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Water-soluble fluorescent conjugated polymer-enzyme hybrid system for the determination of both hydroquinone and hydrogen peroxide

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ABSTRACT

In this paper, a sensitive and simple detecting system was developed for quantitative analysis of both hydroquinone (H_2Q) and hydrogen peroxide (H_2O_2), based on the successful combination of horse radish peroxidase (HRP) and water-soluble conjugate fluorescence polymers $PPESO_3$. In the presence of HRP and H_2O_2, H_2Q could be oxidized to 1,4-benzoquinone (BQ), an intermediate, which plays the main role in the enhanced quenching of the photoluminescence (PL) intensity of $PPESO_3$. The quenching PL intensity of $PPESO_3$ (I_0/I) was proportional to the concentration of H_2Q and H_2O_2 in the range of 1.0×10^{-6} to 2.0×10^{-3} mol/L ($R^2 = 0.996$) and 6.0×10^{-6} to 2.0×10^{-3} mol/L ($R^2 = 0.999$), respectively. The detection limit for H_2Q and H_2O_2 was 5.0×10^{-7} mol/L and 1.0×10^{-6} mol/L, respectively. The present fluorescence quenching method was successfully applied for the determination of H_2Q in the lake water, rainwater, tap-water and chemical plant wastewater samples. Compared with previous reports, the fluorescence quenching approach described in this work is simple and rapid with high sensitivity, which has a potential application for detecting various analytes which can be translated into quinone.

1. Introduction

Phenol compounds such as hydroquinone (H_2Q) are among the major components of pollutants produced by industrial wastewater and agricultural activities. H_2Q is a potentially carcinogenic substance, which causes severe effects on the central nervous system [1]. H_2Q has extremely detrimental effects on humans through oral, dermal, or respiratory tracks and thus represent a serious environmental problems and health hazards [2,3]. Due to the high toxicity and persistence of H_2Q in the environment, the sensitive and fast determination of H_2Q becomes an important subject. Many methods have been reported for the determination of H_2Q, including gas chromatography [4], chemiluminescence [5], amperometric detection and flow injection analysis [6]. However, compared with these methods, optical biosensors based on absorbance and fluorescence detection are more advanced because of several advantages [7,8]. For example, the response mechanism of optical detection is very classic, simple and reliable, and the reactions taking place in sample solutions are not disturbed because optical transducers do not change the component in the solutions. Recently, optical sensors based on fluorescence quenching have been paid more attention. Wu et al. detected phenol optically using an oxygen-sensitive luminescent dye [7]. Wang et al. used a quantum dots-enzyme system to detect phenolic compounds and H_2O_2 [9]. Zhu et al. used molecularly imprinted polymer microspheres prepared through precipitation polymerization for H_2Q recognition [1].

In recent years, conjugated polymers (CPs) have been intensively studied for chemical and biological sensor applications owing to their superior signal amplification and superquenching compared to quantum dots and small molecule dyes [10]. These amplification and superquenching properties are due to the conjugated polymer backbone [11], on which one single quencher molecule can cause an effective and fast quenching. Thanks to these amplification and superquenching properties, CPs show some interesting and useful properties i.e. strong light absorption, strong fluorescence, electroactivity, and good transport properties for charge carriers and excitons [12]. So far, various analytes, such as metal ions [13], small molecules [14], enzymes [15], proteins [16], DNA [17] and RNA [18] have been detected in aqueous solution or on solid substrates. Since CPs quenched by phenol have not been reported previously and indeed might have wide potential application in the development of phenol sensor, we developed a H_2Q sensor based on CPs ($PPESO_3$) quenching.

Based on the enzymatic reaction product of H_2Q can efficiently quench the photoluminescence (PL) intensity of $PPESO_3$, we established a sensitive and simple H_2Q sensor. Meanwhile, the $PPESO_3$ PL intensity can be quenched with the addition of H_2O_2 in the presence of H_2Q, thus detection of H_2O_2 can also be achieved. The detection limits for H_2Q compounds (5.0×10^{-7} mol/L) are low enough to detect the common levels of phenolic pollutants in wastewater and lower than the U.S. Environmental Protection Agency

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estimated wastewater discharge limit of 0.5 mg/L (at 10^{-6} mol/L level) [19].

2. Experiment

2.1. Chemicals

1,4-Diethynylbenzene and Tetrakis(triPHenylPHosphine)palladium ($(PPh_3)_4$-Pd) were purchased from Aldrich Chemical Co. and Hangzhou Kaida Metal Catalyst & Compounds Co. Ltd. (Hangzhou, China), respectively. 2,5-Diiodohydroquinone, dioxane (Tianjin Guangfu Institute of elaborate chemical industry) and 1,3-propanesultone (J&K Chemica) were used as received. Horse radish peroxidase (HRP) was obtained from Sino-American Biotechnology Co. Ltd. H_2Q and benzoquinone (BQ) were purchased from Tianjin Guangfu Fine Chemical Research Institute. All the other chemicals, including CuI, Na_2HPO_4, NaH_2PO_4, H_2O_2 methanol, acetone, ether and DMF were obtained from Beijing Chemical Co. Ltd. Stock solutions of 0.1 mol/L H_2O_2, benzoquinone, hydroquinone, and HRP were freshly prepared daily. All chemicals used were of analytical reagent grade without further purification. The water used in all experiments had a resistivity of 18 MΩ/cm. All the water used in the experiments was deaerated by purging with N_2 for 30 min.

2.2. Instrumentation

All fluorescence measurements were carried out in a 1 cm pathlength quartz cuvette at ambient temperature with a Shimadzu RF-5301 spectrometer. In all optical experiments, the excitation wavelength was 400 nm and the fluorescence intensity referred to the maximum emission of $PPESO_3$ at 520 nm.

2.3. Experimental method

The synthesis of $PPESO_3$ was according to the previous paper [20]. For BQ quenching experiment, 1 mL of 2.0 μmol/L $PPESO_3$ in PBS (pH 7.0) solution and 1 mL of BQ solution with different concentrations from 2.0 μmol/L to 6.0 mmol/L were added to a quartz cuvette. The final volume of every sample is 2.0 mL and the final concentration of $PPESO_3$ is 1.0 μmol/L. Then the mixture was shaken evenly and the spectral information was recorded by spectrofluorophotometer. For the assay of H_2Q, the conjugated polyelectrolyte $PPESO_3$ was diluted to 1.0 μmol/L with PBS (pH 7.0), followed by the addition of 2.0 μg/mL HRP and 3.0 mmol/L H_2O_2. Then, various amounts of H_2Q were added, with the ultimate concentration of H_2Q covered a relatively wide range (1.0×10^{-6} to 2.0×10^{-3} mol/L). The resulting solution (2.0 mL) was shaken evenly kept at room temperature for 14 min before recording the spectral information by spectrofluorophotometer. The method of detecting H_2O_2 was same as that of H_2Q. As H_2Q is easily oxidized under environmental conditions, so deoxidation water were used in each H_2Q detecting experiment. For real samples detection, the system can be used to determine both H_2Q and BQ. Combination of the system and the hybrid without H_2O_2 and/or HRP would be useful to detect H_2Q and BQ individually. The molecular structures of BQ, H_2Q and $PPESO_3$ are shown in Scheme S1 (in supplementary material).

For real samples detection, we chose four kinds of water samples (lake water, rainwater, chemical plant wastewater and tap-water) and all the water samples were diluted 10 times with 0.02 mol/L PBS (pH 7.0). The diluted water samples were added with different concentrations of H_2Q (0.1 mmol/L, 1.0 mmol/L, 2.0 mmol/L) to prepare the spiked samples. Real samples detection was carried out using the procedure described above.

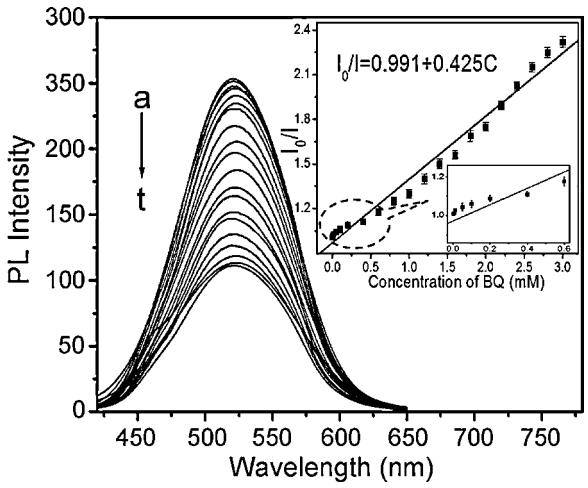


Fig. 1. The PL spectra of 1.0 μmol/L $PPESO_3$ in different concentrations of BQ. a–u represent the concentrations of BQ of 0.001, 0.006, 0.01, 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, 2.8 and 3.0 mmol/L, respectively. The inset shows the linear relationship between I_0/I and concentration of BQ. The excitation wavelength was 400 nm.

3. Results and discussion

3.1. Superquenching of water-soluble $PPESO_3$ by 1,4-benzoquinone

1,4-benzoquinone (BQ) as a classic electron acceptor could shuttle the electron from the conduction band to the valence band of the excited luminescence material, resulting in the quenching of PL intensity [21]. In aqueous solution, $PPESO_3$ exhibited a strong green emission at around 520 nm. When BQ was added to $PPESO_3$ PBS solution, even at very low concentration, the fluorescence of $PPESO_3$ was quenched remarkably. The quenching was enhanced gradually with the increasing quantity of BQ. And the efficiency of fluorescence quenching can be evaluated quantitatively by the Stern–Volmer equation [22].

$$\frac{I_0}{I} = 1 + K_{SV}[Q]$$

where I and I_0 are the fluorescence intensities with and without the quencher, respectively, [Q] is the quencher concentration, and K_{SV} represents the Stern–Volmer constant. From the slope of the Stern–Volmer plot (Fig. 1 inset), K_{SV} is calculated to be 4.25×10^2 L/mol, which shows that BQ is an effective quencher by accepting electron from $PPESO_3$. A linear relationship between I_0/I and concentration of BQ was gained from 1.0×10^{-6} to 3.0×10^{-3} mol/L BQ. The PL intensity of $PPESO_3$ was quenched more than 95% by 8.0 mmol/L BQ (not shown in the figure).

The relationship between the reaction time and PL intensity of $PPESO_3$ was shown in Fig. 2. It can be seen that upon addition of BQ, the PL intensity of $PPESO_3$ quenched immediately due to electron transfer quickly from $PPESO_3$ to BQ, then the fluorescence intensity remained nearly unchanged with further increase in reaction time, which indicated that it was very rapid to reach equilibrium for the interaction between BQ and $PPESO_3$.

To distinguish between static and dynamic mechanisms, temperature dependence of Stern–Volmer equation should be addressed. Fig. S1 (in supplementary material) shows the Stern–Volmer plot for fluorescence quenching system of $PPESO_3$-BQ at two different temperatures. The K_{SV} is 1.10×10^3 L/mol at 313 K while the K_{SV} is 4.25×10^2 L/mol at 288 K. The results show that the Stern–Volmer quenching constant is in proportion to

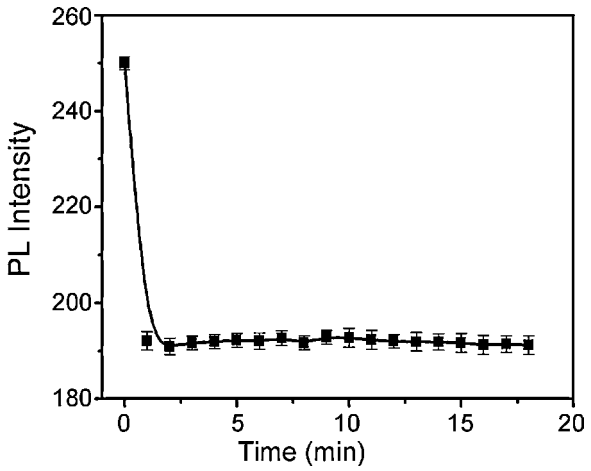


Fig. 2. The relationship between PL intensity of 1.0 μmol/L $PPESO_3$ and the reaction time in the presence of 1.0 mmol/L BQ.

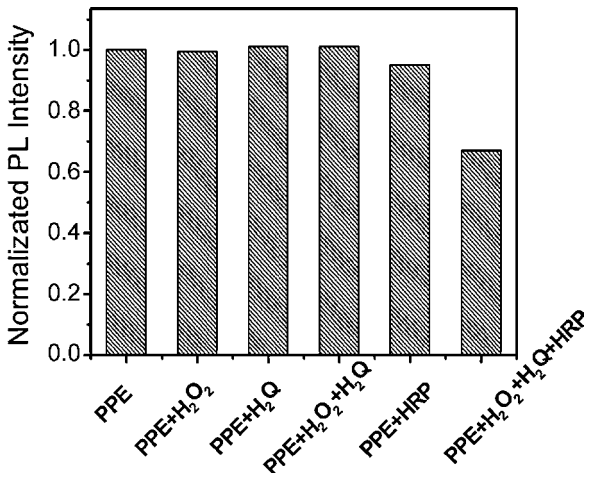
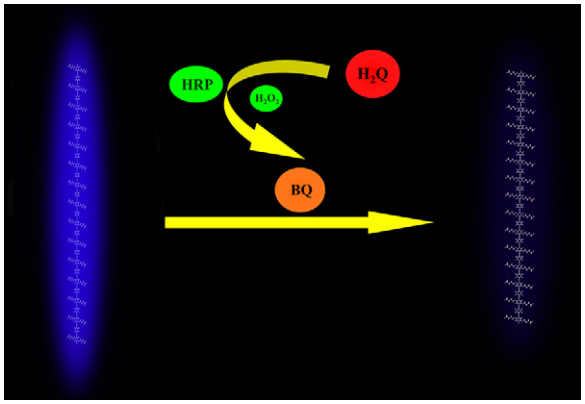


Fig. 3. The effect of HRP as catalyst on the oxidation of H_2Q in the absence/presence of HRP/H_2O_2 in 1.0 μmol/L $PPESO_3$.

temperature, which suggests that dynamic mechanisms should be responsible for the fluorescence quenching of $PPESO_3$ by BQ [23].

3.2. Quenching by hydroquinone in the presence of HRP and H_2O_2

H_2Q can be oxidized into the form of BQ with the catalyzed oxidation action of HRP and H_2O_2 [9]. Taking into account the results in above section, BQ as a quencher could cause a significant quenching of the PL intensity of $PPESO_3$. It is supposed that the quantification of H_2Q can be achieved by measuring the fluorescence quenching of $PPESO_3$ in the presence of HRP and H_2O_2 (Scheme 1). In order to testify the detecting scheme, several control experiments have been carried out. $PPESO_3$ mixed with H_2O_2, H_2Q and HRP separately and the mixtures of two or three were investigated and the results were shown in Fig. 3. It can be seen that neither H_2O_2 nor H_2Q can quench the PL intensity of $PPESO_3$. The influence of sole HRP on the PL intensity of $PPESO_3$ was also very slight which can be ignored. The PL quenching of $PPESO_3$ could not be observed even when both H_2O_2 and H_2Q exist (Fig. 3). It implied that H_2Q cannot be oxidized into BQ without the presence of HRP in the system, thus PL quenching of $PPESO_3$ by BQ would not happen. However, upon sequential addition of HRP, H_2O_2 and H_2Q into an aqueous solution of $PPESO_3$, fluorescence superquenching can be observed remarkably. These results indicate that under catalyzed action of HRP, BQ which is intermediate produced in the oxidation of H_2Q could induce fluorescence quenching of $PPESO_3$. The formation of BQ is essential to quench the fluorescence emission of $PPESO_3$.



Scheme 1. Schematic illustration of $PPESO_3$ fluorescence quenching by H_2Q in the presence of H_2O_2 and HRP.

These results were consistent with Scheme 1 proposed above which affords the feasible and easy route for detection of H_2Q.

3.3. Optimization of experimental parameters for H_2Q detection

In this study, the relationship between the quenching effect and the incubation time was investigated. Fig. 4 shows the fluorescence quenching efficiency of H_2Q on $PPESO_3$ with different incubation time. When 1.0 mmol/L H_2Q was added to the system of 2.0 μg/mL HRP, 1.0 mmol/L H_2O_2 in 0.02 mol/L PBS buffer (pH 7.0), the PL intensity of $PPESO_3$ decreased gradually from 220.7 to 102.8 with the incubation time changed from 0 to 14 min. When incubation time was longer than 14 min, the quenching effect reaches a plain and remained unchanged. The results proved that the processes of catalyzed oxidation of H_2Q to BQ and $PPESO_3$ quenched by BQ finished in 14 min. In this study, the incubation time of 14 min is adopted.

Effect of HRP concentration on the PL intensity of $PPESO_3$ was investigated at three different concentrations of H_2Q and H_2O_2 (1.0, 2.0, 5.0 mmol/L) (Fig. 5). The concentration of H_2Q was equal to that of H_2O_2 because the same mole of them was consumed in the reaction [9]. We found that the quenching effect was enhanced by increasing quantity of H_2Q and H_2O_2. Taking 2.0 μg/mL HRP for

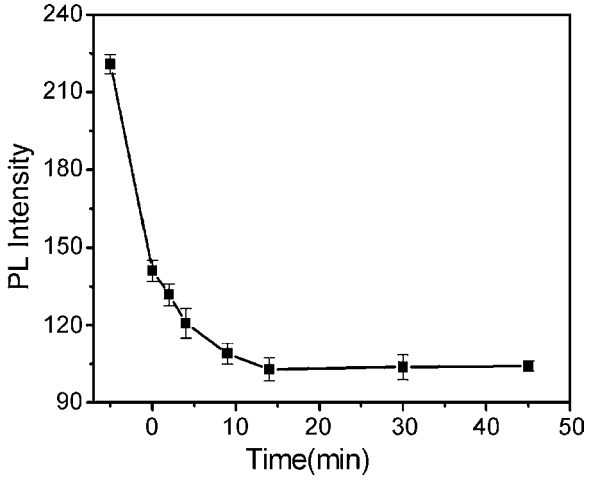


Fig. 4. The relationship between the PL intensity of 1.0 μmol/L $PPESO_3$ and the incubation time in the presence of 1.0 mmol/L H_2O_2 and 2.0 μg/mL HRP with the addition of 1.0 mmol/L H_2Q.

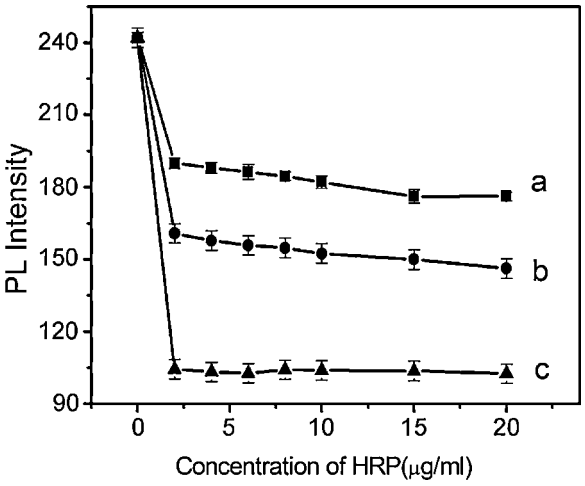


Fig. 5. Effect of different HRP concentrations on the fluorescence quenching of 1.0 μmol/L $PPESO_3$ by H_2Q. With the addition of 1.0 mmol/L H_2Q and 1.0 mmol/L H_2O_2 (a); with the addition of 2.0 mmol/L H_2Q and 2.0 mmol/L H_2O_2 (b); with the addition of 5.0 mmol/L H_2Q and 5.0 mmol/L H_2O_2(c).

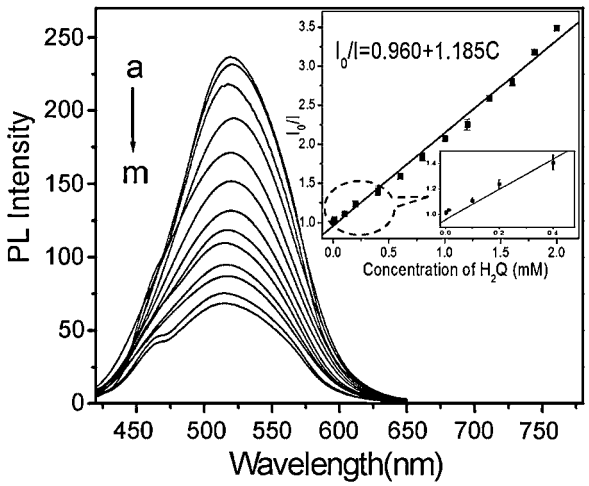


Fig. 6. The effect of H_2Q concentration on the PL intensity of 1.0 μmol/L $PPESO_3$ in the presence of 3.0 mmol/L H_2O_2 and 2.0 μg/mL HRP. a–n represent the concentrations of H_2Q of 0.001, 0.01, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0 mmol/L, respectively. The inset shows the linear relationship between I_0/I and the concentration of H_2Q.

example, the PL intensity of $PPESO_3$ has only 20% decrease when the concentration of H_2Q is 1.0 mmol/L. While it decreased to 160.8 and 104.4 from 240.0 when increasing the concentration of H_2Q to 2.0 mmol/L and 5.0 mmol/L respectively. On the other hand, the PL intensity of $PPESO_3$ decreased dramatically after adding a small amount of HRP and maintained the same when the concentration of HRP reached 2.0 μg/mL for a given concentration of H_2Q and H_2O_2. These results indicate that the quantity of HRP did not depend on the concentration of H_2Q and H_2O_2. Thus, 2.0 μg/mL HRP is adopted in following experiments.

The pH value can influence the HRP activity and stability of the conjugation via electrostatic interaction. So the effect of the pH of buffer solution was studied in this work. We investigated the quenching effect with different concentrations of H_2Q in PBS with pH from 4.0 to 9.0. $PPESO_3$ fluorescence intensity at 520 nm was recorded and the results were shown in Fig. S2 (in supplementary material). It can be seen that the I_0/I at 520 nm increased gradually with the change of pH value from 5.0 to 7.0. The maximal I_0/I which means the largest quenching appeared at pH 4.0 and 7.0. The inset graph shows that the fluorescence emission peak of $PPESO_3$ at pH 7.0 is more symmetrical distribution than that of at pH 4.0. Considering the bioactivity of HRP and symmetrical fluorescence emission peak of $PPESO_3$, we chose PBS of pH 7.0 in this study.

3.4. Detection of H_2Q via the HRP–H_2O_2–$PPESO_3$ system

The quenching effect of H_2Q concentration on the PL intensity of $PPESO_3$ in HRP–H_2O_2 system was further investigated under the optimized condition. Fig. 6 shows the fluorescence spectra of $PPESO_3$ in the presence of 3.0 mmol/L H_2O_2, 2.0 μg/mL HRP and a series of different H_2Q concentrations. It can be seen that the PL intensity of $PPESO_3$ decreased gradually upon increasing concentration of H_2Q, while no obvious changes of spectral widths. We illustrate the corresponding plot showing a linear relationship between I_0/I and H_2Q concentrations in the range of 1.0×10^{-6} to 2.0×10^{-3} mol/L with a correlation coefficient $R^2 = 0.996$. The linear regression equation is $I_0/I = 0.960 + 1.185\,C\,(H_2Q)$ (mmol/L) and the detection limit (3() for H_2Q was found to be 5.0×10^{-7} mol/L, which was better than the reported electrochemical sensor of 1.0×10^{-6} mol/L [1], and had the similar performance as CdTe quantum dots-enzyme hybrid system of 5.0×10^{-7} mol/L [9]. The detection limits for H_2Q are low enough to detect the common levels of phenolic pollutants in wastewater and lower than the U.S. Environmental Protection Agency estimated wastewater discharge limit of 0.5 mg/L (at 10^{-6} mol/L level) [19].

3.5. Detection of H_2O_2 via the HRP–H_2Q–$PPESO_3$ system

According to the conclusion above, H_2Q can be quantitatively analyzed in the HRP–H_2O_2–$PPESO_3$ system. Similarly, H_2O_2 can also be detected by quenching $PPESO_3$ in the presence of HRP and H_2Q, so a detection method for H_2O_2 can be developed using the HRP–H_2Q–$PPESO_3$ system. The detection of H_2O_2 was carried out by adding different concentrations of H_2O_2 to $PPESO_3$ aqueous solution in the presence of 3.0 mmol/L H_2Q and 2.0 μg mL/L HRP in 20 mmol/L PBS buffer (pH 7.0). The results indicated that successive addition of H_2O_2 resulted in remarkable fluorescence quenching of $PPESO_3$ (Fig. 7). The 5.0 mmol/L H_2O_2 exhibits good quenching effects on the PL intensity of $PPESO_3$ with the quenching extent above 90% (not shown in the figure). The inset in Fig. 7 shows the relationship between I_0/I and the concentration of H_2O_2. A linear calibration plot was obtained in the range of

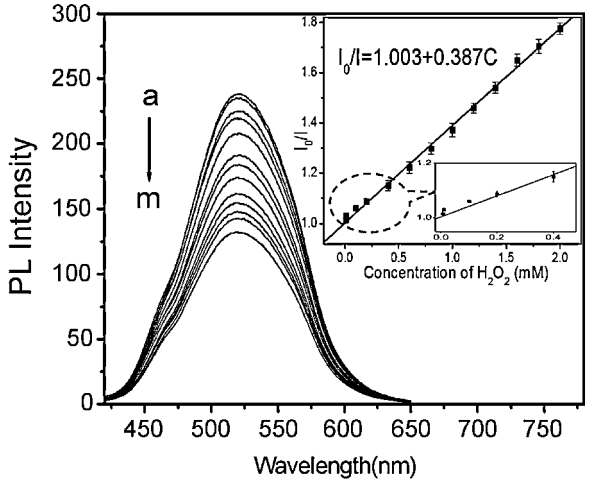


Fig. 7. The effect of H_2O_2 concentration on the PL intensity of 1.0 μmol/L $PPESO_3$ in the presence of 3.0 mmol/L H_2Q and 2.0 μg/mL HRP. a–n represent the concentrations of H_2O_2 of 0.006, 0.01, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0 mmol/L, respectively. The inset shows the relationship between I_0/I and the concentration of H_2O_2.

Table 1
The interference of coexisting ions on the fluorescence quenching of 1.0 μmol/L $PPESO_3$ by H_2Q in the HRP/H_2O_2 system.

Coexisting substance	Tolerable concentration ratios	$\Delta I/I$ (%, $n=3$)[a]
Na^+	180	2.9
K^+	200	0.58
Zn^{2+}	60	3.1
Pb^{2+}	80	−0.92
Cd^{2+}	50	0.44
Al^{3+}	100	−4.8
NO_3^-	120	3.0
Cl^-	200	0.60
Glucose	200	1.08
Benzoic acid	100	−4.7
Sodium benzoate	150	4.92

[a] $\Delta I = I_0 - I$, where I_0 and I are the fluorescence intensities of $PPESO_3$–HRP–H_2O_2–H_2Q system in the absence and presence of interfering species.

6.0×10^{-6} to 2.0×10^{-3} mol/L, the linear regression equation is $I_0/I = 1.003 + 0.387C$ (H_2O_2) (mmol/L) with a correlation coefficient $R^2 = 0.999$. The detection limit (3() for H_2O_2 is 1.0×10^{-6} mol/L, which is close to the early reported (5.0×10^{-7} mol/L) [24]. According to the experiment result above, it is confirmed that the high sensitivity of the proposed H_2O_2 assay is mainly derived from the amplified fluorescence quenching of water-soluble conjugated polymers. And this quenching method may be extensively used to detect biological system with H_2O_2 producing process in the future.

3.6. Interference study

The detection selectivity of $PPESO_3$–HRP–H_2O_2 system for H_2Q was further evaluated with various coexistence ions added. Interference investigation was carried out at a H_2Q concentration of 10^{-4} mol/L with various coexistence substrates added. The ions which usually exist in the wastewater and the water-soluble glucose, benzoic acid and sodium benzoate with chemical structures similar to H_2Q were chosen as the interference ions. The tolerance of each coexistence substrate was taken as the highest concentration yielding a relative error less than ±5%. As shown in Table 1, the results showed that the tolerable concentration ratios of coexisting substance to 10^{-4} mol/L H_2Q was over 180-fold for Na^+, 200-fold for K^+, Cl^-, 100-fold for Al^{3+}; 60-fold for Zn^{2+}, 80-fold for Pb^{2+}, 50-fold for Cd^{2+}, 120-fold for NO_3^-, 200-fold for glucose, 100-fold for benzoic acid and 150-fold for sodium benzoate. It can be seen that the proposed fluorometric method displays a high selectivity for the determination of H_2Q.

Table 2
Analytical results of H_2Q in real water samples.

Samples	Added (mmol/L)	Found (mmol/L)[a]	Recovery (%)
Lake water	0.100	0.104 ± 0.029	104
	1.000	1.003 ± 0.010	100
	2.000	2.073 ± 0.022	104
Rain water	0.100	0.178 ± 0.044	108
	1.000	1.039 ± 0.023	104
	2.000	2.011 ± 0.025	101
Chemical plant wastewater	0.100	0.956 ± 0.048	96
	1.000	0.940 ± 0.023	94
	2.000	1.967 ± 0.015	99
Tap-water	0.100	0.109 ± 0.027	109
	1.000	1.070 ± 0.035	107
	2.000	2.056 ± 0.030	103

[a] Values are mean of three replicates (±S.D.).

3.7. Real samples detection

In order to evaluate the feasibility of the method in the determination of H_2Q in real samples, four kinds of water samples (lake water, rainwater, chemical plant wastewater and tap-water) were analyzed in this study. The results were listed in Table 2. It can be seen that the coexistent substances did not interfere with the determination of H_2Q, the results showed satisfactory recoveries in the range of 94–109%, which indicates that the HRP–H_2O_2 system permits the quantitative determination of H_2Q in the presence of some coexistent substances.

4. Conclusions

In this work, we developed a sensitive and facile fluorescent sensor for detecting H_2Q and H_2O_2 based on the superquenching of fluorescent conjugated polymer. We could successfully detect H_2Q and H_2O_2 with the detection limit of 5.0×10^{-7} mol/L and 1.0×10^{-6} mol/L in the linear range of 1.0×10^{-6} to 2.0×10^{-3} mol/L and 6.0×10^{-6} to 2.0×10^{-3} mol/L respectively. The sensitivity for the detection of H_2Q in this study was much higher than that of previous optical methods. It is the first report regarding water-soluble fluorescent conjugated polymer employed for the detection of phenol compounds under the HRP catalyzed action. This method may provide a basis for the future development of fluorescent conjugated polymer sensor, which may widely be used in detecting H_2Q or H_2O_2 industrial water, environmental analysis, pharmaceuticals, food industry, and so on. Furthermore, with the advantages of simplicity, rapidness, highly efficiency quenching, non-toxicity and easy operation, the fluorescent conjugated polymer has great potential in the development of sensors for widely detecting various analytes with quinone producing process.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.talanta.2011.08.053.

References

[1] X.W. Kan, Q. Zhao, Z. Zhang, Z.L. Wang, J.J. Zhu, Talanta 75 (2008) 22–26.
[2] J. Abdullah, M. Ahmad, L.Y. Heng, N. Karuppiah, H. Sidek, Talanta 70 (2006) 527–532.
[3] L. Gianfreda, G. Iamarino, R. Scelza, M.A. Rao, Biocatal. Biotransform. 24 (2006) 177–187.
[4] C. Sharma, S. Mahanty, S. Kumar, N.J. Rao, Talanta 44 (1997) 1911–1918.
[5] S.L. Fan, L.K. Zhang, J.M. Lin, Talanta 68 (2006) 646–652.
[6] M.E. Rueda, L.A. Sarabia, A. Herrero, M.C. Ortiz, Anal. Chim. Acta 479 (2003) 173–184.
[7] X.J. Wu, Martin, M.F. Choi, X.M. Wu, Analyst 129 (2004) 1143–1149.
[8] P. Paranjpe, S. Dutta, M. Karve, S. Padhye, R. Narayanaswamy, Anal. Biochem. 294 (2001) 102–107.
[9] J.P. Yuan, W.W. Guo, E.K. Wang, Anal. Chem. 80 (2008) 1141–1145.
[10] T.M. Swager, Acc. Chem. Res. 31 (1998) 201–207.
[11] S. Kumaraswamy, T. Bergstedt, X.B. Shi, F. Rininsland, S. Kushon, W.S. Xia, K. Ley, K. Achyuthan, D. McBranch, D. Whitten, Proc. Natl. Acad. Sci. U.S.A. 101 (2004) 7511–7515.
[12] C.Y. Tan, M.R. Pinto, K.S. Schanze, Chem. Commun. (2002) 446–447.
[13] T. Zhang, H.L. Fan, Q.H. Jin, Talanta 81 (2010) 95–99.
[14] R.Y. Zhan, Z. Fang, B. Li, Anal. Chem. 82 (2010) 1326–1333.
[15] Y. Liu, K.S. Schanze, Anal. Chem. 81 (2009) 231–239.
[16] Y.Y. Wang, B. Liu, Langmuir 25 (2009) 12787–12793.
[17] K. Lee, L.K. Povlich, J. Kim, Adv. Func. Mater. 17 (2007) 2580–2587.

[18] B. Liu, S. Baudrey, L. Jaeger, G.C. Bazan, J. Am. Chem. Soc. 126 (2004) 4076–4077.
[19] E. Giti, H. Mehdi, G. Nasser, Int. Biodeterior. Biodegrad. 56 (2005) 231–235.
[20] W.C. Dou, X.G. Su, Luminescence 24 (2009) 45–49.
[21] C. Burda, T.C. Green, S. Link, M.A. El-Sayed, J. Phys. Chem. B 103 (1999) 1783–1788.
[22] J.R. Lakowicz, Principles of Fluorescence Spectroscopy, Plenum Press, NewYork, 1983.
[23] A. Kathiravan, M. Chandramohan, R. Renganathan, S. Sekar, J. Mol. Struct. 919 (2009) 210–214.
[24] T. Zhang, H.L. Fan, G.L. Liu, J. Jiang, J.G. Zhou, Q.H. Jin, Chem. Commun (2008) 5414–5416.