



Cascade Catalysis Effect-Mediated Self-Powered Photoelectrochemical-Colorimetric Dual-Mode Microfluidic Platform for Microcystin-LR Detection

Tingting Wu^{1,3} · Jingui Chen¹ · Junqiang Fu¹ · Yu Du¹ · Xiang Ren¹ · Rui Feng¹ · Huangxian Ju¹ · Qin Wei^{1,2}

Received: 20 March 2026 / Accepted: 1 June 2026
© The Nonferrous Metals Society of China 2026

Abstract

Herein, a microfluidic self-powered photoelectrochemical (PEC) aptasensor integrated with colorimetric analysis was constructed using the MOF-818 nanozyme as a multifunctional signal tag to achieve ultrasensitive detection of microcystin-LR (MC-LR). Firstly, the photoactive material $\text{TiO}_2/\text{AgSbS}_2$ (TOAS) served as a photoanode that stably provided electrons to the CuInS_2 (CIS) photocathode, generating a stable cathodic photocurrent. Second, dual signal amplification was achieved through a complementary DNA (cDNA)-induced DNA strand displacement reaction (SDR) and the efficient cascade catalytic activity of the MOF-818 nanozyme. MOF-818 with superoxide dismutase (SOD)-like and catalase (CAT)-like activity can catalyze the cascade reaction of superoxide anion ($\cdot\text{O}_2^-$), significantly enhancing photocurrent. In the detection of MC-LR, the aptamer specifically binds to MC-LR, releasing cDNA and triggering a DNA cycle amplification reaction, thus significantly enhancing the output signal. Third, based on the excellent peroxidase-like activity of the MOF-818 nanozyme, the constructed biosensor could achieve 3,3',5,5'-tetramethylbenzidine (TMB)-mediated colorimetric detection. Thus, based on the synergistic amplification effect of SDR and the cascade catalysis effect of nanozyme, the microfluidic chip-based PEC/colorimetric detection of MC-LR was realized, with detection limits of 0.59 and 4.2 pg/mL, respectively. Furthermore, the constructed sensor enabled ultrasensitive detection of MC-LR in lake water and milk samples.

Keywords Cascade catalysis effect · Self-powered · Dual-mode · Microfluidic · Microcystin-LR

Tingting Wu and Jingui Chen contributed equally to this work.

✉ Yu Du
duyu_ujn@163.com

✉ Huangxian Ju
hxju@nju.edu.cn

✉ Qin Wei
sdjndxwq@163.com

¹ Key Laboratory of Interfacial Reaction and Sensing Analysis in Universities of Shandong, Collaborative Innovation Center for Green Chemical Manufacturing and Accurate Detection, University of Jinan, Jinan 250022, China

² Department of Chemistry, Sungkyunkwan University, Suwon 16419, Republic of Korea

³ Institute for Smart Materials & Engineering, University of Jinan, Jinan 250022, China

Microcystin (MC), a group of monocyclic heptapeptide, is the most widely distributed and extensively studied toxins produced by cyanobacterial toxins [1–4]. Among hundreds of known microcystins, microcystin-LR (MC-LR), which is one of the most widely distributed and harmful due to its strong hepatotoxicity, seriously affects water safety and human health [5–7]. Common methods for analyzing MC-LR include liquid chromatography–mass spectrometry (LC–MS) [8], the enzyme-linked immunosorbent assay (ELISA) [9], and Raman spectrometry [10]. However, these methods usually require high instrumental costs or time costs. Therefore, developing a more rapid and sensitive MC-LR analysis method that offers simple operation remains a serious challenge.

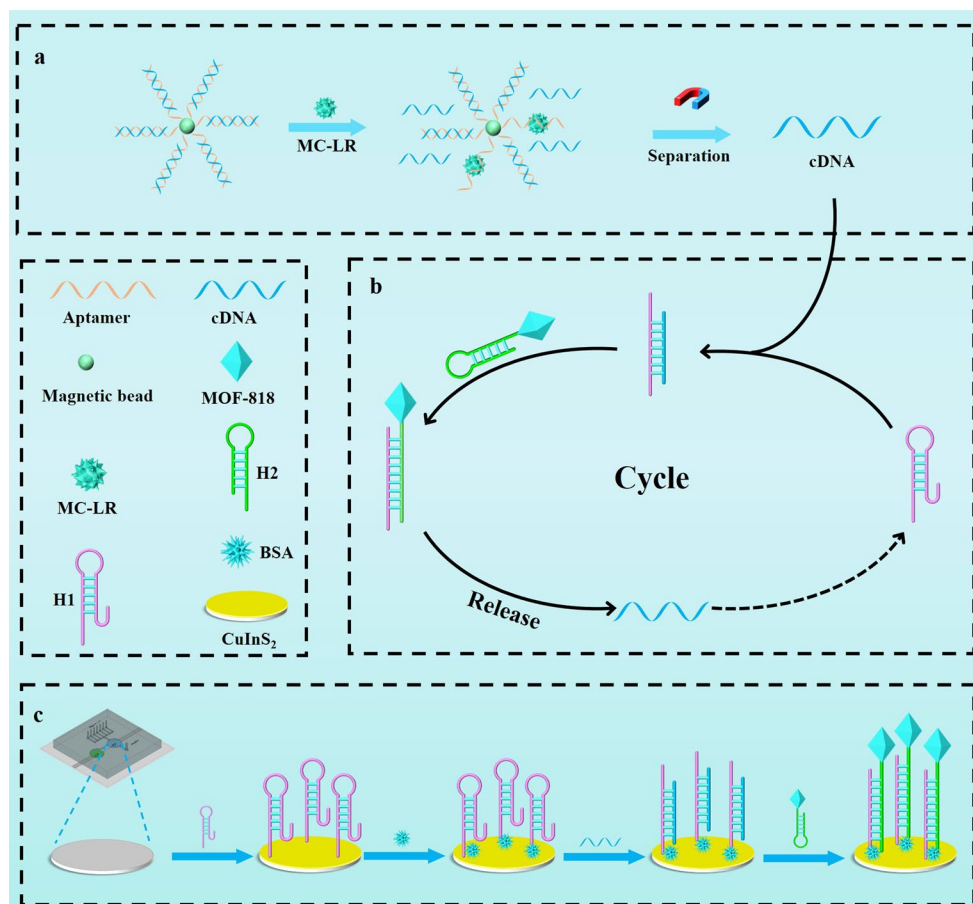
Photoelectrochemical (PEC) technology has attracted considerable interest due to its low background signal, high sensitivity, and excellent stability [11–13]. Compared with the traditional three-electrode system, the dual-electrode

self-powered PEC system has a simpler structure and better anti-interference capability [11]. Thanks to advances in sensing technology and materials science, many innovative self-powered PEC sensors have been developed for various applications, including clinical diagnosis, food safety, and environmental evaluation [14–16]. The selection of materials with strong PEC activity is crucial for constructing self-powered sensors. TiO_2 with high photocatalytic activity has been widely used as a photoactive substrate but suffers from defects such as low visible light utilization [17, 18]. To further improve the photoelectric conversion efficiency of TiO_2 , AgSbS_2 (which has a high light absorption coefficient of $\alpha \approx 10^5 \text{ cm}^{-1}$ [19]) was used as a sensitizer for TiO_2 . The resulting $\text{TiO}_2/\text{AgSbS}_2$ (TOAS) composites showed excellent photoelectric activity. The p-type semiconductor CuInS_2 (CIS) is an ideal substrate material for photoelectric sensing owing to its excellent photoelectric activity and stability [20, 21]. In this paper, MC-LR detection was achieved without an applied voltage by employing the TOAS photoanode to supply electrons to CIS photocathode. More importantly, to further enhance detection performance, this system was integrated into a microfluidic sensing platform, which offers advantages such as miniaturization, low

reagent consumption, simple operation, and enhanced sensitivity and accuracy [22].

In photocathode systems, the key process that determines the output signal is the consumption of photogenerated electrons by dissolved O_2 to produce $\cdot\text{O}_2^-$ [23]. Eliminating $\cdot\text{O}_2^-$ or supplying more O_2 can thus achieve signal amplification. Inspired by this, we employed the MOF-818 nanzyme with superoxide dismutase (SOD)-like and catalase (CAT)-like activities to quench $\cdot\text{O}_2^-$ by converting it into H_2O_2 and O_2 . The generated H_2O_2 was subsequently decomposed into H_2O and O_2 by the CAT activity of the enzyme, thereby promoting electron capture and signal enhancement [24]. To further improve the sensitivity of sensors, DNA-based signal amplification strategies involving DNA strand displacement reactions (SDRs), rolling circle amplifications (RCAs), and exonuclease III (Exo-III)-assisted cycle amplification have become a research hotspot due to their high specificity and signal amplification efficiency at low cost [25–29]. Accordingly, a dual signal amplification strategy combining SDR and the MOF-818 nanzyme was developed (Fig. 1a and b). Besides, the construction process of the microfluidic biosensor was shown in Fig. 1c and the detailed fabrication procedures were provided in the Supplementary Material. The presence of MC-LR triggered aptamer binding, which

Fig. 1 a Magnetic separation process, b schematic diagram of DNA cycle reaction, and c microfluidic biosensor construction diagram



in turn released complementary DNA and initiated an SDR cycle, enabling efficient target recycling. Meanwhile, the peroxidase (POD)-like activity of MOF-818 enabled colorimetric detection, providing a complementary signal readout that minimizes external interference and improves the reliability of results [30].

The synthesis procedures of $\text{TiO}_2/\text{AgSbS}_2$ microelectrodes, CuInS_2 photocathode, and the MOF-818-H2 probe were described in the Supplementary Material. The DNA preconditioning process can be seen in the Supplementary Material.

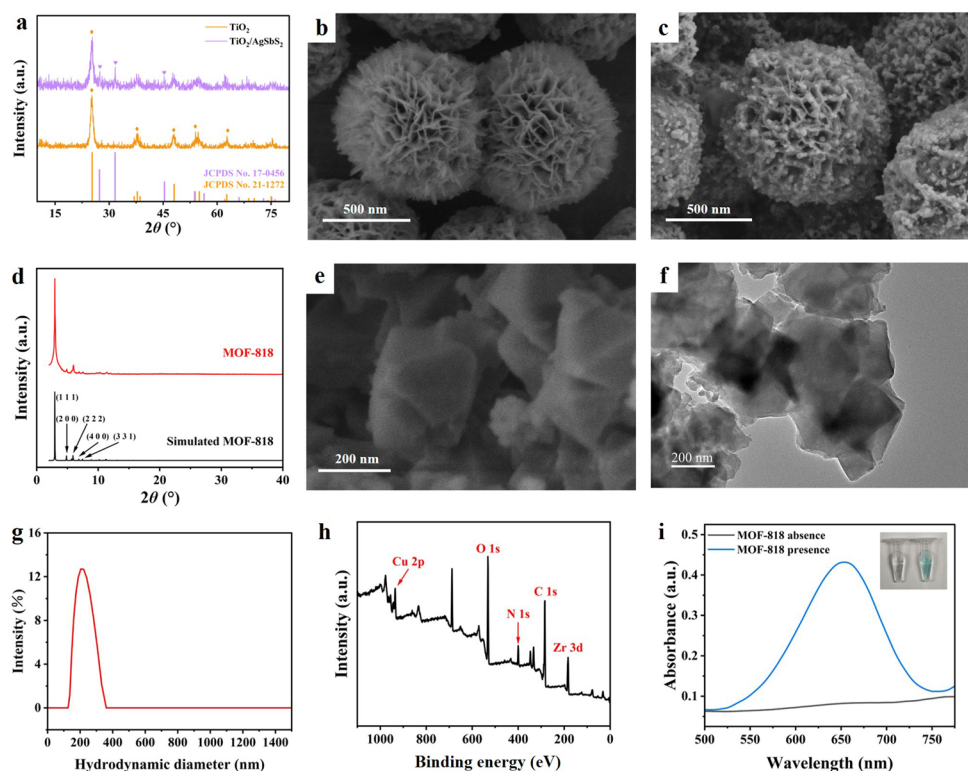
The crystal structures of the material were analyzed by X-ray diffraction (XRD). As depicted in Fig. 2a, the XRD patterns of TiO_2 show distinct peaks at 2θ values of 25.28° , 37.84° , 48.04° , and 62.72° , which correspond to the (101), (004), (200), and (204) faces of TiO_2 (JCPDS No. 21-1272), respectively. For TOAS, the peaks at 27.34° , 31.68° , and 45.30° are attributed to the (111), (200), and (220) crystal planes of AgSbS_2 (JCPDS No. 17-0456), indicating that the synthesis of TOAS was successful. Meanwhile, scanning electron microscopy (SEM) was used to characterize the morphology of the material. The SEM image in Fig. 2b indicates that TiO_2 exhibits a nano-pompon structure consisting of ultrathin nanoflakes. After modification with AgSbS_2 , uniformly distributed AgSbS_2 particles were observed on the surface of TiO_2 nano-pompoms (Fig. 2c). The presence of Ti, O, Ag, Sb, and S elements in the SEM

mapping diagram in Fig. S2 further proves the successful preparation of TOAS.

The XRD diffraction peaks of the prepared MOF-818 are basically consistent with the simulated MOF diffraction peaks (Fig. 2d). And the SEM image in Fig. 2e displays the octahedral morphology of MOF-818, which is further verified by the TEM image (Fig. 2f). In addition, the SEM elemental mapping results (Fig. S3) of MOF-818 prove the uniform distribution of elements such as Cu, Zr, C, N, and O, indicating that the preparation of MOF-818 was successful. The hydrodynamic diameter of MOF-818 is approximately 210 nm as measured using dynamic light scattering (Fig. 2g). For the surface chemical properties of MOF-818, the XPS spectrum (Fig. 2h) reveals the presence of Cu, Zr, C, N, and O.

In addition, the feasibility of the colorimetric method based on the MOF-818 nanozyme was verified through comparative experiments. Figure 2i demonstrated the ultraviolet–visible (UV–vis) absorption spectra of phosphate buffered solution (PBS) containing 50 mmol/L H_2O_2 and 20 mmol/L TMB in the presence and absence of MOF-818. The MOF-818 nanozyme exhibited efficient peroxidase-like activity, oxidizing colorless TMB to the blue oxTMB through the catalytic action of H_2O_2 . Based on this property, colorimetric monitoring of MC-LR was accomplished. Finally, to verify the superiority of the microfluidic sensing chip, a comparison was made with a conventional detection system. As shown in Fig. S4, the smaller reaction volume of

Fig. 2 a XRD patterns of TiO_2 and TOAS; SEM images of b TiO_2 and c TOAS. d XRD pattern, e SEM image, f TEM image, g hydrodynamic diameter distribution, and h XPS spectrum of MOF-818; i UV–vis absorbance spectra of PBS (50 mmol/L H_2O_2 and 20 mmol/L TMB) in the absence and presence of MOF-818 nanozyme



the microfluidic chip allowed the catalytic activity of MOF-818 to be exploited more fully, resulting in a stronger signal. Polyacrylamide gel electrophoresis (PAGE) was utilized to assess the DNA reaction process (Fig. S5). Additionally, Fig. S6 shows the photocurrent signal changes and interfacial properties during sensor construction, indicating that the sensor had been successfully prepared.

UV-vis diffuse reflectance spectroscopy and Mott-Schottky curves (Fig. S7) confirmed that the TOAS photoanode formed a well-matched heterojunction that supplied electrons to the photocathode. Under visible light, photogenerated electrons at the photocathode were captured by dissolved O_2 (Eqs. 1 and 2), whereas holes were consumed by photoanode electrons, boosting carrier separation and amplifying photocurrent (Fig. 3a). The electron spin resonance (ESR) experiment shown in Fig. S8 revealed that only $\cdot O_2^-$ production was only detected under light conditions,

proving the validity of the speculation in Eq. 2. Following the DNA cycle amplification reaction, the MOF-818 modified photocathode consumed $\cdot O_2^-$ to produce H_2O_2 and O_2 (Eq. 3) and then catalyzed the decomposition of H_2O_2 into H_2O and additional O_2 (Eq. 4). The generated O_2 could trap more photogenerated electrons, further enhancing the photocurrent signal. Additionally, the MOF-818 nanozyme enabled colorimetric detection via its oxidase-like activity, catalyzing the oxidation of TMB to produce blue oxTMB (Fig. 3b).

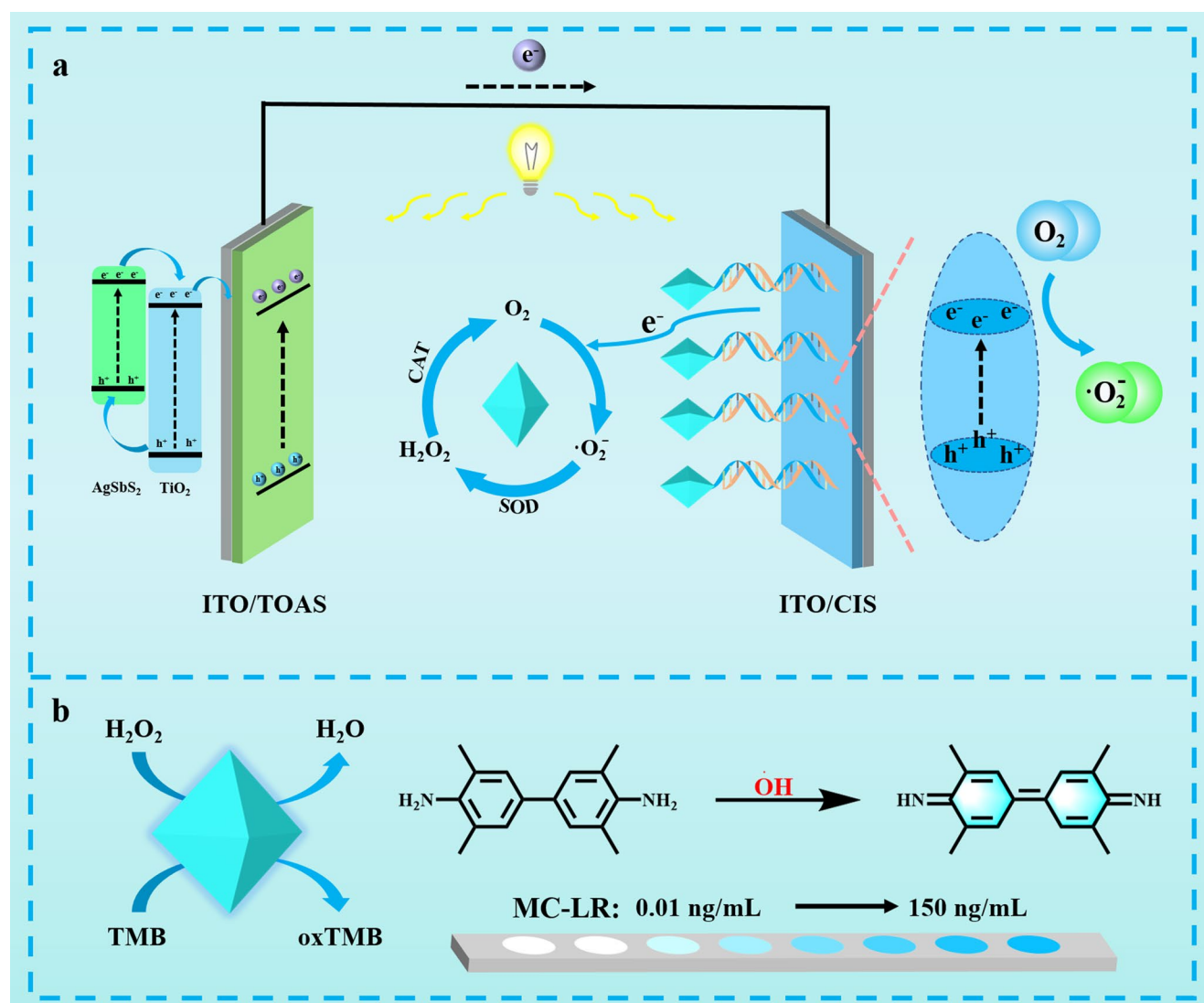


Fig. 3 Possible mechanisms of the designed dual-mode biosensor: **a** PEC method and **b** colorimetric method

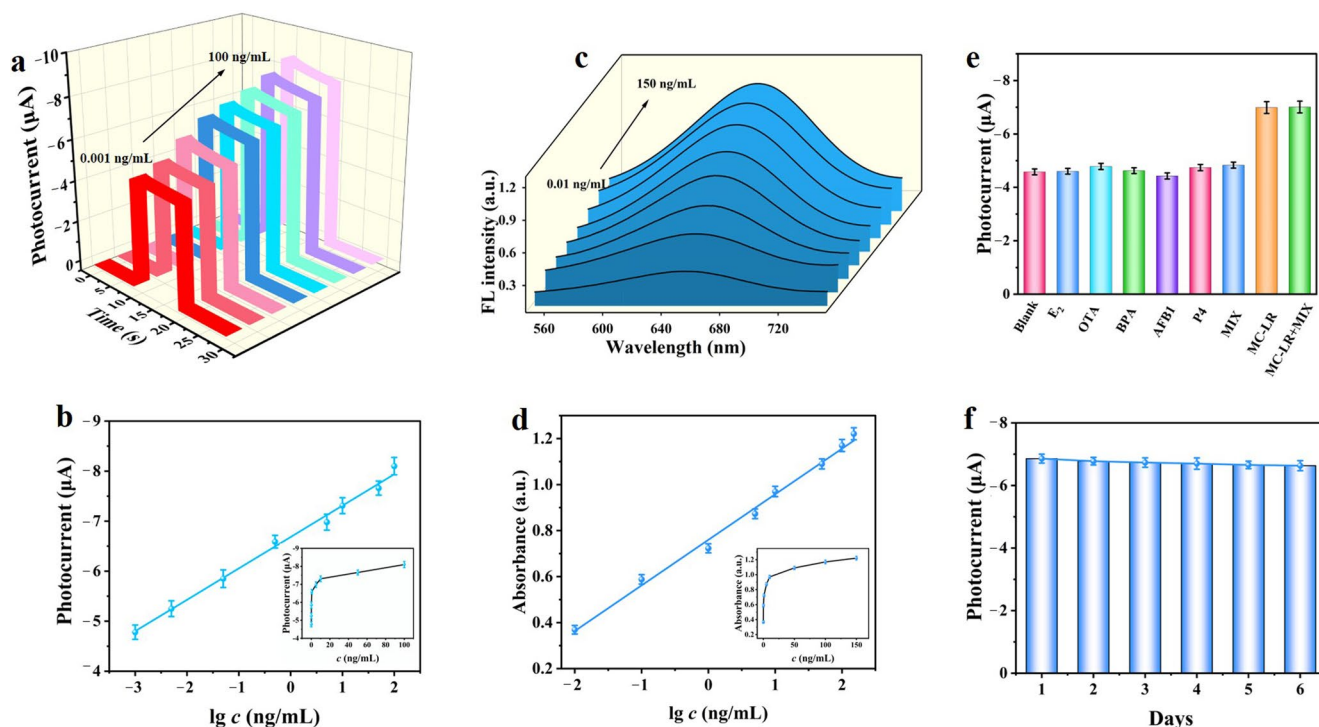


Fig. 4 **a** Photocurrent response and **b** calibration curve for MC-LR PEC determination in the range of 0.001–100 ng/mL; **c** UV–vis spectrum and **d** calibration curve for MC-LR colorimetric determination in

the range of 0.01–150 ng/mL; **e** Selectivity and **f** storage stability tests of the microfluidic biosensor. ($c_{\text{MC-LR}} = 5 \text{ ng/mL}$, error bar = SD, $n = 5$)



Under optimal experimental conditions (Fig. S9), the sensitive PEC/colorimetric detection of MC-LR was accomplished. As shown in Fig. 4a, the photocurrent intensity is enhanced with increasing MC-LR concentration. In the range of 0.001–100 ng/mL (Fig. 4b), the photocurrent exhibited a good linear relationship with the logarithm of the MC-LR concentration ($I = -0.6276 \lg c - 6.683$, $R^2 = 0.994$). The detection limit of the PEC method was as low as 0.59 pg/mL (signal-to-noise ratio, $S/N = 3$). Meanwhile, the colorimetric method has shown satisfactory results. As shown in Fig. 4c, as the MC-LR concentration increased, the solution gradually changed from colorless to blue and the intensity of the absorption peaks in the UV–vis absorption spectrum increased. As shown in Fig. 4d, the calibration curve for the colorimetric method is $F = 0.1983 \lg c + 0.7599$ ($R^2 = 0.993$) in the range of 0.01–150 ng/mL, with a detection limit of 4.2 pg/mL ($S/N = 3$). Remarkably, the proposed dual-mode sensor not only enhanced the reliability of the detection results but also demonstrated significant advantages over other detection methods (Table S3).

Selectivity, reproducibility, and stability are important criteria for evaluating the performance of biosensors [31]. The selectivity of the proposed biosensors was evaluated by choosing different interferents. As shown in Fig. 4e,

the detection signal of the sensor for 5 ng/mL MC-LR did not change significantly under the interference level of 500 ng/mL of estradiol (E_2), ochratoxin A (OTA), bisphenol A (BPA), aflatoxin B1 (AFB1), and progesterone (P4). At the same time, the signal strength of the sensor when detecting interferences alone was nearly identical to the blank value. The above results demonstrate the high selectivity of the proposed biosensor. Five independent sensors were constructed to detect MC-LR (5 ng/mL). As shown in Fig. S10, the relative standard deviation (RSD) of the detection results is 2.06%, proving the good reproducibility of the constructed sensor. Additionally, the operational stability of the sensor was assessed. The PEC intensity did not change significantly under ten light-source switching cycles (Fig. S11), demonstrating the good stability of the constructed sensor. Finally, the storage stability of the designed biosensor was evaluated. As shown in Fig. 4f, after storage at 4 °C for 6 days, the photocurrent retained 96.7% of its initial value, demonstrating the excellent storage stability of the as-proposed PEC immunosensor. In addition, the sensing performance in colorimetric mode was also evaluated (Fig. S12) and this mode showed good selectivity, reproducibility, and stability.

The standard addition method was used to validate the feasibility of the microfluidic PEC sensing platform in real samples. Firstly, LC-MS was utilized to analyze the

concentration of MC-LR in lake water and milk. MC-LR was not detected in any of the tested samples, as indicated by the results. Based on this, MC-LR was spiked into lake water and milk at concentrations of 0.4, 0.8, and 1.2 ng/mL. The detection results are shown in Table S4. The constructed biosensor showed a MC-LR recovery of 97.5%–101.3% in lake water, with RSDs of 2.0%–3.8%. Spiked recoveries in milk were 98.8%–102.5%, with RSDs of 1.6%–3.8%. The above results demonstrate the potential feasibility of the dual-mode aptasensor reported in this work for water quality monitoring.

In summary, a dual-mode microfluidic biosensor was proposed for the ultrasensitive detection of MC-LR using the PEC/colorimetric method. The detection signal was amplified twice using the cDNA-triggered DNA strand substitution reaction and the excellent enzyme catalytic activity of the MOF-818 nanozyme. Notably, the MOF-818 nanozyme can consume superoxide radicals and convert them to O₂, capturing more electrons, as well as catalyzing the TMB-based chromogenic reaction. Thus, biosensors that combine the advantages of microfluidic miniaturization and automation exhibited good detection performance for MC-LR, with detection limits as low as 0.59 pg/mL (PEC) and 4.2 pg/mL (colorimetric). The dual-mode microfluidic biosensor developed in this study showed good selectivity and stability, achieving sensitive detection of MC-LR standard samples in lake water and milk. The present work provides a new approach for the pollution of water and environmental pollution.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s41664-026-00494-y>.

Acknowledgements This study was supported by the National Natural Science Foundation of China (Nos. 22574062, 22574063, and 22504041), the Natural Science Foundation of Shandong Province (No. ZR2024QB058), Shandong Province Science and Technology Small and Medium Enterprises Innovation Ability Enhancement Project (No. 2025TSGCCZZB0987), the China Postdoctoral Science Foundation (No. 2023M741360), the Young Talent of Lifting engineering for Science and Technology in Shandong, China (No. SDAST2025QTA057), and Jinan University and Institute Innovation Team Project (No. 202534040).

Author Contributions Tingting Wu: Conceptualization, data curation, writing original draft, Funding acquisition. Jingui Chen: Methodology, Formal analysis. Junqiang Fu: Methodology. Yu Du: Funding acquisition, Formal analysis. Xiang Ren: Formal analysis, review & editing. Rui Feng: Methodology, data curation. Huangxian Ju: Supervision, Formal analysis. Qin Wei: Funding acquisition, Project administration.

Declarations

Competing Interests The authors declare that they have no competing financial interests or personal relationships that could have influenced the work reported in this paper.

References

- Zhong HX, Ji XD, Yang C, Tang CF, Hu X, Cai JJ, et al. Z-scheme heterojunction α -Fe₂O₃/tubular g-C₃N₄ with C defects for photocatalytic degradation of microcystin-LR in water: Generation and effect of critical species ¹O₂. *ACS Catal.* 2024;14:6272–91.
- Bouhaddada R, Nélieu S, Nasri H, Delarue G, Bouaïcha N. High diversity of microcystins in a *Microcystis* bloom from an Algerian lake. *Environ Pollut.* 2016;216:836–44.
- Zhao GH, Du Y, Zhang N, Li Y, Bai GZ, Ma HM, et al. Bimetallic metal-organic frameworks as an efficient capture probe in signal on-off-on electrochemiluminescence aptasensor for Microcystin-LR detection. *Anal Chem.* 2023;95:8487–95.
- Liu YP, Li BY, Zhang HX, Liu Y, Xie P. Participation of fluorescence technology in the cross-disciplinary detection of microcystins. *Coord Chem Rev.* 2022;457:214416.
- Zhang HX, Zhao X, Li YH, Xie P. A meta-analysis on the toxicity of microcystin-LR to fish and mammals. *Environ Pollut.* 2023;330:121780.
- Su RC, Lad A, Breidenbach JD, Kleinhenz AL, Modyanov N, Malhotra D, et al. Assessment of diagnostic biomarkers of liver injury in the setting of microcystin-LR (MC-LR) hepatotoxicity. *Chemosphere.* 2020;257:127111.
- Bostan HB, Taghdisi SM, Bowen JL, Demertzis N, Rezaee R, Panahi Y, et al. Determination of microcystin-LR, employing aptasensors. *Biosens Bioelectron.* 2018;119:110–8.
- Qian ZY, Li ZG, Ma J, Gong TT, Xian QM. Analysis of trace microcystins in vegetables using matrix solid-phase dispersion followed by high performance liquid chromatography triple quadrupole mass spectrometry detection. *Talanta.* 2017;173:101–6.
- Lotierzo M, Abuknesha R, Davis F, Tothill IE. A membrane-based ELISA assay and electrochemical immunosensor for Microcystin-LR in water samples. *Environ Sci Technol.* 2012;46:5504–10.
- Jiang J, Liu M, Xu DL, Jiang T, Zhang JJ. Quantitative detection of microcystin-LR in *Bellamyia aeruginosa* by thin-layer chromatography coupled with surface-enhanced Raman spectroscopy based on in-situ ZIF-67/Ag NPs/Au NWs composite substrate. *Food Chem.* 2024;452:139481.
- Wu TT, Du Y, Gao ZF, Xu K, Dai L, Liu L et al. Dual direct Z-scheme heterojunction with stable electron supply to a Au/PANI photocathode for ultrasensitive photoelectrochemical and electrochromic visualization detection of ofloxacin in a microfluidic sensing platform. *Anal Chem.* 2023;95:1627–1634.
- Tu WW, Zhu LL, Cai TT, Li ZJ, Dai ZH. Integrating multiple probes for simplifying signal-on photoelectrochemical biosensing of microRNA with ultrasensitivity and wide detection range based on biofunctionalized porous ferroferric oxide and hypotoxic quaternary semiconductor. *Biosens Bioelectron.* 2024;243:115781.
- Yang PL, Hou XL, Gao X, Peng YX, Li QF, Niu QJ, et al. Recent trends in self-powered photoelectrochemical sensors: From the perspective of signal output. *Acs Sens.* 2024;9:577–88.
- Wang HY, Wang M, Wang H, Ren X, Wang H, Wei Q, et al. Detection of NSE by a photoelectrochemical self-powered immunosensor integrating RGO photocathode and WO₃/Mn:CdS nanomaterial photoanode. *Biosens Bioelectron.* 2022;207:114196.
- Zou KX, Xia XQ, Huang YL, Zhang SM, Xu Y, Chen M, et al. Self-powered and dual-amplified photoelectrochemical sensing platform for highly sensitive detection of aflatoxin B1. *Food Chem.* 2025;492:145635.
- Jiang D, Zhang YD, Du XJ, Zhang LH, Shan XL, Wang WC, et al. Plasmonic heterostructure Bi₂S₃/Ti₃C₂ with continuous photoelectron injection mediated near-infrared self-powered photoelectrochemical sensing. *Chem Commun.* 2023;59:1185–8.

17. Shen M, Hu XL. A signal-off anodic photoelectrochemical sensor based on $\text{ZnIn}_2\text{S}_4/\text{TiO}_2$ heterojunction for dopamine detection. *Talanta*. 2025;281:126800.
18. Feng CY, Bo TT, Maity P, Zuo SW, Zhou W, Huang KW, et al. Regulating photocatalytic CO_2 reduction kinetics through modification of surface coordination sphere. *Adv Funct Mater*. 2024;34:2309761.
19. Han JH, Liu ZF, Guo KY, Zhang XQ, Hong TT, Wang B. AgSbS_2 modified ZnO nanotube arrays for photoelectrochemical water splitting. *Appl Catal B-Environmental*. 2015;179:61–8.
20. Lu KN, Liu DQ, Zhao DY, Bai XY, Hong CH, Jia NQ. Self-powered molecular imprinted photoelectrochemical sensing platform of sialic acid employing $\text{WO}_3/\text{Bi}_2\text{S}_3$ photoanode and CuInS_2 photocathode. *Talanta*. 2023;259:124499.
21. Zhao DY, Guo YY, Bi WH, Li X, Duan R, Guo L. Effects of CuInS_2 nanoparticles on the alignment control of liquid crystals. *Nano Res*. 2022;15:7542–8.
22. Zhao Y, Hu XG, Hu S, Peng Y. Applications of fiber-optic biochemical sensor in microfluidic chips: A review. *Biosens Bioelectron*. 2020;166:112447.
23. Feng JH, Li N, Du Y, Ren X, Wang XY, Liu XJ, et al. Ultra-sensitive double-channel microfluidic biosensor-based cathodic photo-electrochemical analysis via signal amplification of SOD-Au@PANI for cardiac troponin I detection. *Anal Chem*. 2021;93:14196–203.
24. Chao DY, Dong Q, Yu ZX, Qi DS, Li MH, Xu LL, et al. Specific nanodrug for diabetic chronic wounds based on anti-oxidase-mimicking MOF-818 nanozymes. *J Am Chem Soc*. 2022;144:23438–47.
25. Li F, Zhou YL, Yin HS, Ai SY. Recent advances on signal amplification strategies in photoelectrochemical sensing of microRNAs. *Biosens Bioelectron*. 2020;166:112476.
26. Zhao QQ, Gao ZF, Liu XJ, Song XZ, Wu D, Ma HM, et al. Dual-signal integrated aptasensor for Microcystin-LR detection via in situ generation of silver nanoclusters induced by circular DNA strand displacement reactions. *Anal Chem*. 2023;95:14317–23.
27. Yang LY, Xiong Q, Zhao LY, Zhang WQ, Zhao Y, Yi B, et al. A fluorescent aptasensor for emetic *Bacillus cereus* detection based on DNA-functionalized magnetic separation coupled with rolling circle amplification. *Food Bioscience*. 2024;61:104567.
28. Ma RN, Wang LL, Wang HF, Jia LP, Zhang W, Shang L, et al. Highly sensitive ratiometric electrochemical DNA biosensor based on homogeneous exonuclease III-assisted target recycling amplification and one-step triggered dual-signal output. *Sens Actuators B-Chemical*. 2018;269:173–9.
29. Dai YF, Furst A, Liu CC. Strand displacement strategies for biosensor applications. *Trends Biotechnol*. 2019;37:1367–82.
30. Fu YM, Du CC, Zhang QQ, Xiao K, Zhang XH, Chen JH. Colorimetric and photocurrent-polarity-switching photoelectrochemical dual-mode sensing platform for highly selective detection of mercury ions based on the split G-quadruplex-hemin complex. *Anal Chem*. 2022;94:15040–7.
31. Zhou YL, Deng L, Qing HD, Li SL, Li K. Enhanced photoelectrochemical performance of $\text{CoOOH}/\text{ZnCdS}$ -Vs via co-catalyst and defect engineering for detection of Cu^{2+} and D-penicillamine. *J Anal Test*. 2025;9:646–61.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.