

Dual-Mode Colorimetric and RGB Detection of Sulfide Based on a Magnetic $\text{Fe}_3\text{O}_4/\text{CoFe}_2\text{O}_4/\text{Ce-BDC}$ Hybrid Nanozyme

Qingyuan Weng

Nanjing Medical University

Xinyi Wen

Nanjing Medical University

Tianyuan Wei

National Clinical Research Center of Kidney Diseases, Nanjing Medical University

Qing Zhang

Nanjing Medical University

Wanying Zhu

Nanjing Medical University

Junli Hong

junlihong@njmu.edu.cn

Nanjing Medical University

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Abstract

Sulfide (S^{2-}), a ubiquitous and highly reactive anion in natural and industrial environments, poses severe threats to aquatic ecosystems and human health even at trace levels, necessitating rapid and precise detection methods. This study presents a dual-mode sensing strategy by integrating a magnetic $Fe_3O_4/CoFe_2O_4/Ce-BDC$ (denoted as FCF/Ce-BDC) nanozyme with TMB/ H_2O_2 chromogenic chemistry to construct peroxidase-mimetic hybrids. The FCF/Ce-BDC catalyst efficiently oxidizes 3,3',5,5'-tetramethylbenzidine (TMB) in the presence of hydrogen peroxide (H_2O_2), generating a blue product (oxTMB, $\lambda_{max} = 651\text{nm}$). The subsequent reaction of sulfide under acidic conditions scavenges reactive oxygen species (ROS), predominantly hydroxyl radicals ($\cdot OH$), and reduces oxidized 3,3',5,5'-tetramethylbenzidine (oxTMB), leading to a pronounced decrease in absorbance at 651 nm and a visually discernible color transition from blue to colorless. This dual-signal response enables quantitative analysis via both conventional spectrophotometric absorbance measurement and smartphone-based RGB colorimetry, achieving detection limits of $0.29\text{ }\mu\text{M}$ (absorbance mode) and $31.26\text{ }\mu\text{M}$ (RGB mode), respectively. We fabricated three portable, field-deployable sensors for on-site sulfide detection: a hydrogel film, a cotton fabric strip and a cotton swab. The hydrogel sensor leverages ion-mediated crosslinking to modulate reaction kinetics and ensure reproducible color development, whereas the cotton-based substrates exploit capillary-driven fluid transport to enrich analyte concentration, thereby enhancing sensitivity and mitigating matrix interference. This study not only advances the rational design of multifunctional nanozymes but also delivers a validated, application ready framework for their safe and selective use in environmental water matrices and human whole blood, enabling real time, cost effective, and operationally simple tracking of target pollutants without compromising analytical reliability.

1. Introduction

Sulfide (S^{2-}) species, commonly present as sulfide ions or dissolved hydrogen sulfide, are widespread in natural waters and are frequently generated during anaerobic decomposition, mining operations, wastewater discharge and certain food-processing or fermentation practices. Beyond industrial settings, sulfide formation can occur in seafood processing and other food-production chains, where residual sulfide presents a genuine food-safety concern. Because sulfide and hydrogen sulfide are both highly reactive and toxic, even trace exposures may impair respiratory and neurological function, induce tissue hypoxia, and at higher doses, cause acute respiratory failure or death [1]. In biological systems, sulfide readily reacts with metalloproteins and other biomolecules, disturbing oxygen transport and metabolic homeostasis [2]. Chronic or repeated exposure is also associated with gastrointestinal and neurological disorders [3]. Together, these hazards make sensitive, accurate and user-friendly methods for on-site sulfide monitoring a practical necessity for protecting public health and preserving environmental quality.

Conventional analytical techniques for sulfide quantification-electrochemical sensors [4], fluorescent nanoprobes [5], chromatographic separations (including headspace or gas chromatography), surface-enhanced Raman scattering and plasma-based emission spectroscopies offer excellent sensitivity and

selectivity in laboratory settings [6]. However, these methods typically require costly instrumentation, elaborate sample preparation and specialized operators, which limits their suitability for rapid field screening or routine checks outside centralized laboratories. Optical colorimetric assays, by contrast, deliver rapid, low-cost and instrument-light alternatives that provide immediate visual readouts. When combined with smartphone-based imaging and RGB extraction, colorimetric approaches become especially appealing for decentralized monitoring because they enable semiquantitative or quantitative readout with minimal user training and no dedicated analytical equipment.

From a materials-design perspective, hybrid architectures that combine metal-organic frameworks (MOFs) with conductive porous organic or carbonaceous coatings provide an attractive route to high-performance sensing platforms [7–9]. Conductive, π -conjugated porous networks or carbon-based layers can promote molecular adsorption and improve electron transport, while MOFs supply catalytically active metal centers and tunable coordination environments [10, 11]. Coating or integrating MOF-decorated nanoparticles with such surface layers suppresses particle aggregation, enhances structural robustness, and builds hierarchical pore networks that accelerate substrate diffusion [12, 13]. These synergistic effects can markedly improve the activity and stability of biomimetic catalysts, including nanozymes that emulate natural oxidoreductases [14, 15].

Guided by these design principles, we constructed a ternary, magnetically recoverable $\text{Fe}_3\text{O}_4/\text{CoFe}_2\text{O}_4/\text{Ce-BDC}$ hybrid nanozyme. In this composite, the mixed-valence Fe and Co sites contribute to H_2O_2 activation and reactive oxygen species generation, while the Ce-BDC component provides a porous coordination environment that facilitates substrate enrichment and electron transfer [16, 17]. The magnetic Fe_3O_4 domain endows the material with convenient magnetic separation and reusability, thereby improving the operational practicality of the system. Owing to the synergistic integration of these components, the resulting composite exhibits pronounced POD-like activity, which can be effectively exploited for chromogenic sensing applications.

We applied this Fe-Co-Ce nanozyme to a TMB/ H_2O_2 chromogenic system to establish a dual-mode assay for sulfide detection. Under acidic conditions, the nanozyme catalyzes the oxidation of TMB to its blue oxidized product (oxTMB, $\lambda_{\text{max}} = 651 \text{ nm}$) [18]. Sulfide perturbs this reaction through multiple complementary pathways: it scavenges reactive oxygen species generated during catalysis, thereby diminishing the oxidative flux [19]. Its reducing nature enables it to chemically reduce or otherwise consume the oxidized TMB species [20]. Moreover, it can further suppress the intrinsic catalytic activity of the nanozyme by interacting with surface-active metal sites and disturbing the redox cycling of Fe, Co and Ce centers [21–23]. Collectively, these effects lead to a pronounced attenuation of the absorption band at 651 nm and a distinct visible color transition from blue toward colorless, enabling sensitive quantification via both conventional spectrophotometry and smartphone-based RGB analysis.

To translate the chemistry into practical, field-ready formats, we immobilized the nanozyme and chromogenic reagents on three low-cost platforms-ionic-crosslinked hydrogel beads, cotton-fabric colorimetric arrays and prefunctionalized cotton swabs-each tailored to balance reagent immobilization,

mass transfer and ease of readout. The hydrogel approach provides controlled reagent release and stable chromogenic kinetics, while the cotton-based substrates exploit capillary-driven enrichment and rapid liquid handling to accelerate response and reduce matrix interference. We validated the method in representative complex matrices, including spiked lake water and serum, and the results suggest satisfactory performance in lake water, while serum analysis showed that matrix-associated reducing species may affect the apparent recovery to some extent.

In summary, the present work integrates a Fe-Co-Ce ternary nanozyme with simple, user-friendly sensing interfaces to deliver a rapid, sensitive and portable toolkit for sulfide surveillance. By combining high catalytic activity, magnetic recyclability and smartphone-compatible dual readouts, the proposed system addresses major practical constraints of on-site environmental and human health monitoring and offers a modular strategy that can be adapted to other analytes of interest.

2. Experimental Part

2.1 Reagents and Instruments

All reagents and instruments are provided in the supplementary materials.

2.2 Material Synthesis

All reagents and detailed synthesis steps for Fe_3O_4 nanoparticles, FCF particles, and the final FCF/Ce-BDC composite material are provided in Section S1 of the supporting documents.

2.3 POD-like Activity

To evaluate the POD-like activity of FCF/Ce-BDC, TMB was used as the chromogenic substrate. A reaction mixture containing 30 μL of FCF/Ce-BDC, 20 μL of TMB at varying concentrations, 50 μL of H_2O_2 , and 100 μL of sodium acetate buffer (0.2 M, pH 3.5) was incubated at 37 $^\circ\text{C}$ for 5 min. The ultraviolet-visible absorption spectra were recorded, and the kinetic parameters were fitted to the Michaelis-Menten equation to obtain K_m .

2.4 Dual-mode Determination of Sulfide

For dual-mode detection, varying concentrations of hydrogen sulfide solutions (10 μL) were added to a mixture containing 50 μL of TMB (10 mM), 50 μL of H_2O_2 (10 mM), 50 μL of FCF/Ce-BDC and use ABS (0.2 M, pH 3.5) to bring the volume up to 500 μL . After incubation at 37 $^\circ\text{C}$ for 20 min, the UV absorbance and RGB values of the reaction mixture were measured. The limit of detection (LOD) was calculated as $\text{LOD} = 3$, where δ represents the standard deviation of the blank signal ($n = 20$) and S denotes the slope of the calibration curve.

2.5 Fabrication of On-site Sensors

Using FCF/Ce-BDC as the active component, three types of carriers (hydrogel, cotton fabric, and cotton swab) were prepared via immobilization. The procedures for sample loading and color development are described in Sections S2-S4 of the Supporting Information. The hydrogel requires 10 min for color development, whereas the fabric and cotton swab require 5 min.

2.6 Analysis of Real Samples

Healthy human serum and lake water were selected as samples and subjected to specific pretreatment measures, as detailed in Section S6 of the Supporting Information. These samples were then used for dual-mode detection. The pH of the test samples was adjusted to 3.5 using acetic acid/sodium acetate buffer, and dual-mode detection was performed as described in Section.

3. Results and Discussion

3.1 Feasibility and Perceived Strategies

- The synthesis of the FCF/Ce-BDC nanozyme is illustrated in Scheme 1A. The composite exhibits pronounced POD-like activities as well as excellent structural stability, which together enable dual-mode sensing. In the presence of H_2O_2 the FCF/Ce-BDC catalyst activates peroxide to produce hydroxyl radicals ($\cdot\text{OH}$) that oxidize TMB into its blue oxidized form (oxTMB) [24, 25]. Consequently, the absorbance band of oxTMB around 651 nm is markedly enhanced when H_2O_2 is present. After adding the solution containing sulfides, the absorbance of the system at 651 nm decreased significantly, and a visible color change from blue to colorless was observed by the naked eye (Fig. 2A). Based on these complementary effects, we therefore establish a dual-readout colorimetric sensing scheme for sulfide detection that combines spectrophotometric absorbance changes with naked-eye / smartphone-extracted RGB analysis.

3.2 Characterization of FCF/Ce-BDC

- Transmission electron microscopy (TEM; 120 kV; Fig. 1B) reveals that the synthesized material exhibits a hierarchical composite structure derived from the integration of Fe_3O_4 , CoFe_2O_4 , and Ce-BDC components. Scanning electron microscopy further shows a roughened outer surface with an interconnected porous morphology, indicating the successful incorporation of the Ce-BDC framework (Fig. 1C). Nitrogen adsorption-desorption analysis (BET) gives a specific surface area of $17.0077 \text{ m}^2\cdot\text{g}^{-1}$ and an average pore diameter of 23.25841 nm, confirming the mesoporous nature of the composite, which is beneficial for substrate diffusion and interfacial interactions (Fig. 1E). The composite exhibited strong magnetic responsiveness, as evidenced by the M-H curve and rapid magnetic separation. Within 10 seconds of magnetic exposure, a clear phase boundary was observed, highlighting its excellent recyclability (Fig. 1I). In addition, X-ray photoelectron spectroscopy (see Table S1) and elemental mapping (Fig. 1J-1N) confirm the uniform distribution and expected chemical states of Fe, Co, Ce, O and C within the composite. Detailed experimental

parameters and full spectral data are provided in Section S5 of the Supporting Information (Fig. S2 and S3).

3.3 Structure-performance Relationship Analysis

- Based on the structural characteristics described above, the $\text{Fe}_3\text{O}_4/\text{CoFe}_2\text{O}_4/\text{Ce-BDC}$ hybrid architecture provides a favorable platform for catalytic reactions. The mesoporous structure and enlarged surface area facilitate the diffusion and adsorption of small-molecule substrates such as TMB and H_2O_2 , thereby improving their accessibility to active sites [26, 27]. Meanwhile, the integration of multiple metal centers (Fe, Co and Ce) enables synergistic redox interactions, which are beneficial for efficient H_2O_2 activation and reactive oxygen species generation [28]. As summarized in Table S2, Fe_3O_4 exhibited a K_m of 0.1634 mM and a V_{max} of $1.487 \times 10^{-7} \text{ Ms}^{-1}$, while $\text{Fe}_3\text{O}_4/\text{FeCo}_2\text{O}_4$ showed a slightly lower K_m of 0.1576 mM together with a much higher V_{max} of $2.839 \times 10^{-7} \text{ Ms}^{-1}$, indicating improved catalytic efficiency after FeCo_2O_4 coupling. Upon further coating with Ce-BDC, the ternary $\text{Fe}_3\text{O}_4/\text{FeCo}_2\text{O}_4/\text{Ce-BDC}$ composite displayed a higher apparent K_m of 0.1966 mM and a V_{max} of $2.029 \times 10^{-7} \text{ Ms}^{-1}$. The increase in K_m suggests a moderate reduction in substrate affinity, which is reasonably attributed to partial masking of active sites and the additional diffusion barrier introduced by the outer Ce-BDC layer. Nevertheless, the V_{max} remained markedly higher than that of bare Fe_3O_4 , confirming that the hierarchical heterostructure still preserves efficient catalytic turnover. The retained magnetic properties enable the rapid separation and reuse of the catalyst, thereby enhancing the practicality of the system. Overall, these characteristics contribute to the excellent POD-like activity of the $\text{Fe}_3\text{O}_4/\text{CoFe}_2\text{O}_4/\text{Ce-BDC}$ nanozyme.

3.4 POD-like Activity of FCF/Ce-BDC

- TMB was oxidized to oxTMB in the presence of H_2O_2 , and the FCF/Ce-BDC/ H_2O_2 /TMB system displayed the characteristic blue product with an absorption maximum at 651 nm, indicating that the composite possesses pronounced POD-like activity. To verify the role of reactive oxygen species during the catalytic process, isopropyl alcohol was used as a $\cdot\text{OH}$ scavenger and was found to markedly suppress the absorbance at 651 nm, suggesting that $\cdot\text{OH}$ is the participating in the redox reaction of this system (Fig. S4D). In addition, DMPO-based ESR measurements produced the typical 1 : 2 : 2 : 1 quartet signal, further confirming the generation of $\cdot\text{OH}$ during nanozyme catalysis (Fig. 2C).
- The catalytic behavior of the composite was then evaluated by Michaelis-Menten kinetics. Lineweaver-Burk analysis across different TMB and H_2O_2 concentrations gave apparent K_m and V_{max} values, demonstrating favorable substrate affinity and efficient catalytic turnover ($K_m = 0.1966 \text{ mM}$, $V_{max} = 2.029 \times 10^{-7} \text{ Ms}^{-1}$). The effect of component loading was also examined in Table S3. When the Ce-BDC content was reduced to half of the standard formulation, the catalytic response decreased markedly and reliable kinetic fitting could not be obtained. In contrast, excessive loading

of the outer framework led to poorer dispersion and reduced catalytic stability. The optimized composition (Ce-BDC : CoFe_2O_4 : Fe_3O_4 = 1.2 : 1.3 : 1) therefore provided the best balance between activity and structural stability.

- Mechanistically, the catalytic performance arises from the cooperative contribution of the three domains. The $\text{Fe}^{2+}/\text{Fe}^{3+}$ sites in the magnetic component catalyze H_2O_2 decomposition via Fenton-type pathways to generate $\cdot\text{OH}$ [29]. The co-containing domain facilitates redox cycling and promotes electron transfer between metal centers, thereby enhancing ROS production [30]. Meanwhile, the Ce-containing MOF layer, featuring mixed $\text{Ce}^{3+}/\text{Ce}^{4+}$ states, accelerates H_2O_2 activation and further amplifies radical generation [31]. Together, these synergistic effects account for the enhanced POD-like behavior of the hybrid nanozyme.

3.5 Impacts of Sulfide on FCF/Ce-BDC Catalyzed POD-like Reaction

- We then investigated the response of the FCF/Ce-BDC/TMB system to sulfide. As shown in Fig. 2A, the catalyst-TMB mixture initially exhibited a deep blue color as a result of oxTMB formation. Upon addition of 100 μM sulfide, the solution gradually faded and eventually became nearly colorless, accompanied by a pronounced decrease in the absorption band at 651 nm (Fig. 2A). This observation indicates that sulfide interferes with the chromogenic process and suppresses the accumulation of oxTMB.
- Sulfide may affect the system through multiple routes. First, under acidic conditions, it can rapidly scavenge reactive oxygen species generated during H_2O_2 activation, thereby reducing the amount of oxidant available for TMB conversion [32], [33]. Second, sulfide can directly reduce oxTMB, leading to decolorization of the blue product and attenuation of the 651 nm signal [34]. Third, pre-incubation of the nanozyme with sulfide significantly weakened its catalytic output, suggesting that sulfide may also suppress the intrinsic enzyme-mimetic activity by interacting with surface metal centers and partially blocking active sites [35].
- To further support this interpretation, control experiments were performed. As shown in Fig. S4A and S4B, the nanozyme efficiently oxidized TMB to blue oxTMB, whereas the subsequent addition of ascorbic acid restored the colorless state by reducing oxTMB. In a similar manner, sulfide induced rapid fading of the blue color, consistent with its reductive and ROS-scavenging behavior (Fig. S4A). At the same time, we subjected the FCF/Ce-BDC to a 5-minute pre-treatment with the sulfide solution. Subsequently, we measured the activities of the nanoenzymes in the experimental group and the control group. The results showed that, at the response value and K_m levels, the activity of the nanoenzymes after pre-treatment with the sulfide solution decreased (Fig. S4C). Collectively, these results demonstrate that sulfide disrupts the nanozyme-catalyzed TMB oxidation process through ROS scavenging, product reduction, and partial inhibition of catalytic sites, thereby enabling sensitive colorimetric detection.

3.6 Dual-mode Determination of Sulfide

- To determine optimal operating conditions, we systematically screened reaction time, temperature and buffer pH for both spectrophotometric and RGB readout modes. For the colorimetric and RGB measurements the best performance was obtained after a 20 min incubation at 37 °C. The reaction pH strongly influenced the nanozyme activity and the redox balance of the system; although activity was acceptable near neutral, an acidic environment favored rapid oxidation/reduction dynamics and reproducible signal modulation, so pH 3.5 was selected as the working condition (Fig. S1A-S1E).

Under these conditions, sulfide sensing produced a concentration-dependent hypochromic response: the absorbance at 651 nm decreased linearly with increasing S^{2-} concentration over the 10–300 μM range ($y = 0.0026x + 0.9388$, $R^2 = 0.9819$), yielding a colorimetric limit of detection of 0.29 μM (Fig. 2H), achieving a lower detection limit than most reported methods in Table S4, including the HJ 1226–2021 methylene blue spectrophotometric method (LOD = 1.03 μM) (Fig. 2H). Statistical analysis using a t-test indicated no significant difference ($p > 0.05$) between the proposed method and the HJ 1226–2021 standard method in Table S5.

- For portable field use, RGB values were captured with ColorPicker software under standardized illumination (6500 K) and controlled ambient conditions; an adaptive RGB processing model was applied to compensate for matrix-induced color bias (Fig. S5). The mean channel metric, G-B, exhibited a robust linear correlation with sulfide concentration across 10–300 μM ($y = 0.2678x - 54.7799$, $R^2 = 0.9822$), corresponding to an RGB-mode LOD of 31.26 μM (Fig. 2G). When both spectrophotometric and smartphone-RGB approaches were applied to identical sample batches, the two readouts produced highly consistent concentration estimates (Fig. 2I), confirming the complementarity and practical interchangeability of the laboratory and field measurements. All spectral and RGB datasets reported in Fig. 2E-2G were generated from the same pooled sample series to ensure internal consistency.

3.7 On-site Determination of Sulfide Based on Hydrogel Platforms, Cotton Swab Sensors and Cotton Fabric-based Sensors

Aqueous sulfide solution was dripped onto the hydrogel sensor and allowed to react for 20 minutes. For portable biosensing, the ColorPicker software was used to capture the colorimetric image, from which RGB chromaticity values were extracted. As shown in Scheme 1E, the RGB values were correlated with sulfide concentration ($y = -0.2718x - 92.1982$, $R^2 = 0.9786$), and the limit of detection (LOD) was 28.72 μM (Fig. 3A-B).

- Different sample concentrations (500 μL) were applied to the pre-functionalized swab tip and incubated for 1 minute. The hierarchical porous structure of cotton fibers enabled rapid permeation

and molecular enrichment. The swab handle was then manually broken, and atmospheric pressure and gravity drove the flow of H_2O_2 and TMB solutions from the swab body to the tip, ensuring self-mixing of reagents (Scheme 1G). After a 2-minute chromogenic reaction, the color change at the swab apex was captured using a smartphone imaging system (Fig. 3D), and analyte concentrations were quantified using ColorPicker software. The results showed a strong linear correlation ($y = 0.1181x - 13.2235$, $R^2 = 0.9907$) between colorimetric intensity and analyte concentration (10–300 μM), with an LOD of 29.74 μM (Fig. 3C). This sensor utilizes the cotton swab's fibrous network to integrate sample pretreatment and signal visualization into distinct regions, offering a practical solution for on-site detection.

Different concentrations of NaHS (10 μL) or samples were placed on the colorimetric interface of the cotton fabric for 5 minutes. Then, 10 μL of a TMB (10 mM) and H_2O_2 mixture in NaAc-HAc buffer (pH 4.0) was added for the color reaction. After 5 minutes, the sulfide concentration was measured using the hydrogel method (Scheme 1F). The RGB value exhibited a linear correlation with sulfide concentration ($y = 0.1509x - 20.2105$, $R^2 = 0.9800$), and the LOD was 30.58 μM (Fig. 3E-F). This cotton-based sensor leverages the capillary action of the fabric for synchronous sample transportation and reaction, offering a low-cost, scalable, and efficient solution for on-site rapid detection.

3.8 System/Technology Comprehensive Performance Evaluation

- To evaluate the selectivity of the dual-mode sensor for sulfide, a panel of common coexisting ions and salts frequently present in polluted waters, including PbCl_2 , CaCl_2 , Na_2SO_4 , NaCl , K_2CO_3 and ZnSO_4 , was examined. Most inorganic ions exerted only limited influence on the colorimetric and RGB responses. However, the sensor still exhibited a clear and concentration-dependent response to sulfide under the tested conditions, indicating its practical applicability in typical environmental matrices (Fig. 4A). When stored at 4 °C for 120 days, the FCF/Ce-BDC nanozyme retained its catalytic performance and RGB response with only minimal attenuation, demonstrating good storage stability under refrigerated conditions (Fig. 4B).
- Using standard method evaluation procedures, the sensor's analytical metrics-accuracy, precision and repeatability-were assessed. Eight replicate measurements of a 10 μM sulfide standard gave relative standard deviations below 2.5% for spectrophotometric colorimetry and below 3.0% for smartphone RGB quantification, confirming excellent reproducibility (Fig. 4C). To conduct a rigorous specificity test, we prepared a mixed interference sample containing one of the eight potential interferents (excluding reductive interferents), with each interferent at a concentration of 10 mM. Compared with the pure sulfide sample, the deviation of the measured sulfide response was less than 5%, indicating a very high specificity for detection in complex matrices by both methods (Fig. 4D).

Table 1
Determination Results of Sulfide in Healthy Human Serum (n = 3)

Sample	Detected (μM)	Added (μM)	Colorimetric sensor			RGB sensor		
			Founded (μM)	Recovery (%)	RSD (%)	Founded (μM)	Recovery (%)	RSD (%)
1	2.1	50	51.2	98.1	1.8	49.85	95.5	6.21
		100	101.6	99.5	2.1	98.9	96.8	5.68
		150	150.8	99.1	1.9	146.7	96.4	3.63
2	1.75	50	50.6	97.7	2.3	48.9	94.3	2.16
		100	100.9	99.1	2	97.8	96	2.56
		150	149.2	98.3	2.4	145.6	95.8	3.77
3	2.45	50	52.1	99.3	1.6	50.3	96	2.10
		100	102.4	99.9	1.8	100.5	98.1	3.43
		150	151.6	99.4	2.2	147.9	96.6	4.65

3.9 Determination of Sulfide in Human Serum and Lake Water

- To assess the practicality of the developed sensor in complex matrices, known amounts of sulfide were spiked into human whole blood and lake water and the recoveries were determined. In Table 1 and Table S6, recoveries for these matrices were respectively found to lie within 97.7%-99.9% and 96.11%-104.68% in the spectrophotometric (colorimetric) mode. Using the smartphone-extracted RGB readout, the corresponding recovery ranges were 95.5%-98.1% and 93.52%-103.36%. The close agreement between colorimetric and RGB results across sample types demonstrates that the dual-readout FCF/Ce-BDC + TMB + H_2O_2 system provides accurate and reliable sulfide quantification in real-world samples.
- The dual-mode sensing architecture delivers clear advantages over single-signal assays by combining laboratory-grade absorbance and field-friendly RGB readouts, improving confidence in ambiguous cases, broadening applicability across different user scenarios, and offering a modular design that is amenable to translation into a rapid on-site testing kit. The practical advantages of this platform are reflected in its integrated design. The hierarchical metal-organic framework-covalent organic framework/nanozyme composite provides improved catalytic activity and analytical sensitivity, while the ferroferric oxide magnetic core enables convenient recovery and reuse of the catalyst, helping to reduce reagent consumption and secondary waste. In addition, the cotton fiber-based interface takes advantage of capillary action to enrich analytes efficiently, allowing a compact sample collection-enrichment-detection process that can be completed within

about 5 min without complex pretreatment. This platform combines the advantages of high catalytic efficiency, low cost, and portable operation. The method achieves satisfactory detection sensitivity with the advantage of simple operation. Therefore, it holds promise for routine environmental monitoring and rapid sulfide screening in health-related contexts.

4. Conclusion

- In summary, we report a comprehensive, field-oriented strategy for dual-mode sulfide sensing that couples a high-performance FCF/Ce-BDC nanozyme with three practical detection interfaces. The hydrogel platform delivers improved colorimetric sensitivity and operational robustness by using ionic crosslinking to confine reagents and regulate chromogenic kinetics for accurate on-site measurements. The cotton-fabric arrays exploit cellulose's capillarity and adsorption capacity to preconcentrate analyte and enable synchronous, low-interference color readout. The cotton-swab format takes advantage of the swab's three-dimensional porous architecture to promote rapid permeation, molecular enrichment and reagent self-mixing through axial flow, yielding an exceptionally simple and rapid workflow for field use. Together, these substrates enable faster and more straightforward visual signal readout while remaining inexpensive and user-friendly, addressing key practical challenges in environmental and human health surveillance. Their reliable performance in complex matrices, together with both spectrophotometric and smartphone-based RGB readouts, provides complementary validation of the sensing platform and supports its suitability as a portable, eco-friendly tool for routine sulfide monitoring and early hazard warning.

Declarations

Declaration of Interest Statement

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.

Bioethical approval

Clinical samples were analyzed in accordance with the decision of the bioethical commission No. NMU Ethical Review (2022) 087, issued by the Ethics Committee at Nanjing Medical University. Sample donors provided their consent for collection and use of samples in this study.

Author Contribution

Qingyuan Weng: Writing-original draft, Writing-review&editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. Xinyi Wen: Writing-original draft, Visualization, Validation, Software, Resources,

Methodology, Formal analysis, Data curation. Tianyuan Wei: Investigation, Formal analysis, Data curation, Conceptualization. Qing Zhang: Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. Wanying Zhu: Formal analysis, Data curation, Conceptualization, Visualization, Validation, Software, Project administration. Junli Hong: Writing-review&editing, Writing-original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Data availability

Data will be made available on request.

References

1. Kim DS, Pessah IN, Santana CM (2023) *Toxicol Sci* 192(2):247–264. <https://doi.org/10.1093/toxsci/kfad022>
2. Domán A, Dóka É, Garai D (2023) *Redox Biol* 60:102617. <https://doi.org/10.1016/j.redox.2023.102617>
3. Kumar R, Sykes DJ, Band VI (2025) *Proc. Natl. Acad. Sci. USA* 122 (25), e2503677122. <https://doi.org/10.1073/pnas.2503677122>
4. Mhatre S, Rai A, Ali H et al (2023) *Biotechniques* 76(2):71–80. <https://doi.org/10.2144/btn-2023-0075>
5. Wang Z, Wang X, Han S (2026) *Microchim Acta* 193(4):242. <https://doi.org/10.1007/s00604-026-07983-y>
6. Sánchez-Cachero A, Jiménez-Moreno M, Fariñas NR et al (2023) *Microchim Acta* 190(12):476. <https://doi.org/10.1007/s00604-023-06032-2>
7. Roh H, Kim D, Cho Y et al (2024) *Adv Mater* 36(27):2312382. <https://doi.org/10.1002/adma.202312382>
8. Qu L, Xu Y, Cui W et al (2025) *Anal Chim Acta* 1336:343307. <https://doi.org/10.1016/j.aca.2024.343307>

9. Shen Y, Chen R, Wang Y et al (2025) *Microchim Acta* 192(10). <https://doi.org/10.1007/s00604-025-07564-5>
10. Chalermnon M, Thomas SR, Chin JM et al (2025) *Inorg Chem Front* 12(21):6435–6459. <https://doi.org/10.1039/D5QI01201E>
11. Yu W, Li A, Lu Z (2026) *Sep Purif Technol* 387:136625. <https://doi.org/10.1016/j.seppur.2025.136625>
12. Yue D, Li RM, Zheng HT et al (2025) *ACS Appl Mater Interfaces* 17(24):36252–36259. <https://doi.org/10.1021/acsami.5c08672>
13. Liang Y, Yang X, Wang X et al (2023) *Nat Commun* 14(1):5223. <https://doi.org/10.1038/s41467-023-40973-9>
14. Zhao X, Gao R, Sun H et al (2025) *Coord Chem Rev* 533:216539. <https://doi.org/10.1016/j.ccr.2025.216539>
15. Lin Z, Yuan J, Niu L (2024) *Coord Chem Rev* 520:216166. <https://doi.org/10.1016/j.ccr.2024.216166>
16. Zhang PY, Wang W, Wang WK (2025) *Environ Sci Technol* 59(48):26182–26195. <https://doi.org/10.1016/j.ccr.2024.216166>
17. Zhang W, Wang L, Pei W (2025) *ACS Appl Mater Interfaces* 17(25):36751–36762. <https://doi.org/10.1021/acs.est.5c14046>
18. Chishti B, Fouad H, Seo HK et al (2020) *New J Chem* 44(26):11291–11303. <https://doi.org/10.1039/C9NJ05955E>
19. Akaike T, Morita M, Ogata S et al (2024) *Free Radical Biol Med* 222:539–551. <https://doi.org/10.1016/j.freeradbiomed.2024.07.007>
20. Ge F, Sun Y, Li H et al (2025) *Reac Kinet Mech Catal* 138(4):1993–2008. <https://doi.org/10.1007/s11144-025-02856-6>
21. Ni X, Marutani E, Shieh M et al (2024) *Angew Chem Int Ed* 63(6). <https://doi.org/10.1002/anie.202317487>
22. Li W, Cai T, Tian J et al (2025) *Anal Chim Acta* 1337:343566. <https://doi.org/10.1016/j.aca.2024.343566>
23. Sun W, Zhu C, Song J et al (2023) *Adv Healthc Mater* 12(23):2300385. <https://doi.org/10.1002/adhm.202300385>
24. Cheng Q, Du X, Fu Z et al (2024) *Polymers* 16(12):1747. <https://doi.org/10.3390/polym16121747>
25. Liu Y, Zhou X, Zhu W (2023) *Inorg Chem* 62(37):15022–15030. <https://doi.org/10.1021/acs.inorgchem.3c01874>
26. Zhang X, Wang J, Chang N et al (2024) *Molecules* 29(9):2117. <https://doi.org/10.3390/molecules29092117>
27. Xing Z, Tian J, Asiri AM et al (2014) *Biosens Bioelectron* 52:452–457. <https://doi.org/10.1016/j.bios.2013.09.029>

28. Jiang S, Sun X, Kong RM et al (2025) *Colloids Surf B* 256:115052.
<https://doi.org/10.1016/j.colsurfb.2025.115052>
29. Huang L, Zhao Y, Bai Y et al (2025) *Catalysts* 15(6):549. <https://doi.org/10.3390/catal15060549>
30. Duan X, Sheng D, Zhu P (2025) *Adv Funct Mater* 35(42):2509426.
<https://doi.org/10.1002/adfm.202509426>
31. Su P, Du X, Zheng Y et al (2022) *Chem Eng J* 433:133597. <https://doi.org/10.1016/j.cej.2021.133597>
32. Misak A, Grman M, Bacova Z (2018) *Nitric Oxide* 76:136–151.
<https://doi.org/10.1016/j.niox.2017.09.006>
33. Wu G, Wan F, Fu H et al (2015) *J Bacteriol* 197(22):3563–3572. <https://doi.org/10.1128/jb.00603-15>
34. Zhang T, Li S, Li R (2025) *Anal Chim Acta* 1348:343795. <https://doi.org/10.1016/j.aca.2025.343795>
35. Oh H, Guo H, Chung MW (2026) *Appl Catal B* 383:126048.
<https://doi.org/10.1016/j.apcatb.2025.126048>

Figures

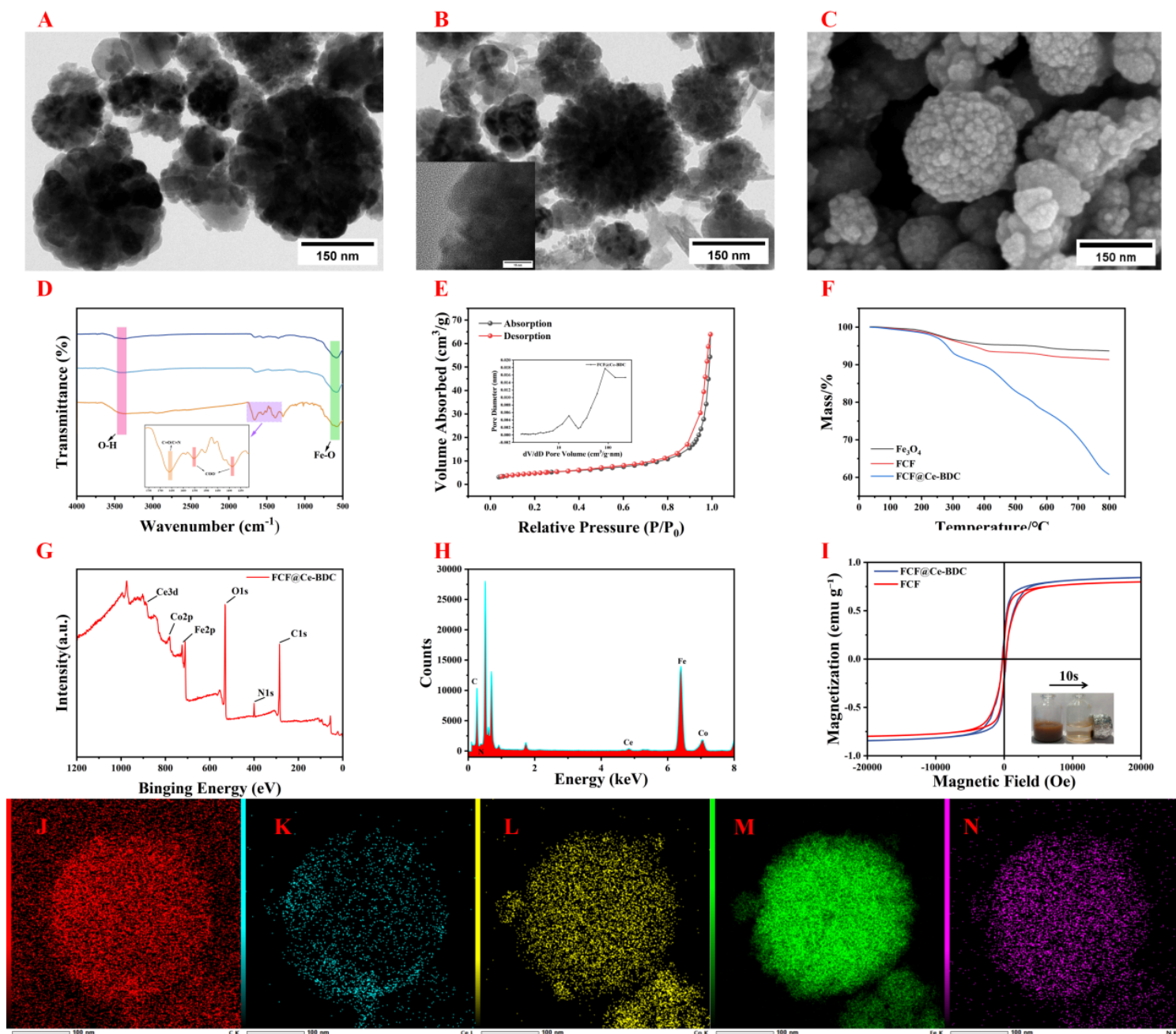


Figure 1

(A) TEM images of FCF. (B) TEM images of FCF/Ce-BDC. (C) SEM images of FCF/Ce-BDC. Inset of (B): HRTEM images of FCF/Ce-BDC. (D) FT-IR spectra of Fe_3O_4 , FCF, and FCF/Ce-BDC. (E) N_2 adsorption and desorption isotherms of FCF/Ce-BDC. Inset of (E): Pore size distribution of FCF/Ce-BDC. (F) TGA curves for Fe_3O_4 , FCF and FCF/Ce-BDC. (G) XPS spectrum of FCF/Ce-BDC. (H) EDS spectrum of FCF/Ce-BDC. (I) Hysteresis curves of FCF and FCF/Ce-BDC. (J)-(N): Elemental mapping of FCF/Ce-BDC.

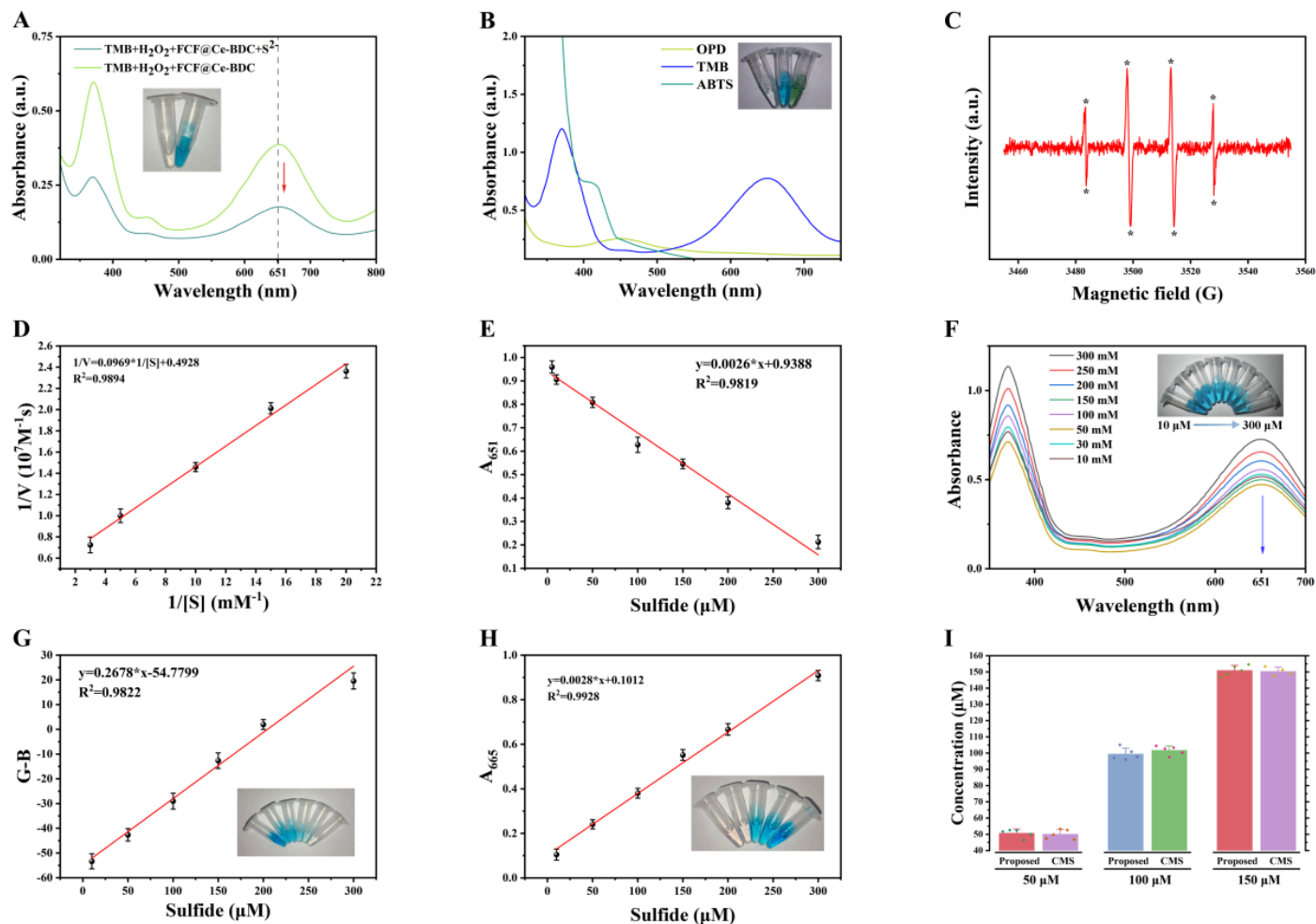
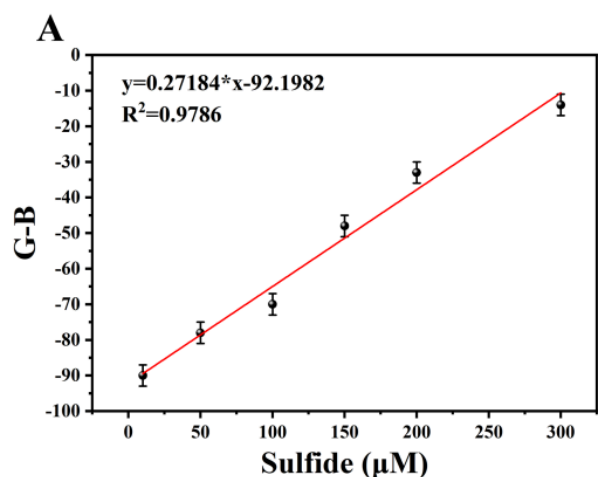
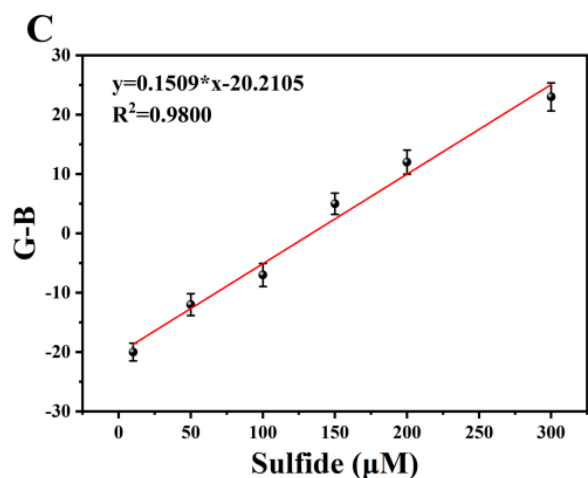
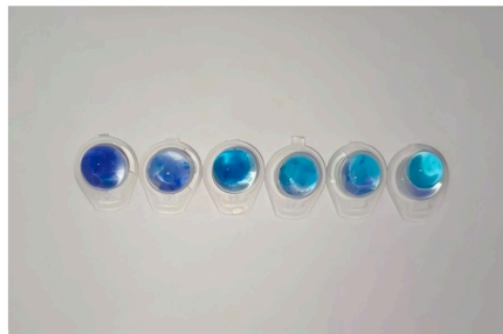


Figure 2

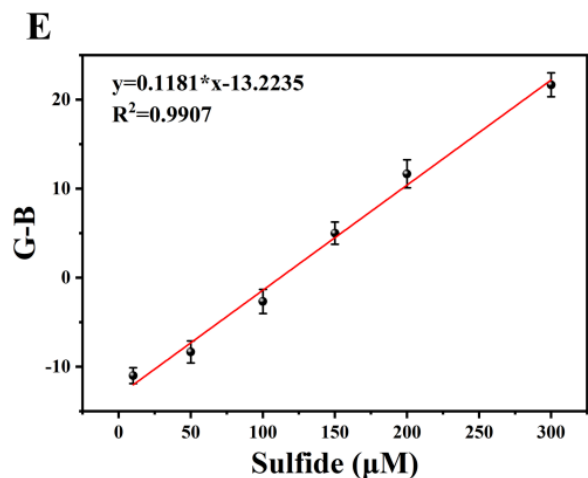
(A) UV-Vis absorption spectra of different systems. (B) Universality of POD-like activity of FCF/Ce-BDC. (C) Electron spin resonance (ESR) spectrum of DMPO + FCF/Ce-BDC. (D) Double-reciprocal plots of FCF/Ce-BDC ($n = 3$). (E) Linearity of A_{651} versus the logarithm of sulfide concentration ($n = 3$). (F) Changes in system UV absorption values at different sulfide concentrations. (G) Linear relationship between RGB value and sulfide concentration ($n = 3$). (H) Linearity of A_{665} versus sulfide concentration ($n = 3$). (I) Comparison of detection values for samples with different concentrations obtained by the proposed colorimetric method and the Chinese standard method (CMS) ($n = 5$).



B



D



F

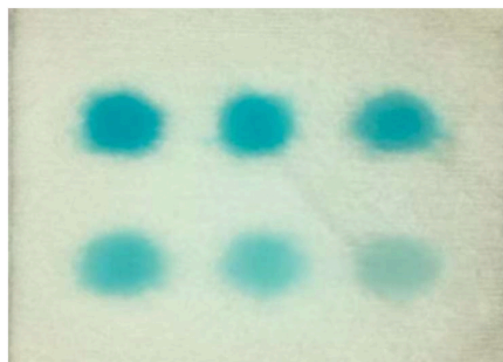


Figure 3

(A) Linear relationship between RGB value and sulfide level in hydrogel platform ($n = 3$). (B) Changes in color of hydrogel platform system at different sulfide concentrations. (C) Linear relationship between RGB value and sulfide level in cotton swab sensor ($n = 3$). (D) Changes in color of cotton swab sensor system at different sulfide concentrations. (E) Linear relationship between RGB value and sulfide level in cotton-fabric-based sensor ($n = 3$). (F) Changes in color of cotton-fabric-based sensor system at different sulfide concentrations.

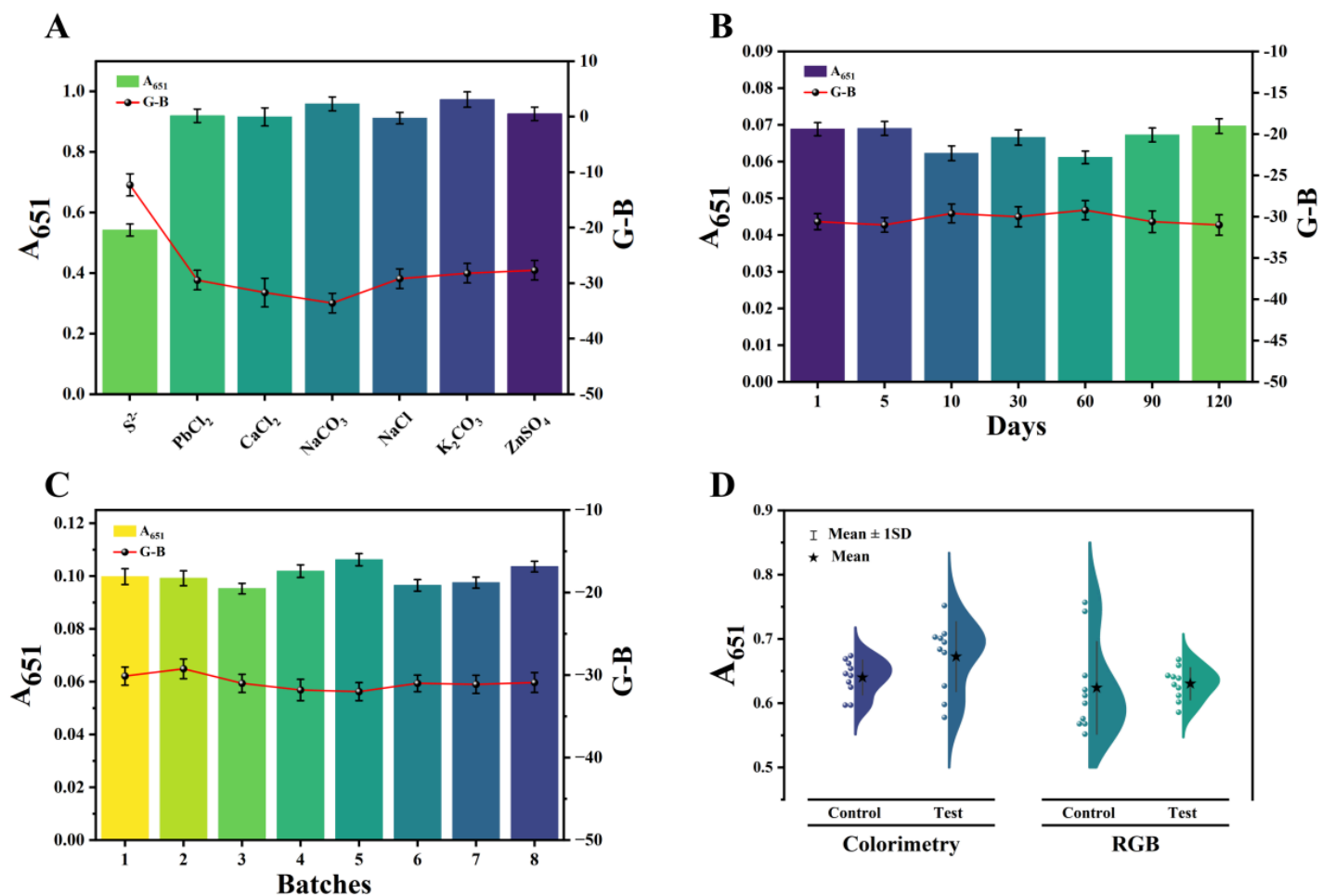


Figure 4

(A) Sulfide selectivity of reaction system ($n=3$). (B) Stability of dual-mode sensor based on FCF/Ce-BDC over 120 days ($n=3$). (C) Precision of dual-mode sensor based on FCF/Ce-BDC ($n=3$). (D) Specificity of dual-mode sensor based on FCF/Ce-BDC ($n=10$).

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