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The water-soluble bicyclic 2-pyridone-based fluorescent probe for fast and selective detection of hypochlorite

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ABSTRACT

As a strong oxidizer, hypochlorite (ClO^-) are widely employed as bleaching agents and disinfectants. Determination of ClO^- is required to ensure bactericidal effects and avoid hazards caused by excessive residual chlorine. Herein, the derivative bicyclic 2-pyridone, namely DHIP-Py, was prepared successfully to establish a new ClO^--quantitative method. The probe exhibits excellent ClO^- selectivity over other ROS and anions/cations, high sensitivity (LOD = 1.32 μmol/L), fast response (<5 s), and wide-pH tolerance (pH 4∼10). Benefit from its good water solubility, DHIP-Py is well suited for water sample analysis and has been successfully applied to detect ClO^- in real-world food and environmental samples, including tap water, bottled water and river water. The detection results were essentially identical to that of obtained from traditional DPD method. Moreover, visual detection of ClO^- *via* filter paper-based solid sensor and imaging of ClO^- in *Escherichia coli* were also achieved by DHIP-Py. These satisfactory results demonstrate that this bicyclic 2-pyridone-based hypochlorite probe is a promising free chlorine chemosensor with great potential for analytical applications.

Hypochlorite (ClO^-) has been widely used in our daily life and industry. For instance, as a bleaching agent for household cleaning, paper or textiles industry, or as a disinfectant for water treatment, environmental sterilization and food processing [1–3]. The concentration of residual chlorine in the public water-supply system, pools, foods, tableware surfaces, *etc.* must meet the national and World Health Organization (WHO) standards [4,5]. Low levels of residual chlorine cannot counteract microbial contamination and proliferation, while excessive ClO^- endangers human health, leading to inflammation, tissue damage, and various diseases [6,7]. Therefore, accurately quantify ClO^- is indispensable for water safety, food quality, environmental monitoring and disease prevention.

Traditional analytical methods, such as iodometric titration, electrochemistry [8,9], colorimetry [10,11], have been well established to detect ClO^-. Recently, fluorometric analysis has attracted more and more interest due to its high sensitivity, good selectivity and high spatial-temporal resolution for non-invasive bioimaging [12]. In general, hypochlorite fluorescent probes could be constructed by matching elaborately selected fluorophores with ClO^--specific recognition sites [13–16]. To date, inspired by the strong oxidizability of ClO^-, numerous representative recognition mechanisms have been reported (Scheme S1 in Supporting information), including ring-opening of rhodamine [17–19], cleavage of C=C or C=N [20–23], oxidation of *p*-methoxyphenol [24], S/Se/Te [25–28], dimethylthiocarbamate (DMTC) [29], boric acid/borate [30,31], *etc.* However, most of them suffer from modest selectivity, poor water solubility and complex multistep synthesis. Thus, development of new hypochlorite probes to address these issues is still of great necessity.

From previous report, carbon dots (CDs) prepared from citric acid (CA) and ethylenediamine derivatives were developed as ClO^- sensors [32–35]. Interestingly, bicyclic 2-pyridones were proved to contribute to the molecular state photoluminescence of such CDs [36]. Therefore, we put forward the hypothesis that bicyclic 2-pyridone scaffold might respond to ClO^- (Scheme 1a). As part of our research in fluorescent probes [37–40], we have introduced

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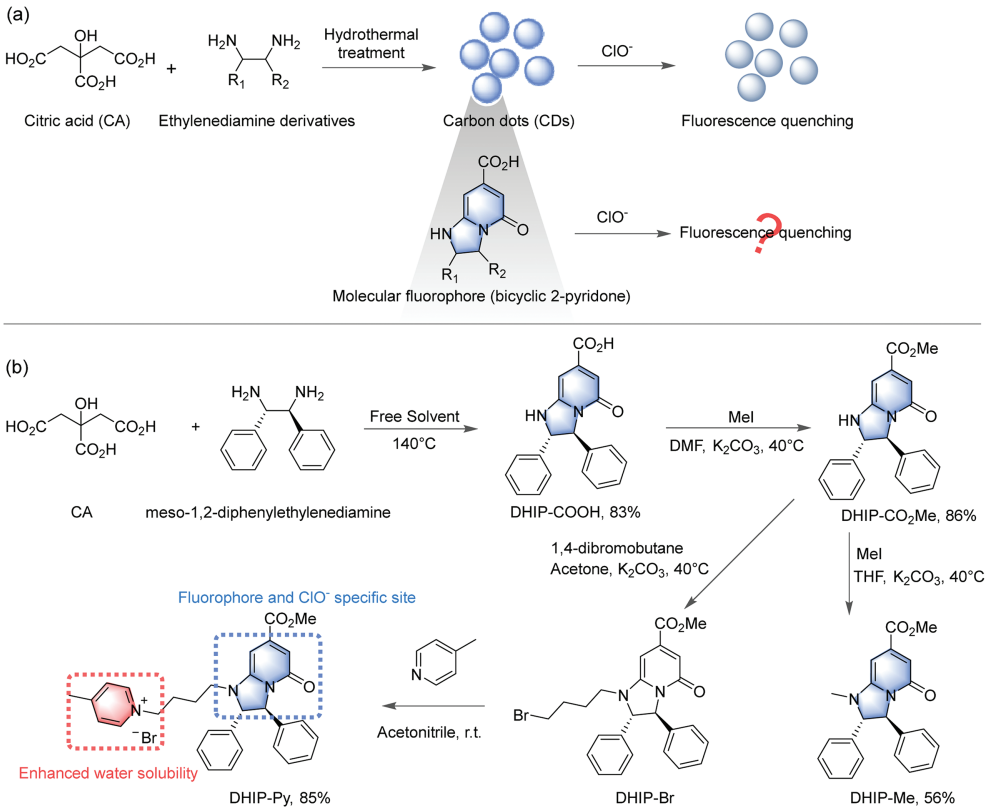

Scheme 1. (a) The molecular scaffold of ClO^- probes inspired by ClO^--responsive carbon dots synthesized from CA and ethylenediamine derivatives; (b) The synthetic scheme and structures of DHIP series probes.

a solvent-free, catalyst-free and high-yield synthesis approach for bicyclic 2-pyridones, and demonstrated their potential in endoplasmic reticulum imaging [41]. To verify the above hypotheses and expand the application scope of bicyclic 2-pyridones, we set out to synthesize a series of compounds bearing this fluorophore (Scheme 1b) and study their signaling behavior to ClO^-. Our findings might introduce a novel strategy for designing reaction-based ClO^- fluorescent probes and provide some insights for clarifying the recognition mechanism of CDs on ClO^-.

First, DHIP-CO_2H was readily synthesized from CA and *meso*–1,2-diphenylethylenediamine in 83% yield [41]. The bright fluorescence of DHIP-CO_2H can be quenched by ClO^-, but disturbed by most metal ions (Fig. S1 in Supporting information), implying DHIP-CO_2H is not a good candidate for ClO^- sensing. Next, we tried to prepare and test its derivatives. Esterification of DHIP-CO_2H with CH_3I yields DHIP-CO_2Me. Further nucleophilic substitution at secondary amine with CH_3I or 1,4-dibromobutane give DHIP-Me and DHIP-Br, respectively. DHIP-Br reacts with 4-methylpyridine to form DHIP-Py, in which a pyridinium moiety was introduced to increase water solubility. The optical data are summarized in Fig. S2 and Table S1 (Supporting information). It can be seen that the absorption peak of the DHIP series fluorophores is around 380 nm, and the emission peak is in the range of 450~490 nm. They all exhibited high molar extinction coefficients ($5.4 \times 10^3 \sim 12.5 \times 10^3$ $(mol/L)^{-1}$ cm^{-1}) and good fluorescence quantum yields (QY, 19%~92%). The flexible alkyl chain in DHIP-Py may contribute to the non-radiative decay of the excited state energy, leading to a compromised QY. It is worth noting that DHIP-Py obeys Beer's law at concentrations up to 0.5 mmol/L in PBS (Fig. S3 in Supporting information), so it has sufficient water solubility for quantitative applications in practical water samples,

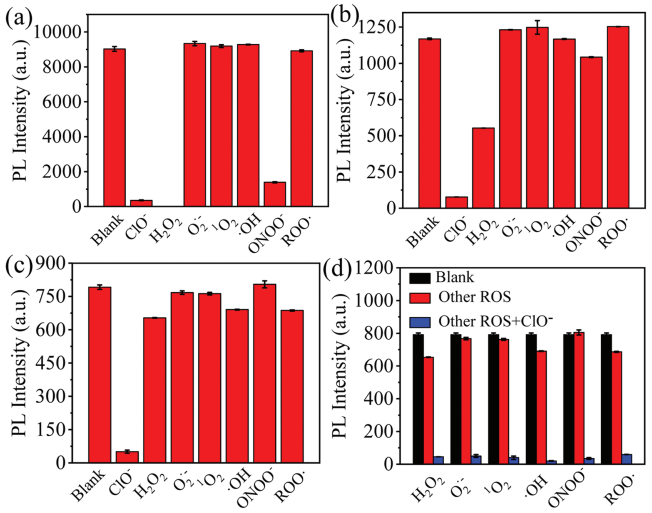

Fig. 1. Fluorescence responses of (a) DHIP-CO_2Me, (b) DHIP-Me and (c) DHIP-Py toward different ROS (100 μmol/L, 10 equiv.). (d) Fluorescence responses of DHIP-Py toward ClO^- in the presence of other ROS.

which is superior to most current detection methods that require the participation of organic solvents.

Then, the optical responses of these three new DHIP fluorophores to ClO^- were examed. 10 equiv. ROS species, including ClO^-, H_2O_2, $O_2^{\bullet-}$, $^1O_2$, $^\bullet OH$, $ONOO^-$ and *tert*–butyl hydroperoxide (TBHP, ^{t}BuOOH, ROO$^\bullet$) were added to 10 μmol/L probe solution, respectively. As shown in Fig. 1a and Fig. S5a (Supporting information), $ONOO^-$, H_2O_2 and ClO^- quenched the fluorescence of

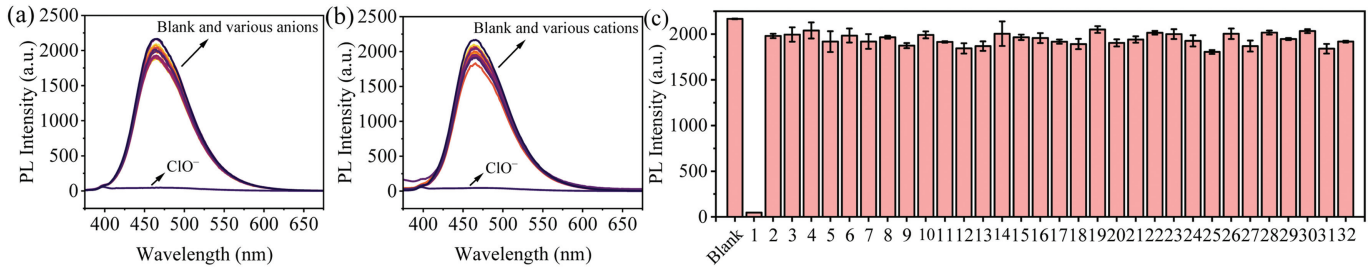

Fig. 2. (a, b) fluorescence spectra changes and (c) fluorescence emssion intensity at 465 nm of DHIP-Py (10 μmol/L) upon addition of different cations, anions or ClO^- (100 μmol/L, 10 equiv.) in PBS buffer (pH 7.4, 10 mmol/L): 1 ClO^-, 2 Ac^-, 3 F^-, 4 Cl^-, 5 Br^-, 6 I^-, 7 CO_3^{2-}, 8 HCO_3^-, 9 $H_2PO_4^-$, 10 HPO_4^{2-}, 11 PO_4^{3-}, 12 NO_2^-, 13 S^{2-}, 14 SCN^-, 15 SO_3^{2-}, 16 SO_4^{2-}, 17 Ag^+, 18 Al^{3+}, 19 Ba^{2+}, 20 Ca^{2+}, 21 Cd^{2+}, 22 Co^{2+}, 23 Cr^{3+}, 24 Cu^{2+}, 25 Fe^{3+}, 26 Hg^{2+}, 27 Mg^{2+}, 28 Mn^{2+}, 29 Na^+, 30 Ni^{2+}, 31 Pd^{2+} and 32 Zn^{2+}.

DHIP-CO_2Me. H_2O_2 and ClO^- also caused a significant decrease in the fluorescence intensity of DHIP-Me at 482 nm (Fig. 1b and Fig. S5b in Supporting information). As for DHIP-Py, when other ROS species were added, no distinct changes were observed in the emssion spectra, while ClO^- triggered a 15-fold fluorescence quenching at 477 nm (Fig. 1c and Fig. S5c in Supporting information). In general, the results reveled that among the four bicyclic 2-pyridone compounds, only DHIP-Py has the ability to selectively respond to ClO^-. Notably, even in the coexistence of other competing ROS, DHIP-Py still respond well to ClO^- (Fig. 1d), demonstrating its excellent specificity. The enhanced ROS selectivity can be explained by the sterically hindered *n*–butyl substituent.

To further confirm the selectivity of DHIP-Py toward ClO^- in complicated actual sample, we investigated the effects of various common cations (Na^+, Al^{3+}, Ba^{2+}, Ca^{2+}, Cu^{2+}, Cr^{3+}, Co^{2+}, Cd^{2+}, Mg^{2+}, Hg^{2+}, Fe^{3+}, Zn^{2+}, Pd^{2+}, Ni^{2+}, Mn^{2+}, Ag^+) and anions (Ac^-, F^-, Br^-, Cl^-, I^-, CO_3^{2-}, HCO_3^-, $H_2PO_4^-$, HPO_4^{2-}, PO_4^{3-}, NO_2^-, S^{2-}, SCN^-, SO_3^{2-}, SO_4^{2-}) on ClO^- sensing in PBS buffer (pH 7.4, 10 mmol/L). Likewise, DHIP-Py was treated with 10 equiv. analytes, respectively. Mixed well and scan the fluorescence spectra within 1 min. As shown in Fig. 2, none of the testing species caused a remarkable decrease in fluorescence as ClO^- did. This phenomenon illustrates that DHIP-Py-based sensing system has good selectivity for ClO^-, indicating its potential applications in complex samples.

To ensure better sensitivity, we further optimized response time. The detection kinetic curve in Fig. 3a shows that the fluorescence intensity of the mixture of DHIP-Py and ClO^- reaches a plateau within 5 s. Thus, after mixing the sample to be tested and the probe, the fluorescence spectrum could be scanned immediately or the fluorescence intensity at emssion maximum could be recorded for quantitative. Next, we evaluated the effect of pH values. As illustrated in Fig. 3b, the fluorescence intensity of DHIP-Py itself remained almost constant over a wide pH range (4–10), showing good stability. Upon the addition of ClO^-, a comparable switch-off sensing behavior was observed at different pH. This pH-independent detector could be used in a wider range of applications. In addition to PBS, deionized water, Na_2HPO_4-NaH_2PO_4 buffer (pH 7.4, 0.2 mol/L) and Na_2HPO_4-citric acid buffer (pH 7.4, 0.1 mol/L) can also be used as the reaction medium for ClO^- detection (Fig. S6 in Supporting information). However, DHIP-Py in Tris–HCl buffer (pH 7.4, 0.1 mol/L) did not respond to ClO^-, which could be attributed to hypochlorite deterioration form the UV–vis spectra (Fig. S7 in Supporting information).

With pre-optimized test conditions in mind, the quantitative signaling behavior of DHIP-Py was explored by fluorescence titration with ClO^- in PBS buffer (10 mmol/L, pH 7.4). It can be seen from Fig. 3c, with the increase of ClO^- dose, the emission peak at 465 nm gradually disappeared. The plot of the fluorescence intensity against ClO^- concentration is displayed in Fig. 3d. As shown, the signal decrement was linearly correlated with the added ClO^- within 8.5 equiv. ($R^2 = 0.9925$). From the concentration-dependent calibration curve, the detection limit (LOD = $3\sigma/k$) for ClO^- in PBS

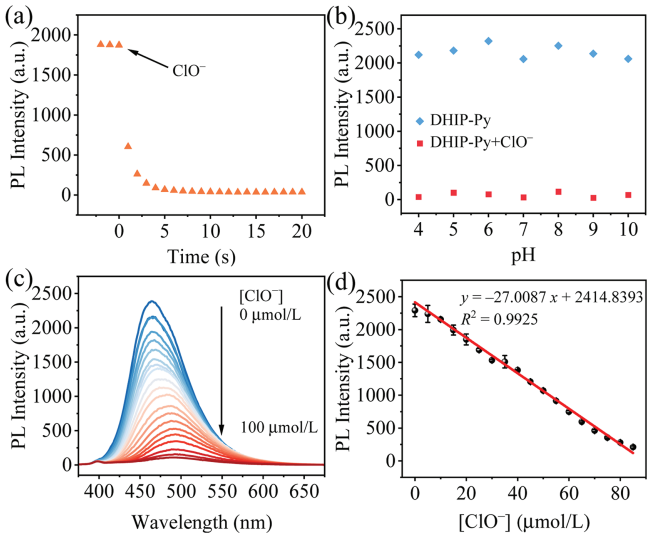

Fig. 3. (a) Time-dependent and (b) pH-dependent fluorescence response of DHIP-Py (10 μmol/L) toward ClO^- (10 equiv.). (c) Fluorescence spectra changes of DHIP-Py (10 μmol/L) upon addition of increasing amount of ClO^- (0~100 μmol/L) in PBS (pH 7.4, 10 mmol/L). (d) Linear relationship between fluorescence intensity at 465 nm of DHIP-Py (10 μmol/L) versus concentrations of ClO^-.

was estimated to be 1.32 μmol/L (0.069 ppm). That is, the sensitivity of DHIP-Py is comparable to that of the traditional DPD colorimetric method (LOD = 0.02 ppm), which is one of the most commonly used methods for determining residual chlorine in water. Nevertheless, it should be pointed out that the DPD method is not selective enough in identifying HClO/ClO^-, due to *N*,*N*–diethyl-*p*-phenylenediamine (DPD) also reacts with other oxidants, such as peracetic acid and hydrogen peroxide, and the DPD method has been reported to detect these two [42,43].

To obtain evidence for the transformation of DHIP-Py to DHIP-ClO in the presence of ClO^- (Scheme S2), the HRMS spectrum of the signaling mixture (DHIP-Py and ClO^-) was recorded. HRMS sample was prepared by mixing NaClO (100 μmol/L, 10 equiv.) and DHIP-Py (10 μmol/L) in PBS solution (pH 7.4, 10 mmol/L) for 2 min, and the spectrum was obtained without any further treatment (Fig. S8 in Supporting information). The peak at $m/z = 386.2225$ found in ESI-MS spectrum was corresponded to compound DHIP-ClO (calcd. for $[C_{25}H_{28}N_3O]^+ = 386.2227$). In addition, ^1H NMR titration experiment was carried out in D_2O (Fig. S9 in Supporting information). After gradual addition of ClO^-, except for the two protons on 2-pyridone appeared at δ 6.25, 6.16 shifted to δ 6.04, 6.01 (pink shading), and the three characteristic protons of -CO_2Me at δ 3.85 shifted to δ 3.27 (yellow shading), the other protons (gray shading) in the molecular structure almost unchanged, confirming our proposed mechanism.

Table 1
Determination of hypochlorite concentration in representative water samples.

Water samples	Concentration of ClO^- (mg/L)	
	DPD method	This method
Tap water (Laboratory)	0.632 ± 0.056	0.651 ± 0.001
Bottled water 1[a]	0.532 ± 0.017	0.571 ± 0.006
Bottled water 2[b]	0.558 ± 0.017	0.579 ± 0.004
Tuojiang water[c]	0.190 ± 0.026	0.211 ± 0.032

[a] Purchased from a local supermarket and spiked with NaClO, China Resources C'estbon Beverage (China) Co., Ltd.
[b] Purchased from a local supermarket and spiked with NaClO, Nongfu Spring Co., Ltd.
[c] Filtered through a 0.22 μm filter membrane and spiked with NaClO, Xihua University, Chengdu, China.

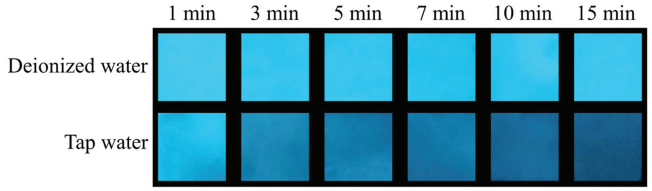

Fig. 4. Fluorescence images of DHIP-Py-treated filter papers immersed in tap water or deionized water for different times.

Encouraged by the outstanding sensing performances of DHIP-Py, we subsequently employed the DHIP-Py-based fluorometry method to analyze ClO^- in tap water and spiked samples (river water and bottled water) prepared by adding ClO^-. As shown in Fig. S10 (Supporting information), a satisfactory working plot was obtained and used to estimate the concentration of hypochlorite in the four water samples. Alternatively, ClO^- concentrations in the same samples were separately determined using the standard residual chlorine measurement DPD method. The data are summarized in Table 1, where essentially identical results were obtained from two independent measurements, indicating that the DHIP-Py-based method is reliable and feasible for the quantitative detection of ClO^- in real-world food and environmental samples. In addition, for visual detection of ClO^-, filter paper strips were impregnated with DHIP-Py (5 mmol/L) CH_3CN solution and then dried in air at 25 °C to get the solid support sensors. After immersing the solid support sensor in tap water, a decrease in fluorescence intensity was clearly observed under the UV analyzer as the immersion time increased (Fig. 4). Paper sensors are easy to produce and can be stored under ambient conditions. Therefore, DHIP-Py enables low-cost and simple monitoring of ClO^- in houselife by the naked eye.

As described above, ClO^- is one of the most widely used disinfectant in our daily life and industries. Meanwhile, in the human body, hypochlorite produced by neutrophils also plays important physiological role in fighting a broad range of invading microorganisms. It is generally believed that the antimicrobial mechanism is tightly relevant to hypochlorite-caused protein denaturation of bacterial cell walls and the viruses capsid, phospholipid destruction, irreversible enzymatic inactivation, lipid/fatty acid degradation, DNA/RNA damage, *etc.* [44–48]. Tracking the level of ClO^- by fluorescence imaging in microorganisms, such as *E. coli*, will help to further elucidate its bactericidal mechanism and provide a visualization tool for the research of hypochlorite-associated physiological processes. Keep this in mind, the fluorescence sensing of ClO^- with DHIP-Py in *E. coli* was carried out. As seen in Fig. 5, compared to cells treated with DHIP-Py only, fluorescence was significantly attenuated in cells sequentially incubated with probe and hypochlorite. This result validated that DHIP-Py could response to ClO^- in *E. coli*.

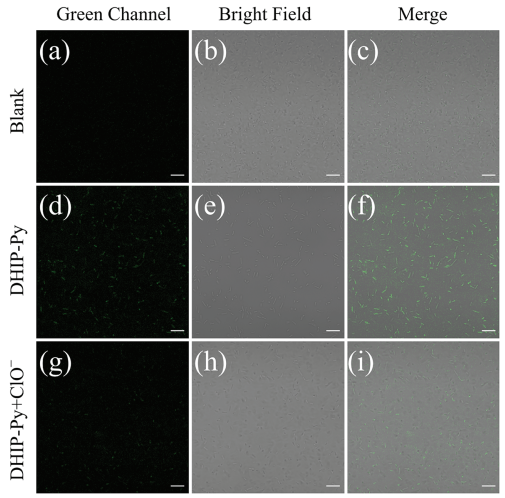

Fig. 5. Confocal fluorescence images of *E. coli* (a–c) stained with 20 μmol/L DHIP-Py for 45 min (d–f), and then further treated with 5 equiv. ClO^- (g–i) for another 20 min. λ_{ex} = 405 nm, λ_{em} = 410–554 nm. Scale bar: 10 μm.

In summary, in order to obtain a novel hypochlorite-responsive fluorescent skeleton, a series of bicyclic 2-pyridone derivatives were synthesized in good yields. Through spectral characterization and ROS testing, a distinctly selective fluorescence sensing platform for hypochlorite has been achieved using the water-soluble DHIP-Py. The rapid nature of the reaction between DHIP-Py and ClO^- produced a considerable signal output within 5 s of mixing at room temperature in the pH rang of 4–10. Also, DHIP-Py displayed good ClO^- sensing performance with a dynamic range of 0–8.5 equiv. and the limit of detection was 1.32 μmol/L. Ultimately, the experimental results show that DHIP-Py not only can accurately determine the residual chlorine in tap water, bottled water and river water like the traditional DPD method, but also responds well to ClO^- in bacteria. The oxidation-hydrolysis mechanism of 2-pyridone provides a candidate for designing reaction-based hypochlorite chemosensors. Further structural modifications are underway to extend the emission wavelength of the fluorophore for lower interference and broader biological applications.

Declaration of competing interest

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

Acknowledgments

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.cclet.2022.107922.

References

[1] M. Loretz, R. Stephan, C. Zweifel, Food Control 21 (2010) 791–804.
[2] S.M. Russell, S.P. Axtell, J. Food Protect. 68 (2005) 758–763.
[3] A. Sarjit, G.A. Dykes, Int. J. Food Microbiol. 203 (2015) 63–69.
[4] T. Aoki, M. Munemori, Anal. Chem. 55 (1983) 209–212.
[5] N. Wilhelm, A. Kaufmann, E. Blanton, D. Lantagne, J. Water Health 16 (2018) 112–125.
[6] T.G. Favero, D. Colter, P.F. Hooper, J.J. Abramson, J. Appl. Physiol. 84 (1998) 425–430.
[7] H. Feng, Z.Q. Zhang, Q.T. Meng, et al., Adv. Sci. 5 (2018) 1800397.
[8] Y. Xiong, J. Tan, S.W. Fang, et al., Talanta 167 (2017) 103–110.
[9] R.A. Costa, C.L.M. Morais, T.R. Rosa, et al., Microchem. J. 156 (2020) 104968.
[10] Y.H. Qin, A.U. Alam, S. Pan, et al., Sens. Actuators B: Chem. 255 (2018) 781–790.
[11] S. Kumaravel, T.S.T. Balamurugan, S.H. Jia, H.Y. Lin, S.T. Huang, Anal. Chim. Acta 1106 (2020) 168–175.
[12] N. Ahmed, W. Zareen, Y. Ye, Chin. Chem. Lett. 33 (2022) 2765–2772.
[13] C.P. Ren, W. Nie, J.Q. Leng, Z.B. Liu, Prog. Chem. 33 (2021) 942–957.
[14] J. Lv, F. Wang, T.W. Wei, X.Q. Chen, Ind. Eng. Chem. Res. 56 (2017) 3757–3764.
[15] D. Wu, L. Chen, Q. Xu, X. Chen, J. Yoon, Acc. Chem. Res. 52 (2019) 2158–2168.
[16] K.J. Wang, D.Z. Xi, C.T. Liu, et al., Chin. Chem. Lett. 31 (2020) 2955–2959.
[17] J. Lv, Y.H. Chen, F. Wang, et al., Dyes Pigments 148 (2018) 353–358.
[18] K. Li, J.T. Hou, J. Yang, X.Q. Yu, Chem. Commun. 53 (2017) 5539–5541.
[19] Y. Xia, X.Y. Liu, D. Wang, et al., Chin. Chem. Lett. 29 (2018) 1517–1520.
[20] S.Z. Liu, D. Yang, Y.J. Liu, et al., Sens. Actuators B: Chem. 299 (2019) 126937.
[21] Y.H. Zhang, H. Teng, Y. Gao, et al., Chin. Chem. Lett. 31 (2020) 2917–2920.
[22] Q. Hu, C.Q. Qin, L. Huang, et al., Dyes Pigments 149 (2018) 253–260.
[23] H.Q. Xiong, L. He, Y. Zhang, et al., Chin. Chem. Lett. 30 (2019) 1075–1077.
[24] J.J. Hu, N.K. Wong, Q.S. Gu, et al., Org. Lett. 16 (2014) 3544–3547.
[25] C. Duan, M. Won, P. Verwilst, et al., Anal. Chem. 91 (2019) 4172–4178.
[26] M. Vedamalai, D. Kedaria, R. Vasita, I. Gupta, Sens. Actuators B: Chem. 263 (2018) 137–142.
[27] C.C. Chang, F. Wang, J. Qiang, et al., Sens. Actuators B: Chem. 243 (2017) 22–28.
[28] S. Wang, B.T. Zhu, B.Y. Wang, et al., Chin. Chem. Lett. 32 (2021) 1795–1798.
[29] L. Shi, S. Yang, H.J. Hong, et al., Anal. Chim. Acta 1094 (2020) 122–129.
[30] J.S. Lan, J. Guo, X.Y. Jiang, et al., Anal. Chim. Acta 1094 (2020) 70–79.
[31] W. Shu, L.G. Yan, Z.K. Wang, et al., Sens. Actuators B: Chem. 221 (2015) 1130–1136.
[32] X.C. Li, S.J. Zhao, B.L. Li, et al., Coordin. Chem. Rev. 431 (2021) 213686.
[33] Y.J. Ding, J. Ling, J.F. Cai, et al., Anal. Methods 8 (2016) 1157–1161.
[34] Y.P. Lin, B.X. Yao, T.T. Huang, et al., Microchim. Acta 183 (2016) 2221–2227.
[35] H. Lee, Y.C. Su, H.H. Tang, et al., Nanomaterials 11 (2021) 1831.
[36] Y. Xiong, J. Schneider, E.V. Ushakova, A.L. Rogach, Nano Today 23 (2018) 124–139.
[37] Q. Song, Y. Liu, L.L. Cai, et al., Chin. Chem. Lett. 33 (2022) 2212-2212.
[38] F.S. Shan, L.J. Fu, X.Y. Chen, et al., Chin. Chem. Lett. 33 (2022) 2942–2948.
[39] H. Zhang, K. Li, L.L. Li, et al., Chin. Chem. Lett. 30 (2019) 1063–1066.
[40] M.Y. Li, P.C. Cui, K. Li, et al., Chin. Chem. Lett. 29 (2018) 992–994.
[41] X. Ran, Q. Zhou, J. Zhang, et al., Org. Chem. Front. 8 (2021) 3631–3638.
[42] G.S. Cavallini, S.X. de Campos, J.B. de Souza, C.M.D. Vidal, Int. J. Environ. An. Ch. 93 (2013) 906–918.
[43] R. Schick, I. Strasser, H.H. Stabel, Water Res. 31 (1997) 1371–1378.
[44] K.M. Gebendorfer, A. Drazic, Y. Le, et al., J. Biol. Chem. 287 (2012) 6892–6903.
[45] L. Guo, Y. Sun, Y. Zhu, et al., Food Res. Int. 129 (2020) 108887.
[46] S. Ujimine, S. Tone, M. Saito, S. Yamada, Med. Mol. Morphol. 50 (2017) 178–184.
[47] S. Fukuzaki, Biocontrol Sci. 11 (2006) 147–157.
[48] J.Y. Maillard, A.C. Hann, V. Baubet, R. Perrin, J. Appl. Microbiol. 85 (1998) 925–932.