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Colorimetric assay based on NiCo₂S₄@N,S-rGO nanozyme for sensitive detection of H₂O₂ and glucose in serum and urine samples†

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Traditional bimetallic sulfide-based nanomaterials often have a small specific surface area (SSA), low dispersion, and poor conductivity, thereby limiting their wide applications in the nanozyme-catalytic field. To address the above issues, we herein integrated NiCo₂S₄ with N,S-rGO to fabricate a nanocomposite (NiCo₂S₄@N,S-rGO), which showed a stronger peroxidase-mimetic activity than its pristine components. The SSA (155.8 m² g⁻¹) of NiCo₂S₄@N,S-rGO increased by ~2-fold compared to NiCo₂S₄ with a pore size of 7–9 nm, thus providing more active sites and charge transfer channels. Based on the Michaelis–Menten equation, the affinity of this nanocomposite increased 40% and 1.1~10.6-fold compared with NiCo₂S₄ with N,S-rGO, respectively, highlighting the significant enhancement of the peroxidase-like activity. The enhanced activity of this nanocomposite is derived from the joint participation of ·OH, ·O₂⁻, and photogenerated holes (h⁺), and was dominated by h⁺. To sum up, N,S-codoping, rich S-vacancies, and multi-valence states for this nanocomposite facilitate electron transfer and accelerate reaction processes. The nanocomposite-based colorimetric sensor gave low detection limits for H₂O₂ (12 μM) and glucose (0.3 μM). In comparison with the results detected by a common glucose meter, this sensor provided the relative recoveries across the range of 97.4–101.8%, demonstrating its high accuracy. Moreover, it exhibited excellent selectivity for glucose assay with little interference from common co-existing macromolecules/ions, as well as high reusability (>6 times). Collectively, the newly developed colorimetric sensor yields a promising methodology for practical applications in H₂O₂ and glucose detection with advantages of highly visual resolution, simple operation, convenient use, and satisfactory sensitivity.

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1 Introduction

Diabetes is a chronic disease caused by insulin secretion defects or insulin dysfunction. Severe diabetes can lead to various acute and chronic complications, such as cardiovascular disease, diabetic ketoacidosis, renal dysfunction, insomnia, and so on.^{1,2} The International Diabetes Federation (IDF) projects that nearly 592 million people worldwide will have diabetes by 2035.³ Timely monitoring of patients' blood glucose and urine sugar level plays an extremely important role in the prevention and control of diabetes. Hydrogen peroxide (H₂O₂) acts as one of the important signaling molecules regulating fundamental biological processes, while an escalated level of H₂O₂ can trigger irreversible oxidative damage of lipids, proteins and DNA, as

well as some diseases such as neurodegeneration, diabetes, Alzheimer's disease, and even cancer.⁴ Thus, it is of practical significance to develop a rapid, sensitive, efficient and inexpensive H₂O₂ and glucose assay methodology.

At present, a variety of approaches for the detection of glucose and H₂O₂ have been established, such as enzymatic methods,⁵ glucose meters,⁶ electrochemical non-enzymatic methods,^{7–11} high performance liquid chromatography (HPLC),¹² capillary zone electrophoresis,¹³ Fourier transform infrared spectroscopy (FT-IR),¹⁴ *etc.* The aforementioned methods have many kinds of drawbacks, such as difficult storage of natural enzymes, complex pretreatment procedures prior to chromatographic, spectrometric, and electrochemical detection, low sensitivity of glucose meter, *etc.*^{15,16} Relatively, colorimetric approaches based on horseradish peroxidase (HRP) have attracted much attention because of their simplicity, rapidity, small background interference, and high sensitivity.¹⁷ However, HRP, an important natural enzyme, is costly to prepare and not easily stored after denaturation, heating or chemical changes. In recent years, novel nanozymes with peroxidase-like activity have been developed as alternatives to address the above issues of natural enzymes, such as high cost, difficult storage, *etc.* It is worth noting that their

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applications in the detection of glucose and H_2O_2 have become a research hotspot.^{18,19}

Since the first introduction of Fe_3O_4 with peroxidase-like activity,²⁰ various nanomaterials have been widely developed as various colorimetric sensing platforms, including metal oxides,²¹ biological carbon-based materials,²² metal organic frameworks with porous structure,²³ and various nanohybrids and their derivatives.²⁴ Zhou's team (2022) prepared Cu/N co-doped carbon-based nanozyme (Cu/NC NS) by pyrolysis by utilizing two-dimensional Cu nanosheet as metal precursor, $\text{g-C}_3\text{N}_4$ as nitrogen source and carbon substance, which possessed superior peroxidase-like activity of copper based nanomaterials.²⁵ Liu's teamwork (2019) synthesized a novel nanozyme by decorating highly dispersed ultrafine IrO_2 nanoparticles on reduced graphene oxide (rGO) nanosheets, and found that the IrO_2 @rGO exhibited intrinsic peroxidase-like activity to catalyze 3,3',5,5'-tetramethylbenzidine (TMB) oxidation to produce a blue color in the presence of H_2O_2 .²⁶ He and coworkers (2021) prepared porphyrin functionalized urchin-like CuCo_2O_4 nanospheres and successfully developed a colorimetric sensor for dopamine detection in human serum based on the inhibitory effect on TMB. By virtue of the synergistic-enhancing oxidase activity between 2D Co_3O_4 substrate and Rh nano particles, the obtained 2D Co_3O_4 @Rh catalyzed the oxidation of TMB to blue TMB. By virtue of the synergistic-enhancing oxidase activity between 2D Co_3O_4 substrate and Rh nano particles, the obtained 2D Co_3O_4 @Rh catalyzed the oxidation of TMB to blue TMB with superior oxidase-like performance for visual sensing of bioactive urea and *p*-aminopenol.²⁸ A metal-organic framework-derived NiCo_2O_4 was confirmed to have both peroxidase-like and oxidase-like activities, which could oxidize colorless TMB to blue TMB in the absence of H_2O_2 .²⁹

Compared to the corresponding metal compounds or metal oxides, the transition metal sulfides have better redox properties and are considered as promising nanoenzymes.³⁰ Borthakur *et al.* (2021) fabricated transition metal sulfide/porous rGO-based nanohybrids with intrinsic peroxidase-like activity, and developed a simple colorimetric sensor utilizing the feature that Hg(II) inhibited nanozymes.³¹ The bimetallic sulfide, especially for NiCo_2S_4 , is feasible for constructing a colorimetric sensing platform based on its high peroxidase activity from complex crystal structure and polyvalent state.³² However, the small specific surface area (SSA) and poor electrical conductivity affect the catalytic activity and stability of NiCo_2S_4 . Comparatively, owing to high SSA and stability, rGO is often employed to improve the conductivity and structural stability of NiCo_2S_4 and to increase the active sites and catalytic efficiency.^{33,34} Liu and coworkers (2022) synthesized $\alpha\text{-Fe}_2\text{O}_3$ @rGO to increase the electron transfer ability, prevented the agglomeration of Fe_2O_3 and enhanced its photo Fenton catalytic ability.³⁵ Interestingly, the introduction of heteroatoms such as N, S, and B can also improve the catalytic activity of nanoenzymes. Due to the doping of heteroatoms, the structures of the pristine nanomaterials form a certain degree of lattice distortion, resulting in more defects and changes in electronic structures of the doped atoms near heteroatoms, and thus the catalytic activities of the doped nanomaterials are greatly improved.

Lighted by the previous research findings, this study aims to construct a highly efficient nanozyme by employing the advantages of the doping of heteroatoms, bimetallic sulfide, as well as

high SSA and strong dispersion of rGO. As a proof-of-concept, we anchored NiCo_2S_4 onto the N,S-doped rGO to design a nanocomposite of NiCo_2S_4 @N,S-rGO by a facile hydrothermal method. The as-constructed nanocomposite was confirmed to have higher SSA, stability, and superior peroxidase-mimetic activity than its pristine component NiCo_2S_4 . The catalytic behavior of NiCo_2S_4 @N,S-rGO conformed to the Michaelis-Menten equation, which could oxidize colorless TMB to blue TMB in the presence of H_2O_2 . A series of important variables were optimized to acquire the highly efficient chromogenesis. Under optimized conditions, a visual detection platform based on the as-constructed nanozyme was developed for sensitive detection of H_2O_2 and glucose in human urine and serum samples.

2 Experimental section

2.1 Chemicals and reagents

The following chemicals and reagents were purchased from Aladdin (Shanghai, China): $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$, $\text{Ni}(\text{CH}_3\text{COO})_2 \cdot 4\text{H}_2\text{O}$, thioacetamide (TAA), *p*-benzoquinone (PBQ), isopropanol (IPA), disodium ethylenediamine tetraacetate (EDTA-2Na), ethylene glycol (EG), acetic acid (HAC), dimethyl sulfoxide (DMSO), sodium acetate (NaAc), and TMB. GO was achieved from Xianfeng Nanomaterial Technology Corporation (Nanjing, China). Ultrapure water ($>18.2 \text{ M}\Omega$) was generated with a Milli-Q Gradient system (Bedford, MA, USA). All reagents were used when received without further purification.

2.2 Instruments for synthesis and characterization

The following instruments were used to synthesize the NiCo_2S_4 , N,S-rGO, and NiCo_2S_4 @N,S-rGO: KQ-500DE numerical control ultrasonic cleaner (Kunshan Ultrasonic Instrument Corporation, Kunshan, China), OTF-1200 \times tubular furnace (Hefei Kejing Material Technology, Hefei, China), DHG-9070a electric blast drying oven (Xiwen Biotechnology, Shanghai, China), B15-3 multifunctional constant temperature and speed magnetic stirrer (Shanghai Sile Instrument Corporation, Shanghai, China), and PB-10 pH meter (Sedolis Scientific Instrument, Nanjing, China).

Transmission electron microscopy (TEM) images of the NiCo_2S_4 , N,S-rGO, and NiCo_2S_4 @N,S-rGO were recorded on a Talos F200S (Thermo Scientific, USA), which was operated at an accelerating voltage of 200 kV. X-ray photoelectron spectroscopy (XPS) measurement was conducted on an ESCALAB 250Xi with Al K_{α} source (Thermo Scientific, USA). Fourier transform infrared (FT-IR) spectra were determined on a Bruker Tensor II spectrometer (Berlin, Germany). All ultraviolet-visible absorbance was measured on a UV-2600 spectrophotometer (Shimadzu Company, Tokyo, Japan).

2.3 Preparation of the NiCo_2S_4 , N, S-rGO, and NiCo_2S_4 @N, S-rGO

To prepare the NiCo_2S_4 @N,S-rGO nanocomposite, 31.1 mg of $\text{Ni}(\text{CH}_3\text{COO})_2 \cdot 4\text{H}_2\text{O}$, 59.48 mg of $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$, and 187.82 mg of TAA were dissolved in 5 mL of ethylene glycol and stirred at ambient conditions for 30 min at 500 rpm to achieve a homogeneous solution A. Subsequently, 10 mg of GO was



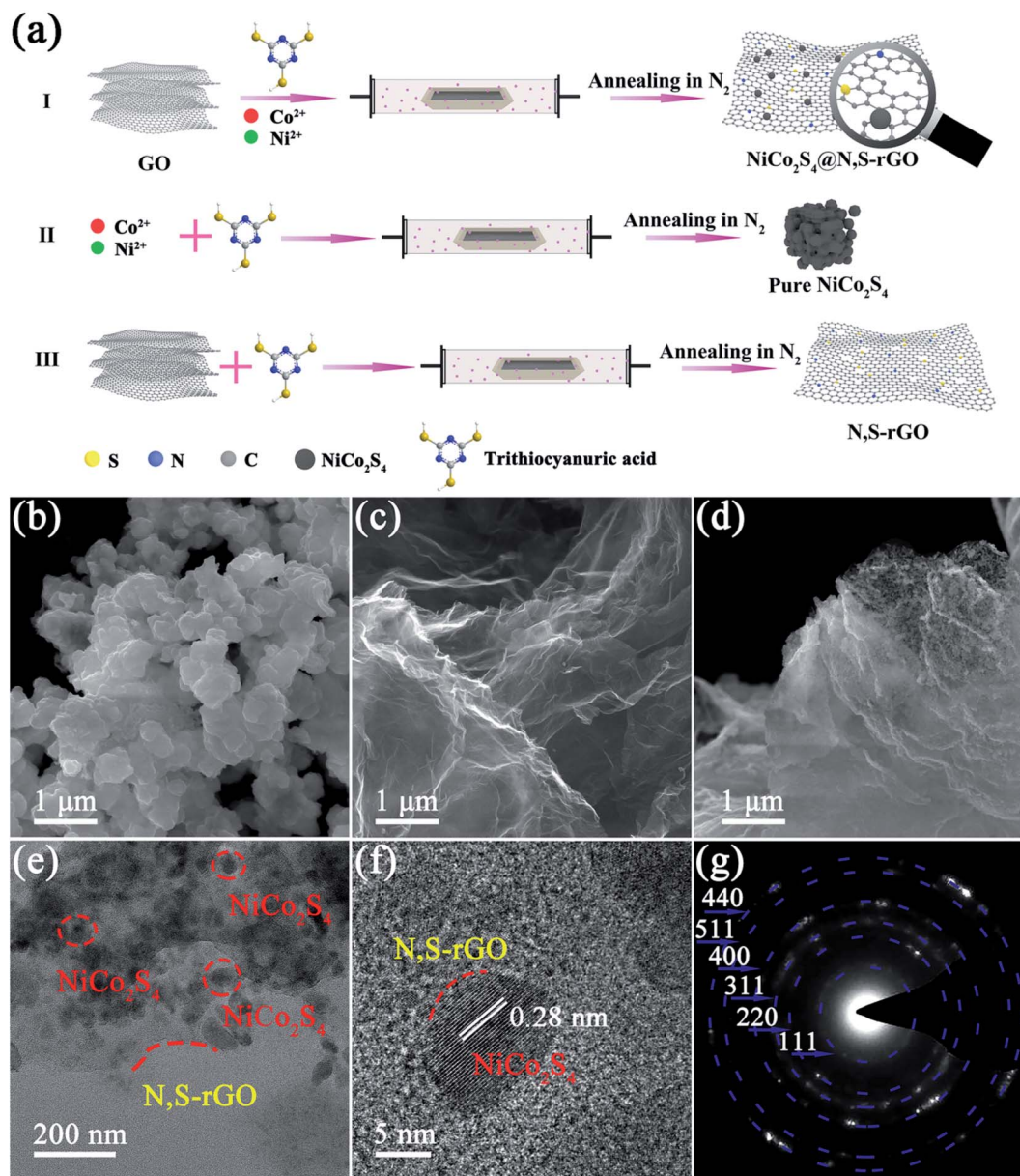


Fig. 1 (a) Schematic diagram of the overall fabrication procedures for the NiCo₂S₄@N,S-rGO. (b) SEM image of the NiCo₂S₄. (c) SEM image of the N,S-rGO. (d) SEM image of the NiCo₂S₄@N,S-rGO. (e) TEM image of the NiCo₂S₄@N,S-rGO. (f) HRTEM image of the NiCo₂S₄@N,S-rGO. (g) Selected area electron diffraction (SAED) of the NiCo₂S₄@N,S-rGO.

added to 2 mL of ethylene glycol and sonicated for 30 min to make it well dispersed, and the resultant solution was dropwise added to the aforementioned solution A under ultrasonic conditions. The final mixed solution was calcined at 300 °C under N₂ atmosphere with a heating rate of 5 °C min⁻¹ for 60 min. The calcined material was washed with deionized water and ethanol alternately three times, and oven-dried at 60 °C. The final dark gray material was NiCo₂S₄@N,S-rGO (Fig. 1a(I)).

By way of contrast, NiCo₂S₄ was acquired in the absence of GO in the synthetic procedures (Fig. 1a(II)), and N,S-rGO was obtained without adding cobalt and nickel salts in the preparation processes (Fig. 1a(III)).

2.4 Peroxidase-like activity of the NiCo₂S₄@N,S-rGO

The catalytic reaction of TMB (a typical chromogenic substrate) was used to evaluate the peroxidase-like activity of NiCo₂S₄@N,S-rGO. In brief, 60 μL of NiCo₂S₄@N,S-rGO (1 mg mL⁻¹), 200 μL of TMB (6 mM) and H₂O₂ (50 mM) were incubated at 40 °C for 20 min in 2 mL of NaAc-HAc buffer solution (pH 4.0). The 652 nm absorbance of reaction solution was recorded on a UV-2600 spectrophotometer.

2.5 Sample preparation

Human serum and urine samples were gratis supplied by the First Affiliated Hospital of Wenzhou Medical University (Wenzhou, China). The samples were stored at 4 °C for



subsequent use within 15 days. Prior to use, the pretreated serum samples were diluted by 100-fold for H₂O₂ and glucose assay.

2.6 Ethics statement

All experiments were performed in accordance with the guidelines of the Institutional Animal Care and Use Committee. Experiments were approved by the ethics committee at Suzhou University of Science and Technology, as well as Wenzhou Medical University. Informed consents were obtained from human participants of this study.

2.7 H₂O₂ and glucose assay

As for H₂O₂ assay, 60 μL of 1 mg L^{-1} NiCo₂S₄@N,S-rGO suspension was added to 1700 μL NaAc-HAC buffer solution (20 mM, pH 4.0), which was referred to solution B. Subsequently, 200 μL of 6 mM TMB (dissolved with DMSO) and 40 μL of H₂O₂ solution at varying concentrations were added to solution B and mixed ultrasonically. The mixed solution was incubated at 40 °C for 20 min, and the resulting blue solution was filtered with 0.45 μm nylon member filter, diluted with Milli-Q ultrapure water and subjected to UV-vis spectral analysis at 652 nm.

The procedures for detecting glucose were similar to H₂O₂ assay, except for that the different concentrations of H₂O₂ solutions were replaced by the glucose solutions after incubation with glucose oxidase (GO_x) at 40 °C for 30 min. Under the optimized experimental conditions, the cyclability of the prepared nano-enzyme was studied. NiCo₂S₄@N,S-rGO washed with ethanol and water, centrifuged and filtered for collection.

3 Results and discussion

3.1 Characterization of NiCo₂S₄@N,S-rGO and its precursors

The overall preparation process of NiCo₂S₄@N,S-rGO is vividly elaborated in Fig. 1a. Briefly, the mixed solution of CoCl₂, Ni(OCOCH₃)₂ and TAA was dripped into the suspension of GO, and the Ni²⁺ and Co²⁺ were well dispersed and integrated with GO due to the electrostatic adsorption (Fig. 1a(I)). Under N₂

atmosphere, C=S, C-N, and -NH₂ in TAA provided N and S sources for the as-fabricated nanocomposite, and an excessive S source was conducive to the formation of vacant sites onto the nanosheets. The NiCo₂S₄, N,S-rGO, and NiCo₂S₄@N,S-rGO were morphologically characterized by SEM and TEM. Owing to the absence of GO, the NiCo₂S₄ showed agglomerates, which were composed of irregular particles (Fig. 1b). As exhibited in Fig. 1c, N,S-rGO nanosheets contained abundant folds. For the NiCo₂S₄@N,S-rGO, a large number of small particles were distributed on the surface of N,S-rGO nanosheets, thereby avoiding agglomeration of NiCo₂S₄ and providing more reactive sites. Moreover, the TEM and HRTEM images of NiCo₂S₄@N,S-rGO demonstrated the homogeneous dispersion of NiCo₂S₄ nanoparticles on the N,S-codoped graphene sheets (Fig. 1e and f). More interestingly, the HRTEM image showed that the N,S-rGO nanosheets were well integrated with the NiCo₂S₄ particles to form the uniform composite structure with the lattice fringes of ~ 0.28 nm, which accorded well with the (311) plane of NiCo₂S₄ (Fig. 1f). The clear boundary between NiCo₂S₄ and N,S-rGO proved that the Ni and S atoms were well dispersed on the surface of N,S-rGO. The corresponding selected area electron diffraction (SAED) patterns displayed the polycrystallinity of NiCo₂S₄, which was associated with the bright circular rings of the (111), (220), (311), (400), (511), and (440) planes of NiCo₂S₄. Furthermore, EDS elemental mapping (Fig. S2.†) demonstrated the presence of Ni, Co, S, C, N, evidencing the formation of NiCo₂S₄@N,S-rGO.

By XRD analysis, we observed very clear diffraction peaks for both NiCo₂S₄ and NiCo₂S₄@N,S-rGO (Fig. 2a). The diffraction peaks (2θ) at 16.34°, 26.83°, 31.59°, 38.32°, 47.41°, 50.46°, and 55.33° were in good agreement with the crystals (111), (220), (311), (400), (511), and (440) of the hexagonal phase of NiCo₂S₄ (JCPDS#20-0782), which was consistent with what has been reported previously.^{36,37} These XRD data provide strong evidence that the as-fabricated nanocomposite did not change structure of the pristine nanomaterial, which was in keeping with our SAED test results.

Through Raman spectral analyses (500–2000 cm^{-1}), two peaks were found at 1350 cm^{-1} and 1590 cm^{-1} (Fig. 2b), corresponding to the characteristic Raman modes of carbon in D-

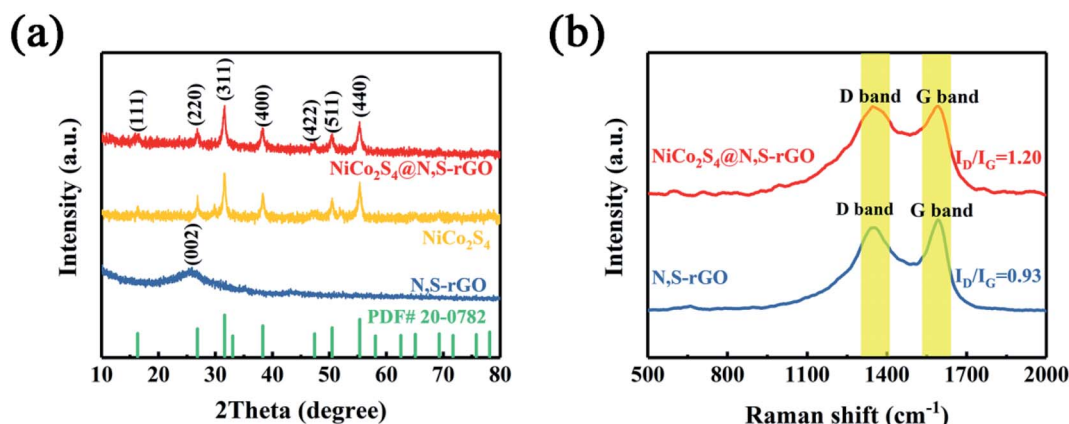


Fig. 2 (a) XRD patterns of the NiCo₂S₄@N,S-rGO, NiCo₂S₄ and N,S-rGO. (b) Raman spectra of the NiCo₂S₄@N,S-rGO, and N,S-rGO.

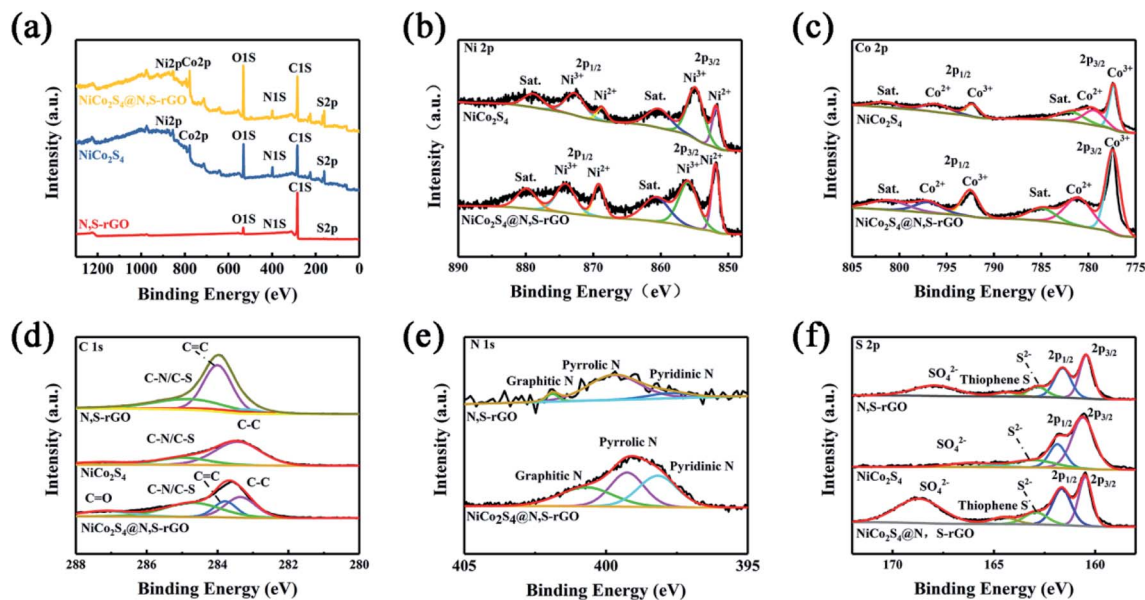


Fig. 3 (a) XPS spectra of the $\text{NiCo}_2\text{S}_4@N,S\text{-rGO}$, NiCo_2S_4 and $N,S\text{-rGO}$; (b) Ni 2p; (c) Co 2p; (d) C 1s; (e) N 1s; and (f) S 2p.

band (disordered carbon) and G-band (ordered graphite carbon), respectively. The G-band, the main characteristic peak of graphene, is caused by the in-plane vibration of sp^2 hybrid carbon atoms. D-band is generally regarded as the disordered vibration peak of graphene and is used to characterize structural defects or edges in graphene samples.³⁸ Compared to $N,S\text{-rGO}$, the $\text{NiCo}_2\text{S}_4@N,S\text{-rGO}$ composite had a higher I_D/I_G ratio, implying that graphene in the composite had more defect sites, which might strongly affect the electron transfer characteristics. By IR spectra (Fig. S1†), the presence of many kinds of oxygenated functional groups (C=O, C=C, and C-O) indicated the successful recombination of NiCo_2S_4 and $N,S\text{-rGO}$. It is worth mentioning that C=O, C-N, and other functional groups provide many types of active sites for the peroxidase-like activity of nanocomposite.

XPS spectroscopy was employed to characterize the composition of NiCo_2S_4 , $N,S\text{-rGO}$, and $\text{NiCo}_2\text{S}_4@N,S\text{-rGO}$ (Fig. 3a). Correspondingly, the peaks at 872.8 and 855.0 eV were attributed to Ni^{3+} , while the peaks at 868.7 and 851.7 eV to Ni^{2+} (Fig. 3b). In particular, the 163 eV peak corresponding to S_2^{2-} indicated the occurrence of S vacancy in the $\text{NiCo}_2\text{S}_4@N,S\text{-rGO}$. The peaks at 792.5 and 777.4 eV belonged to Co^{3+} , while those at 796.3 and 779.4 eV were ascribed to Co^{2+} (Fig. 3c). The multivalence states of complex Co and Ni were favorable for the strengthening of electrical conductivity, especially trivalent Co and Ni. The C 1s core-level spectrum showed the peaks with the binding energies of 287.3, 284.6, 283.8 eV for C=O, C-N/C-S, C=C bonding, respectively (Fig. 3d). These peaks revealed the successful doping of the N and S heteroatoms into the carbon matrix, which was in general agreement with the results of $N,S\text{-rGO}$. Also, the high-resolution spectra of S and N verified the efficient incorporation of heteroatoms. As for the N 1s spectra of $\text{NiCo}_2\text{S}_4@N,S\text{-rGO}$ and $N,S\text{-rGO}$, these deconvolution peaks at 400.9, 399.3, and 398.3 eV were ascribed to graphitic N, pyrrolic-

type N, and pyridine-type N, respectively (Fig. 3e). With regard to the XPS spectrum of S 2p, the peaks at 161.6 and 160.4 eV corresponded to the peaks of S^{2-} , and the 164.5 eV peak for the $N,S\text{-rGO}$ and $\text{NiCo}_2\text{S}_4@N,S\text{-rGO}$ was thiophene S (Fig. 3f), indicating that S atoms were doped in the carbon-based heterocyclic structure.

Fig. S3† displays distinct EPR signals of S-vacancy with a g-factor of 2.004. In contrast to NiCo_2S_4 , the $\text{NiCo}_2\text{S}_4@N,S\text{-rGO}$ showed the higher EPR signal, suggesting an abundance of S-vacancy on its surface. S vacancies provided more active sites and contact sites, which were favorable for the transfer of electrons, and the enhancement of its catalytic activity.

N_2 adsorption-desorption isotherms were adopted to analyze SSAs and pore size distributions (PSDs) of the $\text{NiCo}_2\text{S}_4@N,S\text{-rGO}$, NiCo_2S_4 , and $N,S\text{-rGO}$. As illustrated in Fig. 4a, all isotherms exhibited typical IV curves of hysteresis loop at the higher relative pressure (0.45–1.0), demonstrating their mesoporous structure. The SSA of $\text{NiCo}_2\text{S}_4@N,S\text{-rGO}$ was calculated to be $155.8 \text{ m}^2 \text{ g}^{-1}$, which was ~ 2 -fold greater than that of NiCo_2S_4 ($54.2 \text{ m}^2 \text{ g}^{-1}$). The dominant PSDs of $\sim 7\text{--}9 \text{ nm}$ for three mesoporous materials are shown in Fig. 4b. Collectively, the enlarged SSAs and the mesoporous characteristics provide a large number of active sites and more charge transfer channels, which are beneficial to adsorption and catalytic reaction, and thus improve the enzyme-mimetic activity of $\text{NiCo}_2\text{S}_4@N,S\text{-rGO}$.

3.2 Peroxidase-like and oxidase-like activities of the $\text{NiCo}_2\text{S}_4@N,S\text{-rGO}$ nanocomposite

To verify the feasibility of the $\text{NiCo}_2\text{S}_4@N,S\text{-rGO}$ sensor, we detected the UV-vis absorption of eight reaction systems at 652 nm (Fig. 5). In the presence of only TMB (system 1#), no 652 nm adsorption peak was observed. Similarly, the solution appeared colorless when containing only H_2O_2 (system 2#). In



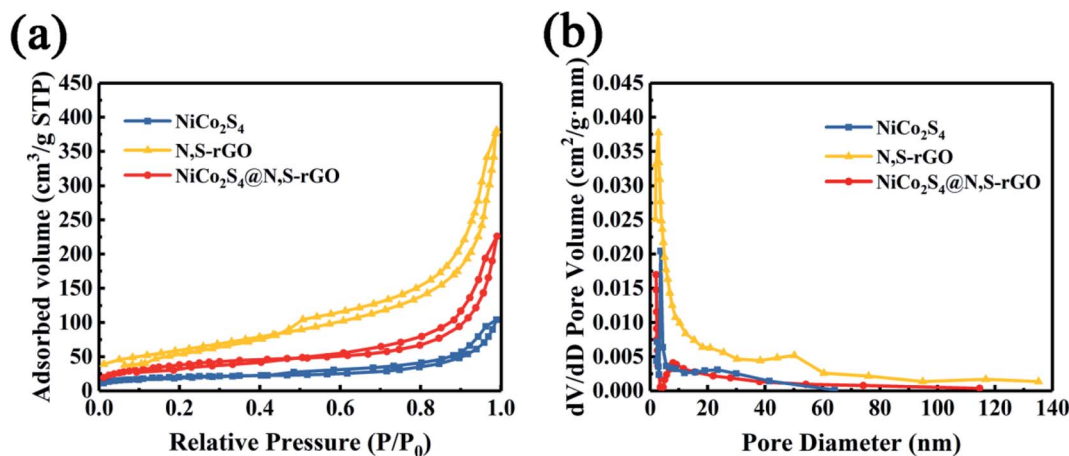


Fig. 4 (a) N_2 adsorption–desorption isotherms of $NiCo_2S_4@N,S-rGO$, $NiCo_2S_4$, and N,S-rGO; (b) The pore-size distribution of $NiCo_2S_4@N,S-rGO$, $NiCo_2S_4$, and N,S-rGO.

the simultaneous presence of H_2O_2 and TMB, the system 3# presented faint blue, illustrating that H_2O_2 could oxidize TMB to TMB_{ox} in such a case. When the N,S-rGO (system 4#), $NiCo_2S_4$ (system 5#), or $NiCo_2S_4@N,S-rGO$ (system 6#) were added to the TMB + H_2O_2 system, the solutions all exhibited the different

degrees of blue color. Although the system 4# displayed light blue color, it was deeper than system 3#, probably because the doping of N and S led to more active sites in graphene and promoted the oxidation of TMB.³⁹ In stark contrast, the addition of $NiCo_2S_4$ (system 5#) yielded dark blue color, demonstrating

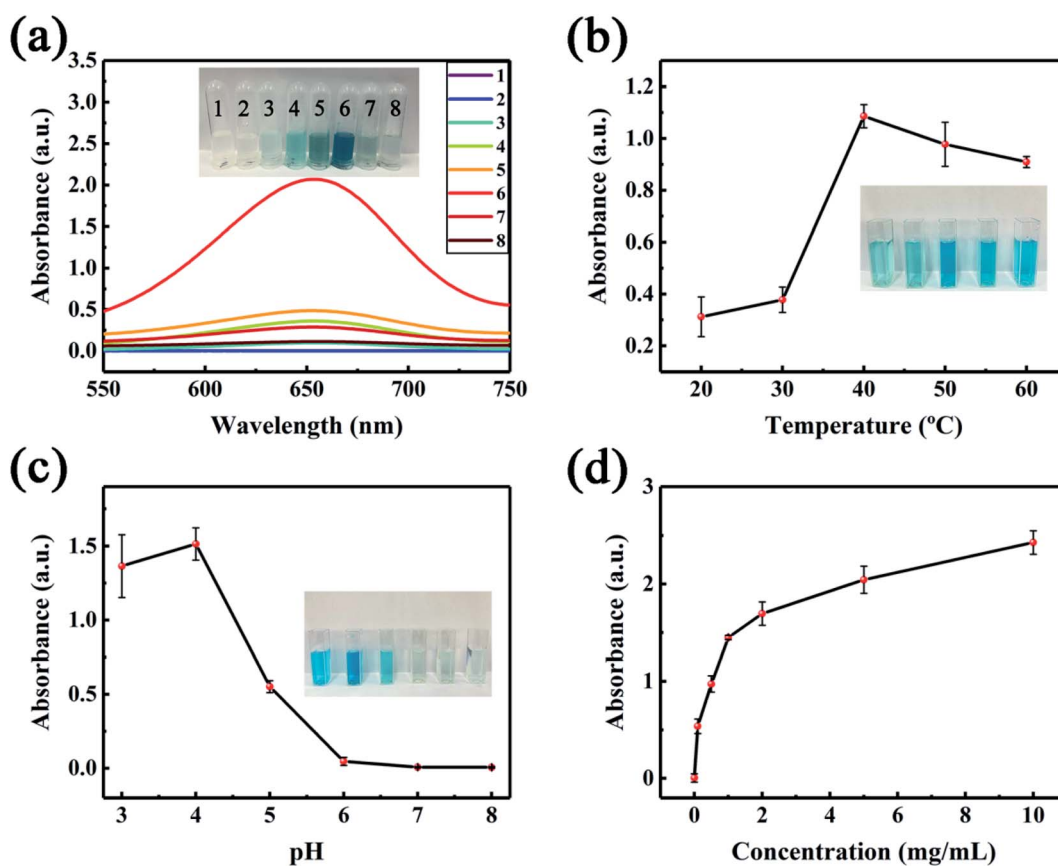


Fig. 5 (a) UV-vis absorption of the different reaction systems: 1, TMB; 2, H_2O_2 ; 3, TMB + H_2O_2 ; 4, r-GO + TMB + H_2O_2 ; 5, $NiCo_2S_4$ +TMB + H_2O_2 ; 6, $NiCo_2S_4@N,S-rGO$ + TMB + H_2O_2 ; 7, $NiCo_2S_4@N,S-rGO$ + TMB; 8, $NiCo_2S_4$ +TMB. Inset is photographs of the different reaction systems. Optimization of $NiCo_2S_4@N,S-rGO$ peroxidase-like colorimetric system. (b) Absorbance of the system at different reaction temperatures (20–60 °C). (c) Absorbance of the system reaction at varying solution pH (3.0–8.0). (d) Absorbance of the reaction system with different concentrations of $NiCo_2S_4@N,S-rGO$ (0–40 $mg L^{-1}$). Inset is the photographs in different reaction systems.



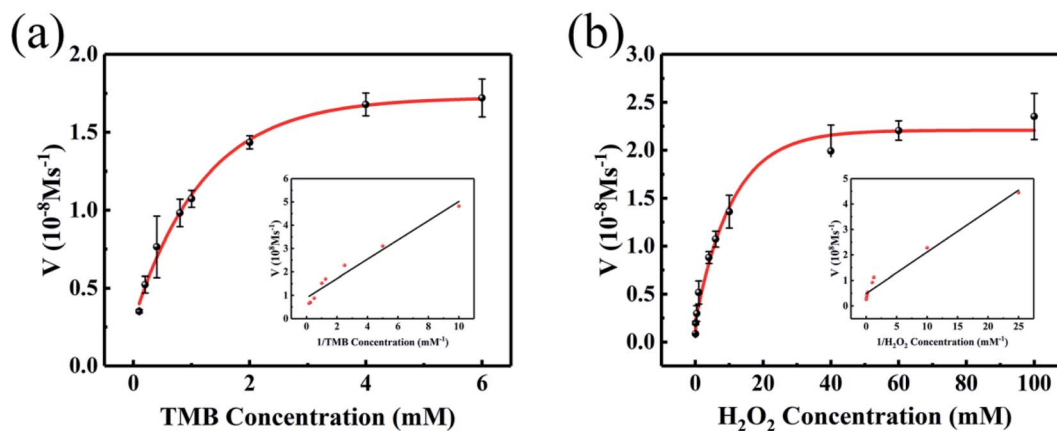


Fig. 6 Steady-state kinetic assay of the $\text{NiCo}_2\text{S}_4@\text{N,S-rGO}$. Michaelis–Menten curves for the $\text{NiCo}_2\text{S}_4@\text{N,S-rGO}$ nanozyme: (a) the concentration of TMB is in the range of 0.1–6.0 mM; (b) the concentration of H_2O_2 is in the range of 0.04–100 mM. Insets are the double reciprocal plots of Michaelis–Menten equation against the concentrations of TMB or H_2O_2 .

that NiCo_2S_4 could promote the oxidation of TMB. The system 6# produced the deepest blue color due to the co-presence of TMB, H_2O_2 , and $\text{NiCo}_2\text{S}_4@\text{N,S-rGO}$, reflecting in the most intense characteristic peak at 652 nm. These findings illustrate that the $\text{NiCo}_2\text{S}_4@\text{N,S-rGO}$ nanocomposite has a superior ability to oxidize TMB to TMB_{ox}, resulting from its larger SSA and rich vacant sites. Worth noting, the systems 7# (TMB + $\text{NiCo}_2\text{S}_4@\text{N,S-rGO}$) and 8# (TMB + NiCo_2S_4) displayed the different degrees of blue, evidencing that both the NiCo_2S_4 and $\text{NiCo}_2\text{S}_4@\text{N,S-rGO}$ also possessed the oxidase-like activity.

3.3 Optimization of the system 6# (TMB + $\text{H}_2\text{O}_2 + \text{NiCo}_2\text{S}_4@\text{N,S-rGO}$)

To achieve the best catalytic efficiency, we optimized the important parameters in the system 6#, including incubation temperature, solution pH, and nanocomposite concentration. As depicted in Fig. 5b, the 652 nm absorbance increased with increases in temperature from 20 to 40 °C; however, the further rising temperature (40–60 °C) led to decreased absorbance intensity. Too low temperature was not conducive to the catalytic oxidation of TMB by $\text{NiCo}_2\text{S}_4@\text{N,S-rGO}$, but too high temperature will lead to the inactivation of TMB. As a result, the deepest blue in the system 6# appeared at 40 °C (inset of Fig. 5a). Under basic conditions, H_2O_2 could be decomposed into O_2 and H_2O , thereby greatly abating the catalytic activity. Under strong acidic conditions, the electron-cloud density of N atoms in TMB was reduced, thus weakening the intermolecular interactions between $\text{NiCo}_2\text{S}_4@\text{N,S-rGO}$ and substrate. Consequently, too high or low solution pH was both unfavorable for the oxidation reaction of TMB. It is obvious in Fig. 5c that the 652 nm absorbance was sharply reduced from pH 4.0 to 6.0, and almost no absorbance occurred from pH 6.0 to 8.0. Thus, we posit that the appropriate solution pH was 4.0. Over the concentration range of 0–10 mg mL^{-1} , the addition of nanocomposite caused the gradual increase in the 652 nm absorbance (Fig. 5d). Especially, when the fortified concentration varied from 0 to 1.0 mg mL^{-1} (0, 0.1, 0.5, and 1.0 mg mL^{-1}), the

652 nm optical densities (ODs) were dramatically enhanced, while slightly increased at 1.0–10.0 mg mL^{-1} . In the UV-vis detection systems, excessive ODs (>2.0) lead to a sharp decline in the responsivity of color recognition due to saturated absorbance. Based on the above findings, 1.0 mg mL^{-1} of the $\text{NiCo}_2\text{S}_4@\text{N,S-rGO}$ nanocomposite was considered as the appropriate spiking level in the subsequent trials.

Table 1 Comparison of the Michaelis–Menten constants (K_m and V_{max}) for $\text{NiCo}_2\text{S}_4@\text{N,S-rGO}$ catalyzed oxidation of H_2O_2

Catalyst	Substrate	$K_m(\text{mM})$	$V_{\text{max}}(10^{-8} \text{ M s}^{-1})$	Ref.
N,S-rGO	H_2O_2	3.8918	0.2672	This work
	TMB	0.6887	0.3706	
NiCo_2S_4	H_2O_2	0.4686	1.0815	This work
	TMB	0.4628	1.1212	
$\text{NiCo}_2\text{S}_4@\text{N,S-rGO}$	H_2O_2	0.3326	2.0479	This work
	TMB	0.3372	1.4956	
HRP	H_2O_2	3.7	8.71	41
	TMB	0.434	10	
Cu–Ag/rGO	H_2O_2	0.634	4.2553	42
	TMB	8.6145	7.0175	
WS_2/rGO	H_2O_2	10.001	0.9332	43
	TMB	22.406	0.9606	

Table 2 Comparison of the analytical performance of $\text{NiCo}_2\text{S}_4@\text{N,S-rGO}$ based colorimetric assay with other colorimetric assay of glucose^a

Nanomaterials	LRs (μM)	LODs (μM)	Ref.
CoOOH nanoflakes	5.3–500	1.20	51
r-CDS	10–400	2.00	52
CoSe ₂ /rGO	5–800	0.55	53
NiCo_2O_4	2–100	1.62	54
$\text{NiCo}_2\text{S}_4@\text{N,S-rGO}$	1–200	0.30	This work

^a LR and LOD denote the abbreviations of linear ranges and limits of detection, respectively.



3.4 Steady-state kinetics of the NiCo₂S₄@N,S-rGO

A typical Michaelis–Menten equation was used to investigate the steady-state kinetics of this colorimetric sensor based on the as-fabricated nanocomposite. TMB and H₂O₂ were chosen as substrates, and each experiment was performed in triplicate by varying the concentration of one substrate (Fig. 6). As well known, a lower K_m value denote a higher affinity between nanozyme and substrate.⁴⁰ As listed in Table 1, the K_m values offered by the nanocomposite were in the range of 0.3326–0.3372 at varying TMB and H₂O₂ levels. Consequently, the affinity by the nanocomposite increased by ~40% and 1.1~10.6-fold as compared to NiCo₂S₄ and N,S-rGO, respectively. Also, the NiCo₂S₄@N,S-rGO provided higher affinity than the common HRP,⁴¹ as well as previously reported Cu–Ag/rGO⁴² and WS₂/rGO.⁴³ These data evidence that the NiCo₂S₄@N,S-rGO greatly enhances the peroxidase-like activity.

3.5 Catalytic mechanism of this nanocomposite

Up to now, many kinds of mechanisms have been proposed to illustrate the catalytic oxidation of TMB by nanozyme, which are mainly involved in several species of reactive oxygen species (ROS), such as $\cdot\text{OH}$, $\cdot\text{O}_2^-$, and h^+ .^{44,45} Herein, we employed three ROS trappers (IPA, PBQ, and EDTA) to scavenge $\cdot\text{OH}$, $\cdot\text{O}_2^-$, and

h^+ , respectively. In contrast to the control group (no scavenger), the system color only slightly decreased after the addition of IPA, while more obvious fading phenomenon occurred upon the addition of both PBQ and EDTA (Fig. 7a). Especially, the system color became almost colorless following the addition of EDTA. These observations suggest that the mechanism regarding the nanocomposite-catalyzed oxidation of TMB is likely due to the common participation of three ROS species in the system. 5,5-Dimethyl-1-pyrroline N-oxide (DMPO) is able to trap ROS transiently, forming DMPO/radical spin adducts capable of forming signals of different shapes. Fig. 7b displays the standard quadruplet with the signal of 1 : 2 : 2 : 1, which is the plot of DMPO/ $\cdot\text{OH}$. Clearly, the high noise and weak signal intensity indicated that only a small amount of $\cdot\text{OH}$ was generated in this system. As vividly elaborated in Fig. 7c, the plot of DMPO/ $\cdot\text{O}_2^-$ illustrated the production of $\cdot\text{O}_2^-$ in the system. When compared to the plot of DMPO/ $\cdot\text{OH}$, the lower noise and higher signal intensity demonstrated that the amount of $\cdot\text{O}_2^-$ was higher than that of $\cdot\text{OH}$. The profile of photo-generated holes (h^+) is shown in Fig. 7d, and the strong signal provided compelling evidence that h^+ was the main active species in the nanocomposite-based enzyme catalytic system. These ESR observations were highly consistent with those of ROS scavengers, and thus the catalytic activity of NiCo₂S₄@N,S-

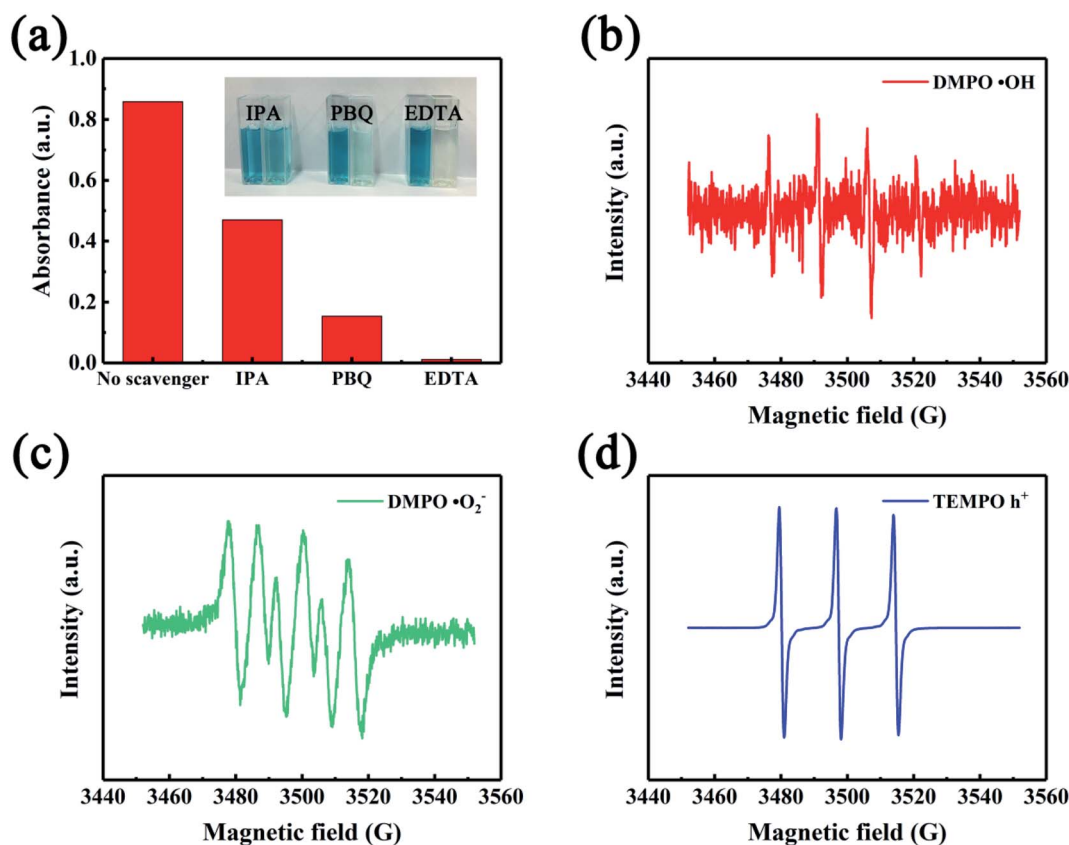
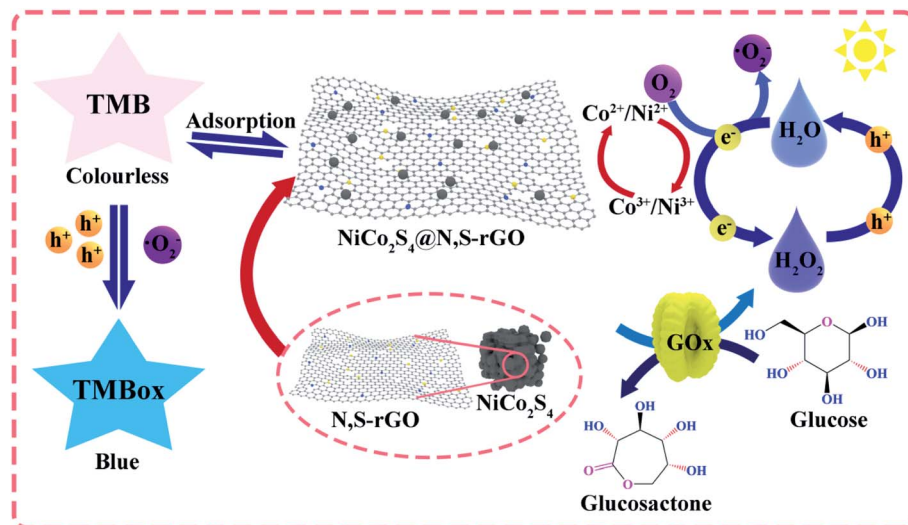


Fig. 7 Mechanistic study of NiCo₂S₄@N,S-rGO catalyzed oxidation of TMB. (a) Free radical scavenging experiment in the NiCo₂S₄@N,S-rGO reaction system. Inset are the photographs under different radical scavengers. (b) EPR spectra of $\cdot\text{OH}$ in the NiCo₂S₄@N,S-rGO chromogenic system. (c) EPR spectra of $\cdot\text{O}_2^-$ in the NiCo₂S₄@N,S-rGO chromogenic system. (d) EPR spectra of photogenerated holes (h^+) in the NiCo₂S₄@N,S-rGO chromogenic system.





Scheme 1 Schematic representation of the NiCo₂S₄@N,S-rGO as a peroxidase mimetic for H₂O₂ and cholesterol detection.

rGO resulted from three radicals collectively and was dominated by h⁺.

Building upon the above analyses, we speculate that the catalytic mechanisms of NiCo₂S₄@N,S-rGO are involved in three aspects: (1) As for this catalytic reaction, TMB molecules can be adsorbed onto the surface of nanocomposite through π - π interactions along with electrostatic attraction. The co-doping of N and S on rGO nanosheets provides abundant functional groups to facilitate the interactions with TMB, thereby improving the catalytic efficiency.⁴⁶ Meanwhile, the large SSA of NiCo₂S₄@N,S-rGO increased the active sites of its precursor NiCo₂S₄. (2) Under irradiation of visible light, the electrons of NiCo₂S₄ are excited at the conduction band (CB), holes are generated at the valence band (VB), and the transfer from CB to VB is promoted by N and S-doped rGO. With the participation of electrons (e⁻), H₂O₂ is converted into O₂, which further forms 'O₂⁻. On the contrary, TMB loses e⁻ to form TMB_{ox} in the reaction with 'O₂⁻ and/or h⁺. (3) N and S co-doping, rich S-vacancy, and complex chemical valence states for the NiCo₂S₄@N,S-rGO facilitate electron transfer and accelerate the reaction progress.⁴⁷ The schematic illustration on the catalytic mechanisms of NiCo₂S₄@N,S-rGO is shown in Scheme 1. Wang's group concluded that catalyst interface structural engineering is advantageous in promoting electronic interactions, bringing redistribution of charges in heterogeneous catalysts, and creating an internal electric field.⁴⁸ This will further induce the formation of ion holes, which can play a bridging role in the reaction and transfer to the reactants, thus enhancing the catalytic activity. Furthermore, this effect is also influenced by the size effect of the nanomaterial on the interfacial support, *i.e.*, in small-sized nanomaterials, the effect is significantly enhanced by the large charge transfer per atom. Collectively, these findings obtained in this study are a good verification of the above-described theory; that is to say that the co-doping of hybrid atoms and the synergistic effect between NiCo₂S₄ and GO jointly promotes the catalysis of nanozyme.

3.6 H₂O₂ and glucose assay using the NiCo₂S₄@N,S-rGO based colorimetric reaction

Because the activity of NiCo₂S₄@N,S-rGO peroxidase was related to H₂O₂ concentration, the quantitative H₂O₂ assay could be achieved by measuring the 652 nm ODs. Fig. 8a–b displays the 652 nm absorbance *vs.* H₂O₂ concentration, which offers a good linear relationship from 0.04 to 50 mM with high correlation coefficient (*R*²) of 0.9989 and low detection limit (LOD) of 12 μ M. In three fortification levels (50, 500, and 1000 μ M), the relative recoveries were in the range of 98.9–102.4% with relative standard deviations (RSDs) of 2.6–4.5%, demonstrating a high experimental accuracy (Table 3).

Additionally, glucose can be oxidized by GOx to produce H₂O₂, which is closely related to the peroxidase activity of natural enzyme or nanozyme. As a result, traditional HRP could be replaced by NiCo₂S₄@N,S-rGO for glucose colorimetric assay. As the concentration of glucose increased, the amount of H₂O₂ increased in concomitant with the rising 652 nm ODs and enhancement of blue color under the catalysis of nanocomposite (Fig. 8a and b). Under optimized conditions (solution pH 4.0, 1.0 mg mL⁻¹ nanocomposite, 20 min incubation at 40 °C), a plot of the 625 nm ODs against glucose concentrations was constructed with the linear equation of $y = 0.00141x + 0.1176$, as well as the correlation coefficient of 0.9788 (Fig. 8a). The linear range (LR) for glucose assay was 1.0–200 μ M, and the limit of quantification (LOQ) and limit of detection (LOD) were 1.0 and 0.3 μ M, respectively, based the 3-fold and 10-fold signal to noise (*S/N* = 3 and 10).^{49,50} These analytical performance metrics were compared to several glucose assays by employing sensors based on other nanomaterials (Table 2). Evidently, this NiCo₂S₄@N,S-rGO nanoenzymatic biosensor achieves a much lower LOD (0.30 μ M) than those of CoOOH nanoflakes (1.20 μ M),⁵¹ r-CDS (2.00 μ M),⁵² CoSe₂/rGO (0.55 μ M),⁵³ and NiCo₂O₄ (1.62 μ M).⁵⁴ Also, it offers a relatively wider LR (1.0–200 μ M) in contrast to other approaches. As such, these comparative



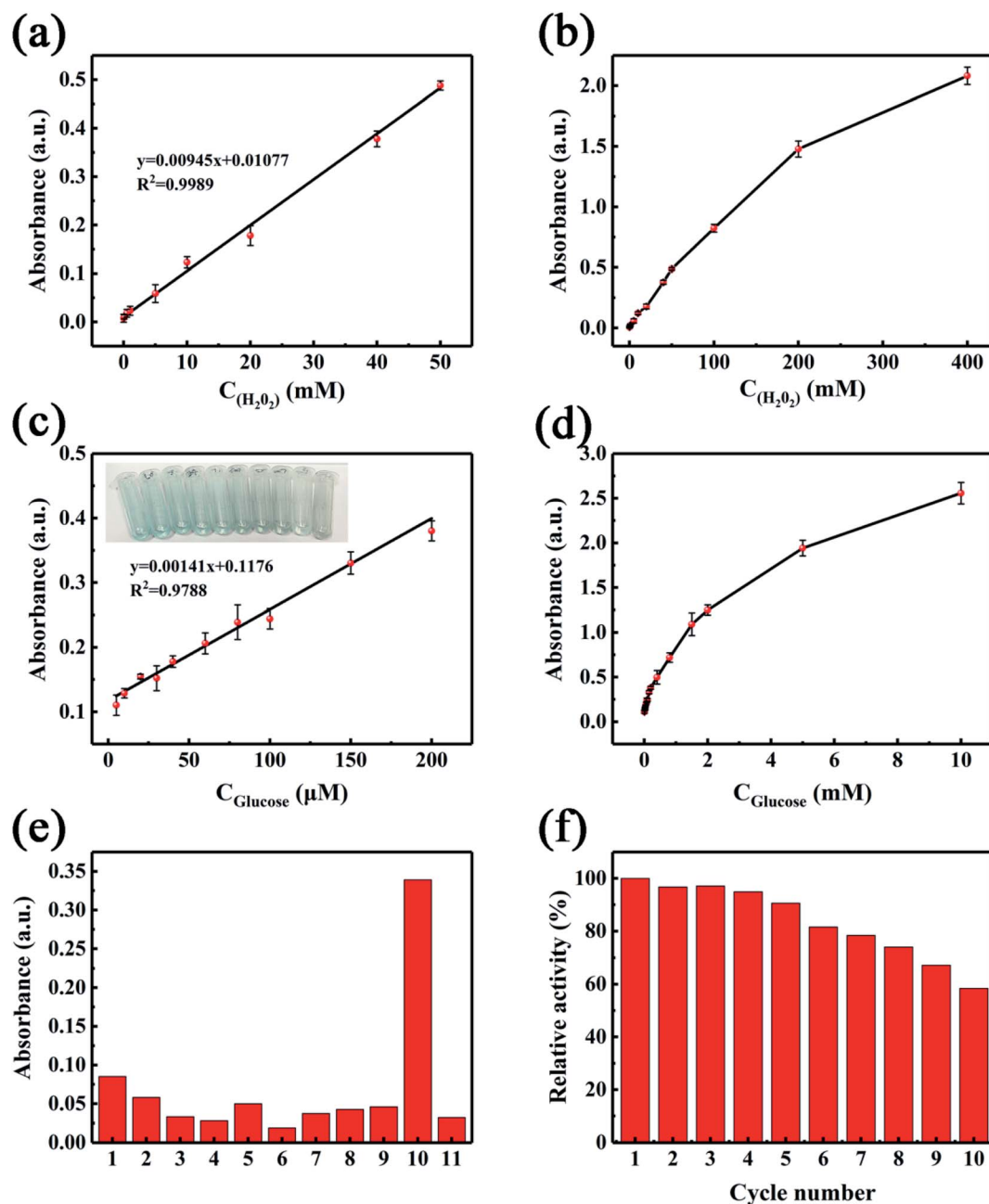


Fig. 8 (a) Calibration curve of absorbance vs. H₂O₂. (b) Real response curve of absorbance vs. H₂O₂ concentration. (c) Calibration curve of absorbance vs. glucose. (d) Real response curve of absorbance vs. glucose concentration. (e) Selectivity of this nanozymic sensing method for glucose. 1, Histidine; 2, Sucrose; 3, Galactose; 4, Fructose; 5, Serine; 6, Ascorbic acid; 7, K⁺; 8, Mg²⁺; 9, Na⁺; 10, Glucose; and 11, Blank. With the exception of glucose, each interference macromolecule or ion was fortified at 5.0 μg mL⁻¹. (f) Reproducibility results of this nanozyme sensing method.

performance metrics demonstrate that the as-constructed nanozymic biosensor is conducive to practical applications in the analytical field of biomolecules.

3.7 Selectivity/anti-interference effect and reusability of the nanocomposite-based colorimetric method for glucose assay

A series of anti-interference experiments were conducted to assess the selectivity of this proposed method under optimized conditions. The co-existing components in human serum

Table 3 The fortified recovery for H₂O₂ based on the colorimetric assay of NiCo₂S₄@N,S-rGO^a

Samples	Added (μM)	Found (μM)	Recovery (%)	RSDs (% , n = 6)
Human serum	—	—	—	—
	50	51.2	102.4	2.6
	500	494.4	98.9	4.5
	1000	992.6	99.3	4.3

^a RSDs represent relative standard deviations.



Table 4 Reliability of this colorimetric assay for glucose based on NiCo₂S₄@N,S-rGO

Samples	Determined by a glucometer (mM)	Determined by this method (mM)	Added (μM)	Found (μM)	Recovery (%)	RSDs (% , n = 6)
Serum 1#	15.62	16.13	5	4.87	97.4	3.12
Serum 2#	5.29	5.42	5	5.09	101.8	2.14

samples include fructose, galactose, sucrose, serine, histidine, ascorbate, K⁺, Ca²⁺, Na⁺, and so on. These components were added at 5.0 μg mL⁻¹ to the diluted serum samples, as described in Section 2.5. As detailed in Fig. 8e, the interference macromolecules/ions had less influences on the 625 nm ODs. It was worth noting that when compared to the blank sample, the 625 nm absorbance reduced to a certain degree following the addition of ascorbic acid, reflecting in the fading of blue color. This phenomenon may be explained by that owing to the reductive property of ascorbic acid, it consumed H₂O₂, one of the main products in the GOx-catalyzed reaction. The reusability of NiCo₂S₄@N,S-rGO as nanozyme is displayed in Fig. 8f. The relative activity remained as high as 81.9% after reusing 6 times, while 58.6% after 10 times. Thus, we posit that the as-fabricated nanozyme can be repeatedly used as a colorimetric sensor at least 6 times.

The feasibility of the as-constructed sensor was evaluated by detecting glucose contents in human serum samples. The concentrations of glucose in two serum samples were detected to be 15.62 and 5.29 μM, while they were 16.12 and 5.42 μM, respectively, by a blood glucose meter. Consequently, the acquired relative recoveries spanned the range of 97.4–101.8% with RSDs of 2.14–3.12% (Table 4). These data/findings offer strong evidence that this colorimetric method based on the NiCo₂S₄@N,S-rGO nanozyme can provide a satisfactory experimental accuracy/precision for glucose assay in human serum samples.

4 Conclusions

Herein, we fabricated the nanocomposite (NiCo₂S₄@N,S-rGO) by a facile calcining approach, and its structure was characterized in detail by virtue of a series of spectral techniques, such as XRD, HRTEM, SEM, and FT-IR. The NiCo₂S₄@N,S-rGO possessed significantly higher peroxidase-like activity than its precursors (NiCo₂S₄ and N,S-rGO), which resulted from the N, S-codoping, rich S-vacancy, and multi-valence states of this nanocomposite. This nanomaterial had typical mesopore structure (pore size of ~7–9 nm), and its SSA increased by ~2-fold over that of NiCo₂S₄, thus producing more active sites and charge transfer channels. Based on ROS scavenging experiments, the enhanced peroxidase-mimetic activity is confirmed to be the combined action of ROS (·OH, ·O₂⁻, and h⁺), among which h⁺ was dominated in the TMB-based chromogenic reaction. Under optimized conditions, the nanocomposite-based sensor gave lower LODs of 12 μM for H₂O₂ and 0.3 μM for glucose, respectively and comparable detection results in contrast to traditional glucose meter. Overall, this work provides a feasible strategy for developing bimetallic sulfides

for H₂O₂ and glucose detection in complex human fluid samples.

Conflicts of interest

The authors declare no conflict of interest.

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