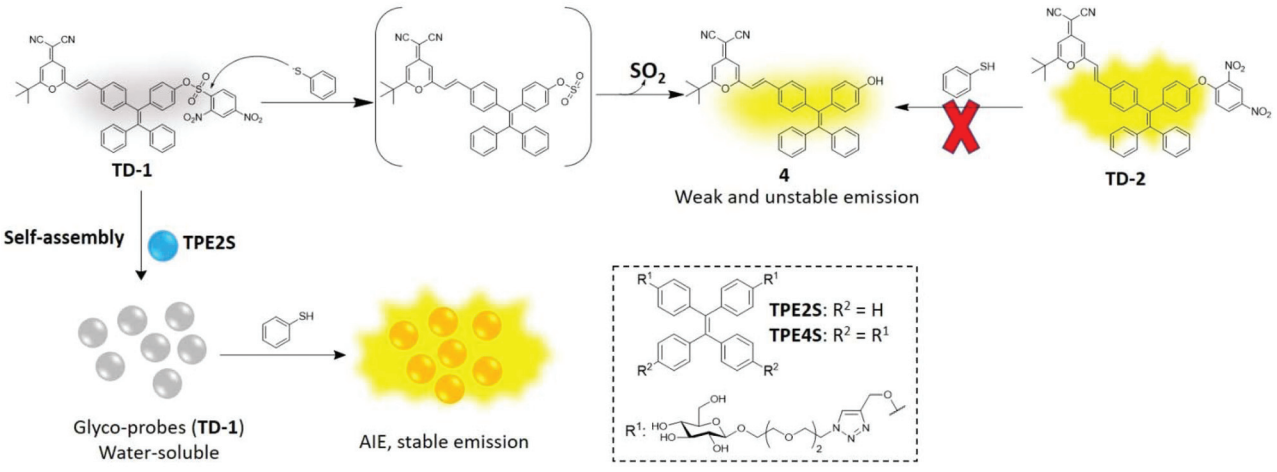
The synthesis procedures of the novel TPE-DCM based fluorescent probe and TPE-based glycoclusters are shown in Scheme S1 of the ESI.† The synthesis of the conjugate started from the known TPE-aldehyde **1**[35] and DCM analogue **2**[36] through an aldolisation/crotonization sequence to afford TPE-DCM **3**. Demethylation of the phenol group with BBr_3 produced fluorescent probe **4**. 2,4-Dinitrobenzene was functionalized on phenol **4** to obtain two fluorescent probes **TD-1** and **TD-2** with different molecular architectures. TPE-based glycoclusters functionalized by two monosaccharides (TPE2S) were synthesized from dipropargyl TPE compound **S5**. Through CuAAC cycloaddition, acetyl protected azide-glucose was conjugated on the TPE core. Then TPE-based glycocluster **5** was deprotected in aqueous MeOH solution with Et_3N to obtain the glycocluster TPE2S. TPE-based glycoclusters (TPE4S) were synthesized according to previous literature.[37]

Response mechanism

The performance of two probes for thiophenol detection was evaluated. The fluorescence of **TD-2** remained unquenched and displayed only a limited fluorescence emission decrease after incubation with thiophenol (Fig. S1, ESI†). In contrast, **TD-1** displayed a much weaker initial fluorescence emission (Φ = 0.003), and an obvious fluorescence enhancement at 570 nm (Φ = 0.083, λ_{ex} = 480 nm) was observed probably due to the recovery of the ICT after reaction with thiophenol, along with a slight red shift of the absorption peak (Fig. S1, ESI†). The mechanism of fluorescence enhancement was proposed as follows: the negative thiophenol (PhS^-) ion was nucleophilic enough to be added to the highly electrophilic *ipso*-carbon atom of the 2,4-dinitrophenyl group. Cleavage of the S–O bond and the release of SO_2 generated phenol derivative **4** (Scheme 1). Mass spectrometry analysis indicated that **TD-1** after responding to thiophenol generated phenol derivative **4** (*m*/*z* 573.3). In contrast, the incubation of **TD-2** with thiophenol did not produce phenol **4** and hence this compound was not further studied herein (Fig. S2a, ESI†). To further prove that 2,4-dinitrobenzene was the leaving group, HPLC analysis was performed to identify **TD-1**, **4** and thiophenol. After incubating a sub-stoichiometric amount of thiophenol with the probe, the corresponding peaks of **TD-1** and **4** were observed. Then **TD-1** was completely converted into compound **4** when using excess thiophenol (Fig. S2b, ESI†).

Spectral properties of TD-1

The sensing performances of **TD-1** (10 μM) for thiophenol in a phosphate buffered saline (PBS) solution (10 mM with 10% THF) were measured. The fluorescence enhancement of **TD-1**



Scheme 1 TPE-DCM based fluorescent probe (**TD-1**) and its glyco-probes self-assembled with TPE-based glycoclusters (TPE2S) for thiophenol (PhSH) detection.

was measured after the addition of an excess of thiophenol at different pH values. We found that the fluorescence intensity kept increasing at pH 3–7 and reached equilibrium above pH 7, which suggests that thiophenolate (PhS^-) requires higher pH values to activate fluorescence. As a result, probe **TD-1** is capable of sensing thiophenol in neutral or basic solutions (Fig. 1a).

Then, we measured the AIE properties of **TD-1** after the reaction with thiophenol (50 μM) in PBS solution (pH 7.3) with different ratios of THF. The stronger emission of **TD-1** in 50% PBS solution indicated that 2,4-dinitrobenzene could not quench the fluorescence completely probably due to the electron rich moieties on the TPE moiety. The weakening of the fluorescence intensity for **TD-1** upon addition of PBS into THF was caused by the ACQ effect. We speculate that the bulky 2,4-dinitrobenzene group restricted the rotation of TPE-DCM, hence blocking the AIE effect. Thereby, the fluorescence of **TD-1** was switched-off by the ICT effect and ACQ effect in aqueous buffer. The fluorescence emission was then largely enhanced by the AIE effect after incubating with thiophenol (leading to fluorophore **4**) when increasing the PBS ratio from 50% to 80% (Fig. 1b). Phenol **4** recovered the AIE properties, and hence displayed an enhanced emission intensity. Furthermore, the addition of PBS buffer led to a decrease of fluorescence emission, suggesting an insufficient water solubility of the probe to function in a pure aqueous medium. We supposed that the aggregation of fluorophore **4** resulted in precipitation and a strong decrease of the soluble material leading to a decreased signal.

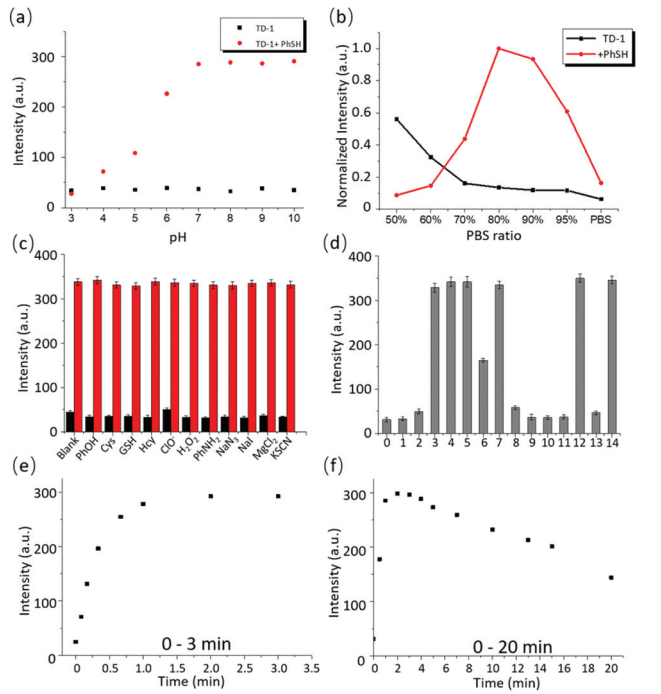


Fig. 1 (a) Fluorescence variations of **TD-1** (10 μM) before and after responding to thiophenol (100 μM) after 3 min in PBS buffer (pH 7.3) with 10% THF (pH was adjusted with 0.6 M HCl or 2 M NaOH). (b) ACQ and AIE effects influenced **TD-1** response to thiophenol (100 μM) with the addition of PBS buffer (pH 7.3) in THF after 10 min. (c) The fluorescence variation of **TD-1** (10 μM) response to potential interfering species (50 μM) without (black bar) or with (red bar) thiophenol (100 μM) after 3 min. (d) **TD-1** (10 μM) response to aliphatic and aromatic thiols (100 μM) after 3 min. Reagents: (0) Blank, (1) 1,2-ethanedithiol, (2) cyclohexanethiol, (3) *m*-$NH_2C_6H_4SH$, (4) *p*-$NH_2C_6H_4SH$, (5) *p*-$MeOC_6H_4SH$, (6) *p*-$NO_2C_6H_4SH$, (7) *p*-MeC_6H_4SH, (8) 2-methyl-2-propanethiol, (9) pyrimidinethione, (10) α-thioglycerol, (11) 2-mercaptobenzo-thiazole, (12) 4,4′-thiobisbenzenethiol, (13) 2-aminoethanethiol hydrochloride, and (14) PhSH. (e) Fluorescence intensity increase of **TD-1** (10 μM) incubated with thiophenol (100 μM) after 3 min. (f) Fluorescence intensity decrease of **TD-1** (10 μM) incubated with thiophenol (100 μM) after 3–20 min due to probe separation from solution.

To test the selectivity of **TD-1** toward thiophenol and the possible interference from other analytes, the probe was incubated with a number of potential interfering species, aliphatic thiols and thiophenol derivatives. The fluorescence signal increased only in the presence of aromatic thiols (Fig. 1d). Other species did not react with the probe and did not interfere with the sensing system when co-incubated with thiophenol (Fig. 1c).

The time-dependent fluorescence enhancement was measured by incubating thiophenol with **TD-1** in PBS buffer. Incubation of excess analyte was required to ensure that all **TD-1** probes are transformed into fluorophore **4**. After the addition of thiophenol, the fluorescence intensity displayed a remarkable enhancement to maximum in 2–3 min (Fig. 1e). However, the fluorescence intensity was not stable and decreased slowly when stirring the solution for more than 3 min (Fig. 1f). We hypothesized that the poor water solubility of compound **4** would lead to aggregated species that would separate from the solution, hence decreasing the fluorescence signal intensity. In our previous studies, TPE-based glycoclusters were found to have excellent water solubility and a similar structure to **TD-1**. For improving the water solubility of **TD-1**, we self-assembled the TPE-based glycoclusters[37] (TPE2S and TPE4S) and **TD-1** to construct a glyco-probe, which was used to detect thiophenol (Scheme 1). We speculated that a better aqueous dispersibility could stabilize the fluorescence emission signal, allowing us to decrease the ratio of THF in PBS buffer.

Spectral properties of glyco-probe

To improve the water solubility and fluorescence stability of **TD-1**, we self-assembled TPE2S with **TD-1** and explored the fluorescence changes after incubating with thiophenol. The results indicated that TPE2S could enhance the fluorescence intensity probably due to an improvement of water solubility (Fig. 2a). Therefore, we compared the fluorescence enhancement efficiency of the two TPE-based glycoclusters (TPE2S and TPE4S) after self-assembly with **TD-1** (Fig. 2b). The TPE2S assembly led to a higher fluorescence intensity than that of the TPE4S assembly with probe **TD-1**, enabling thiophenol sensing in PBS aqueous buffer without the addition of THF. As a result, the TPE2S assembly was used for further investigation. To prove the assembly process, the molecular sizes of TPE2S, **TD-1** and the glyco-probe were measured by dynamic light scattering (DLS, Fig. 2c). TPE2S (blue) and **TD-1** (green) in the aggregated state displayed a large diameter

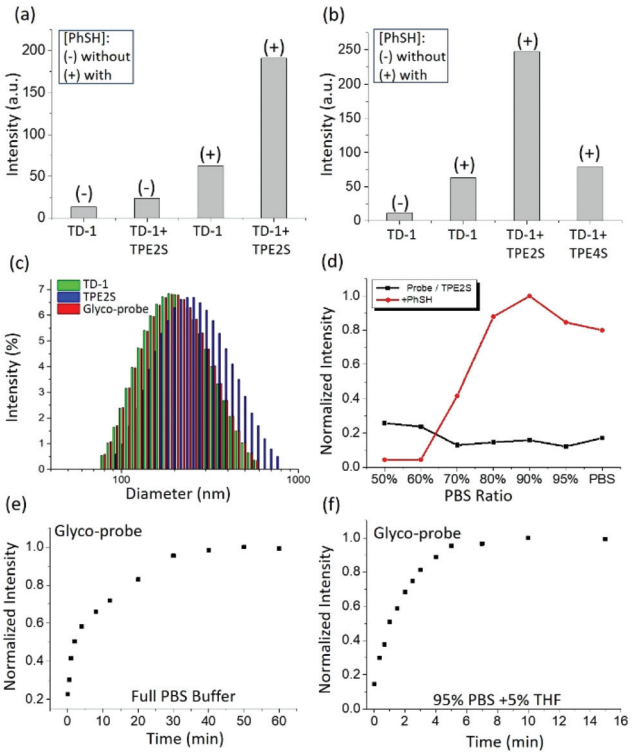


Fig. 2 (a) Fluorescence changes of **TD-1** (10 μM) and glyco-probe after conjugation with TPE2S (10 mM) improved the fluorescence intensity for thiophenol (100 μM) detection in 95% PBS (pH 7.3, 10 mM) with THF. (b) Fluorescence enhancement abilities of TPE2S and TPE4S (10 mM) conjugating **TD-1** (10 μM) and detecting thiophenol (100 μM) in PBS buffer (pH 7.3, 10 mM). (c) DLS measurements of **TD-1**, TPE2S and the glyco-probe. (d) AIE effects influenced the glyco-probe response to thiophenol (100 μM) with PBS buffer (pH 7.3, 10 mM) in THF after 5 min. (e) and (f) Response time of the glyco-probe to thiophenol (100 μM) in PBS buffer or PBS buffer with 5% THF.

(200–300 nm), which indicated that the two molecules were in the aggregated state. The size of the assembled glyco-probe (red) was smaller than that of TPE2S and similar to the size of **TD-1**. We supposed that the molecules of **TD-1** were dispersed and inserted in the hydrophobic core of a glyco-ball conjugated from several TPE2S, and therefore the size of the glyco-probe was similar to that of the aggregated **TD-1**. The optimal ratio between TPE2S and **TD-1** was also investigated. A large excess of TPE2S was required for achieving an optimal response to thiophenol with a 1 : 100 molar ratio of **TD-1** to TPE2S (Fig. S7, ESI†).

Next, we investigated several basic fluorescence properties of the resulting glyco-probes for thiophenol detection. Compared with the AIE properties of **TD-1**, the glyco-probe displayed a better fluorescence increase with a varying PBS percentage of 50%–90% in THF. Importantly, the glyco-probe also displayed a satisfying emission intensity in complete PBS buffer (Fig. 2d). This result suggests that the glyco-probe with excellent water solubility avoided the excessive intermolecular aggregation of compound **4**, and hence was more suitable for thiophenol sensing in aqueous solution. Then, we compared the rate of reactivity of the glyco-probe for thiophenol in PBS buffer (Fig. 2e) or a 95% PBS buffer with 5% THF (Fig. 2f). The glyco-probe displayed a rapidly increased fluorescence signal after incubating with thiophenol, and a stable fluorescence intensity when the probe responded completely over time. These results indicated that the conjugation of TPE2S with **TD-1** improved the water solubility to prevent the probe precipitation. The longer response time (30 min) in PBS buffer in comparison to the mixture of PBS/THF (95 : 5) can be rationalized by the better solubility of thiophenol in THF, leading to a faster reaction time of 5 min.

PhSH quantification

To evaluate the sensitivity of the glyco-probe to thiophenol, the fluorescence signals at 560 nm of **TD-1** and glyco-probe were measured with the addition of thiophenol in PBS/THF (95 : 5) solution. **TD-1** exhibited an unstable fluorescence intensity probably due to the poor water solubility (Fig. 3a and b). In contrast, the glyco-probe showed a linear fluorescence enhancement with increasing thiophenol concentration (Fig. 3c). The linearity was verified from 0 to 14 μM, thus demonstrating that the glyco-probe could be used to detect thiophenol quantitatively (Fig. 3d). After adding more than 14 μM thiophenol, the fluorescence intensity slowly reached a maximal emission intensity probably due to a complete conversion of the probes to compound **4**. The limit of detection (LOD) was calculated to be as low as 9.4 nM, which suggests that the probe could be applied for the determination of trace thiophenol in aqueous solution.

Next, the glyco-probe was evaluated to quantify thiophenol in two real water samples from the Saône River and the Rhône River (Lyon, France). The glyco-probe provided homogeneous fluorescence enhancements upon addition of thiophenol

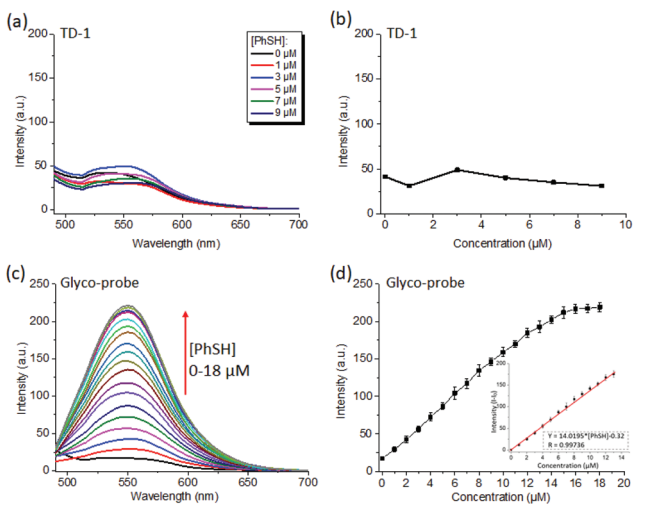


Fig. 3 (a) and (b) Unstable fluorescence variation of **TD-1** (10 μM) response to thiophenol (0–9 μM). (c) Fluorescence enhancement and (d) the linear relationship of glyco-probe response to thiophenol (0–18 μM) in 95% PBS buffer (pH 7.3, 10 mM) with THF after 5 min (λ_{ex} = 480 nm).

Table 1 Analysis of thiophenol concentrations in real water samples

Sample	PhSH spiked (μM)	PhSH recovered (μM)	Recovery (%)
Saône River water	0	Not detected	0
	1.00	0.97 + 0.09	97
	2.00	1.84 + 0.12	92
	3.00	2.86 + 0.11	95
Rhône River water	0	Not detected	0
	1.00	1.05 + 0.06	105
	2.00	2.06 + 0.08	103
	3.00	3.07 + 0.14	102

Conditions: The glyco-probe self-assembled from **TD-1** (10 μM) and TPE2S (10 mM) responded to thiophenol in 95% water samples with THF after 5 min.

(0–3 μM). The fluorescence increase ($I - I_0$) was similar to the results measured in PBS solution (Fig. S10, ESI†). We have also injected exogenously known concentrations of thiophenol (0–3 μM) into the real water samples (Table 1). The fluorescence signal recovery was always found to be near 100% from the expected intensities through analysis using the titration curve. Therefore, the self-assembled glyco-probe between TPE2S and **TD-1** could be used for thiophenol quantification in real water samples.

Conclusion

In summary, the detection of thiophenol is of interest as this toxic compound can pollute drinking water or water used for recreation. The design of a new fluorescent probe with a reactive 2,4-dinitrosulfonate moiety was achieved by the conjugation between a TPE AIEgen and a DCM core. The resulting probe could react with thiophenol to release a phenol group on the TPE-DCM moiety, thus enhancing the fluorescence emission at 570 nm. Nevertheless, the poor water solubility of the resulting phenol did not allow stable measurements. We thus proposed a self-assembly strategy with water-soluble TPE-based glycoclusters, leading to a new glyco-probe for the quantitative and selective detection of thiophenol in PBS solution as well as environmental water samples.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The authors are thankful for the financial support from the Natural Science Foundation of China (No. 21788102, 91853201, 21722801 and 21776078) and the Shanghai Municipal Science and Technology Major Project (No. 2018SHZDZX03) and the China Scholarship Council for a PhD stipend to L. D. (No. 201606740066).

Notes and references

1 A. Eychmüller and A. L. Rogach, *Pure Appl. Chem.*, 2000, **72**, 179–188.
2 J. C. Love, L. A. Estroff, J. K. Kriebel, R. G. Nuzzo and G. M. Whitesides, *Chem. Rev.*, 2005, **105**, 1103–1170.
3 I. Rahman and W. MacNee, *Am. J. Physiol.: Lung Cell. Mol. Physiol.*, 1999, **277**, L1067–L1088.
4 (*a*) M. Zhang, Y. Wu, S. Zhang, H. Zhu, Q. Wu, L. Jiao and E. Hao, *Chem. Commun.*, 2012, **48**, 8925–8927; (*b*) L. Yang, Y. Su, Y. Geng, Y. Zhang, X. Ren, L. He and X. Song, *ACS Sens.*, 2018, **3**, 1863–1869.
5 R. Munday, *Free Radical Biol. Med.*, 1989, **7**, 659–673.
6 T. P. Hell and R. C. Lindsay, *J. Environ. Sci. Health, Part B*, 1989, **24**, 349–360.
7 P. Amrolia, S. G. Sullivan, A. Stern and R. Munday, *J. Appl. Toxicol.*, 1989, **9**, 113–118.
8 J.-X. He, T. Akao and T. Tani, *Chem. Pharm. Bull.*, 2002, **50**, 1233–1237.
9 T. Wang, E. Chamberlain, H. Shi, C. D. Adams and Y. Ma, *Int. J. Environ. Anal. Chem.*, 2010, **90**, 948–961.
10 X. Liu, F. Qi, Y. Su, W. Chen, L. Yang and X. Song, *J. Mater. Chem. C*, 2016, **4**, 4320–4326.
11 X. Xie, M. Li, F. Tang, Y. Li, L. Zhang, X. Jiao, X. Wang and B. Tang, *Anal. Chem.*, 2017, **89**, 3015–3020.
12 G. Yin, T. Yu, T. Niu, P. Yin, H. Chen, Y. Zhang, H. Li and S. Yao, *RSC Adv.*, 2017, **7**, 46148–46154.
13 D. Kand, P. K. Mishra, T. Saha, M. Lahiri and P. Talukdar, *Analyst*, 2012, **137**, 3921–3924.
14 Y. Yue, F. Huo, Y. Zhang, J. Chao, R. Martínez-Máñez and C. Yin, *Anal. Chem.*, 2016, **88**, 10499–10503.
15 J. Li, C. F. Zhang, S. H. Yang, W. C. Yang and G. F. Yang, *Anal. Chem.*, 2014, **86**, 3037–3042.
16 S. Pagidi, N. K. Kalluvettukuzhy and P. Thilagar, *Langmuir*, 2018, **34**, 8170–8177.
17 D. Kand, P. S. Mandal, T. Saha and P. Talukdar, *RSC Adv.*, 2014, **4**, 59579–59586.
18 H. W. Liu, X. B. Zhang, J. Zhang, Q. Q. Wang, X. X. Hu, P. Wang and W. Tan, *Anal. Chem.*, 2015, **87**, 8896–8903.
19 L. Xiong, J. Ma, Y. Huang, Z. Wang and Z. Lu, *ACS Sens.*, 2017, **2**, 599–605.
20 (*a*) W. Jiang, Q. Fu, H. Fan, J. Ho and W. Wang, *Angew. Chem., Int. Ed.*, 2007, **46**, 8445–8448; (*b*) H. Guo, Y. Jing, X. Yuan, S. Ji, J. Zhao, X. Li and Y. Kan, *Org. Biomol. Chem.*, 2011, **9**, 3844–3853.
21 D. G. Khandare, M. Banerjee, R. Gupta, N. Kumar, A. Ganguly, D. Singh and A. Chatterjee, *RSC Adv.*, 2016, **6**, 52790–52797.
22 D. Yu, Q. Zhai, S. Yang and G. Feng, *Anal. Methods*, 2015, **7**, 7534–7539.
23 W. Jiang, Y. Cao, Y. Liu and W. Wang, *Chem. Commun.*, 2010, **46**, 1944–1946.
24 M. Zhang, T. Leng, Y. Shen and C. Wang, *Analyst*, 2018, **143**, 756–760.
25 Z. Guo, A. Shao and W.-H. Zhu, *J. Mater. Chem. C*, 2016, **4**, 2640–2646.

26 X. Wang, Z. Gao, J. Zhu, Z. Gao and F. Wang, *Polym. Chem.*, 2016, **7**, 5217–5220.
27 J. Mei, N. L. Leung, R. T. Kwok, J. W. Lam and B. Z. Tang, *Chem. Rev.*, 2015, **115**, 11718–11940.
28 J. Luo, Z. Xie, J. W. Lam, L. Cheng, H. Chen, C. Qiu, H. S. Kwok, X. Zhan, Y. Liu and D. Zhu, *Chem. Commun.*, 2001, 1740–1741.
29 R. Hu, N. L. Leung and B. Z. Tang, *Chem. Soc. Rev.*, 2014, **43**, 4494–4562.
30 J. Li, N. Kwon, Y. Jeong, S. Lee, G. Kim and J. Yoon, *ACS Appl. Mater. Interfaces*, 2018, **10**, 12150–12154.
31 H. Lin, H. Yang, S. Huang, F. Wang, D. M. Wang, B. Liu, Y. D. Tang and C. J. Zhang, *ACS Appl. Mater. Interfaces*, 2018, **10**, 12173–12180.
32 W. T. Dou, Y. Zhang, Y. Lv, J. Wu, Y. Zang, C. Tan, J. Li, G. R. Chen and X. P. He, *Chem. Commun.*, 2016, **52**, 3821–3824.
33 D. K. Ji, Y. Zhang, Y. Zang, J. Li, G. R. Chen, X. P. He and H. Tian, *Adv. Mater.*, 2016, **28**, 9356–9363.
34 Y. Liu, D. K. Ji, L. Dong, N. Galanos, Y. Zang, J. Li, S. Vidal and X. P. He, *Chem. Commun.*, 2017, **53**, 11937–11940.
35 D. Jana, S. Boxi, P. P. Parui and B. K. Ghorai, *Org. Biomol. Chem.*, 2015, **13**, 10663–10674.
36 G. Zhao, Y. Zhu, S. Guang, F. Ke and H. Xu, *New J. Chem.*, 2018, **42**, 555–563.
37 M. Donnier-Marechal, S. Abdullayev, M. Bauduin, Y. Pascal, M. Q. Fu, X. P. He, E. Gillon, A. Imberty, E. Kipnis, R. Dessein and S. Vidal, *Org. Biomol. Chem.*, 2018, **16**, 8804–8809.