

Machine learning-assisted construction of CDs@Fe-SA nanozymes colorimetric paper-based sensing of acrolein in baked food

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Abstract

Acrolein, classified as a Group 2A carcinogenic pollutant, was generated during the high-temperature processing of food. Traditional detection methods often face challenges in achieving on-site detection and rapid screening. This study presents carbon dot-coupled single-atom iron (CDs@Fe-SA) composite nanozymes, which exhibit high peroxidase-like activity and were synthesized through a green self-assembly strategy. The heterogeneous interface formed by carbon dots and the active center of the single-atom enzyme, Fe-N_x, facilitates electron transfer and significantly enhances catalytic performance, evidenced by a Michaelis constant of 0.52 mM for H₂O₂. The research indicated that N-acetylcysteine markedly inhibited the enzyme-like activity of CDs@Fe-SA, resulting in the fading of the chromogenic catalytic product. Leveraging the specific Michael addition reaction between acrolein and N-acetylcysteine (NAC), the decolorization effect of NAC can be effectively mitigated, thereby establishing a novel colorimetric strategy for the detection of acrolein. The well plate method and a paper-based colorimetric method were subsequently developed to fulfill the requirements for high-throughput and on-site detection scenarios. Results indicate that the linear range of the well plate mode spans from 20 to 1000 μ M, with a detection limit of 12.02 μ M. The paper-based method enables high-precision on-site detection within the range of 0.3 to 2.3 mM. This approach is applicable for detecting acrolein in fried and baked foods, achieving a spiked recovery rate between 97.0% and 115.9%. The dual-mode sensing system established in this study effectively addresses the need for rapid on-site screening. Notably, the incorporation of small sample machine learning algorithms has significantly enhanced the quantitative accuracy of the paper-based method. This research offers novel technical support for food safety.

1. Introduction

Acrolein was a toxic aldehyde generated during the high-temperature thermal oxidation of edible oils. It has been classified as a Group 2A carcinogen by the International Agency for Research on Cancer (IARC) [1]. During food processing operations such as high-temperature frying or baking, when edible oils were heated above 150 °C, they decompose to produce acrolein, which poses a risk to human health [2]. The World Health Organization recommends that daily acrolein intake not exceed 7.5 μ g/kg body weight [3]. Therefore, simple and efficient methods for quantifying acrolein in fried and baked foods are urgently needed. Currently, acrolein detection primarily relies on instrumental techniques such as gas chromatography-mass spectrometry (GC-MS), high-performance liquid chromatography (HPLC), liquid chromatography-mass spectrometry (LC-MS), solid-phase microextraction combined with GC-MS (SPME-GC-MS), and fluorescence methods [4–6]. Although these methods offer high sensitivity and accuracy, they suffer from limitations including expensive instrumentation, complex operation, tedious sample pretreatment, and long analysis times, rendering them unsuitable for rapid on-site screening.

Nanozymes, a class of biomimetic materials that combine the catalytic properties of natural enzymes with the physicochemical features of nanomaterials [7, 8], offer advantages such as low cost, structural

designability, and the integration of multiple enzymatic activities. In food analysis, nanozymes mimic the activities of peroxidase (POD), oxidase (OXD), and other enzymes to enable efficient on-site detection of target analytes through colorimetric readouts^[9, 10]. Among them, single-atom iron nanozymes offer advantages such as atomic-level dispersion, high intrinsic catalytic activity, and a well-defined structure-activity relationship^[11]. Our group synthesized single-atom iron nanozymes with high POD-like activity *via* microwave pyrolysis and constructed a sensor array for identifying antioxidants in fruits and vegetables^[12]. Shen et al. enhanced the POD-like activity of single-atom iron nanozymes through heteroatom doping and developed a three-channel colorimetric sensor array for mycotoxin identification in corn juice^[13]. However, these nanozymes suffer from poor dispersion and a tendency to aggregate. In contrast, carbon dot (CDs)-based nanozymes possess excellent optical properties, water solubility, surface functional groups, and electron transport capacity. For instance, Dong et al. prepared CDs nanozymes with blue fluorescence and photo-responsive OXD-like activity using citric acid and triethanolamine as precursors, enabling nitrite analysis in food *via* a smartphone colorimetric platform^[14]. Fan et al. compared different amino acid precursors and obtained CDs nanozymes with fourfold enhanced activity, which were subsequently used to detect glutathione in pork liver and sheep blood^[15]. Thus, coupling single-atom iron nanozymes with CDs can create a heterointerface that accelerates interfacial electron transfer, enhances POD-like activity, and enables efficient signal amplification^[16, 17].

Paper-based color sensors are cost-effective, simple to fabricate and operate, offering significant advantages for portable detection methods. In recent years, the integration of nanozyme technology with paper-based sensing has further enhanced catalytic signal amplification and portability, showing great promise for on-site rapid food analysis^[18]. For example, Zhou et al. developed a smartphone-assisted MnO₂ nanozyme paper-based sensor to evaluate total antioxidant capacity in food^[19]. Tang et al. improved selectivity by integrating immunotechnology into the nanozyme colorimetric sensing method^[20]. The introduction of 3D printing technology further enhanced the portability and accuracy of the nanozyme paper-based sensor, enabling rapid detection of dexamethasone in food^[21]. However, current on-site quantitative methods for nanozyme paper-based color sensors mainly rely on smartphone photography, manual extraction of RGB values, and trial-and-error establishment of linear relationships between RGB values and sample concentrations, which are prone to errors and low precision. Therefore, intelligently extracting RGB values from captured images and achieving high-precision concentration recognition using small-sample machine learning algorithms would be of great significance.

In summary, a CDs@Fe-SA composite nanozymes was prepared *via* a green induced self-assembly strategy. The composite exhibited significantly higher POD-like activity than either component alone, with K_m values of 0.52 mM for H₂O₂ and 0.89 mM for TMB. The enhanced catalytic efficiency was attributed to interfacial electron transfer between CDs and the single-atom Fe-N_x active centers. N-Acetylcysteine (NAC) was found to effectively inhibit the POD-like activity of CDs@Fe-SA, leading to fading of the TMB

catalytic product. Based on the specific Michael addition reaction between acrolein and NAC, a colorimetric assay was developed. Using high-throughput 96-well plates, this method enabled rapid food screening with a linear range of 20-1000 μM and a detection limit of 12.02 μM . Furthermore, the CDs@Fe-SA nanozymes were immobilized on paper-based sensors; combined with smartphone imaging, automatic RGB extraction, and small-sample machine learning modeling, a new method for on-site precise detection of acrolein was established in the range of 0.3–2.3 mM. This dual-modal sensing platform was successfully applied to the spike- and -recovery detection of acrolein in common baked foods (fries, bread, cookies), yielding recoveries of 97.0-115.9%. These results demonstrate the great potential of the developed approach for rapid on-site food analysis (schematic 1).

2. Experimental section

2.1 Apparatus and reagents

Full details of the reagents and instruments are provided in the Supporting Information.

2.2 Synthesis of CDs@Fe-SA

The synthesis methods of CDs and Fe-SA are based on the research reports of our group, with some modifications made.

Synthesis of CDs^[22]: Phthalic acid (0.8307 g), o-phenylenediamine (0.5407 g), and FeCl_3 (0.027 g) were dissolved in 20 mL of DMF. After ultrasonication for 20 min, the mixture was transferred to a 50 mL autoclave and heated at 160 $^{\circ}\text{C}$ for 6 h. The resulting solution was centrifuged at 10,000 rpm for 5 min, and the supernatant was collected and stored at 4 $^{\circ}\text{C}$.

Synthesis of Fe-SA^[23]: $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (1.16 g), L31 (0.6617 g), and 2-methylimidazole (2-MeIM, 1.32 g) were dissolved in 45 mL of methanol. The mixture was stirred at room temperature for 10 h, centrifuged at 10,000 rpm for 5 min, washed twice with methanol, and dried at 65 $^{\circ}\text{C}$ for 8 h to obtain the ZIF-8 precursor. Subsequently, 0.2 g of ZIF-8 precursor and 0.25 g of $\text{Fe}(\text{acac})_3$ were dispersed in 50 mL of methanol, followed by addition of 2-MeIM (0.46 g) and $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (0.42 g). The mixture was stirred for another 10 h at room temperature, centrifuged, washed twice with methanol, and dried at 65 $^{\circ}\text{C}$ for 8 h to afford Fe-SA. The obtained Fe-SA was then heated in a tube furnace under N_2 atmosphere at a ramp rate of 5 $^{\circ}\text{C} \cdot \text{min}^{-1}$ to 1000 $^{\circ}\text{C}$, held for 1 h, and allowed to cool to room temperature to yield the final Fe-SA powder.

Synthesis of CDs@Fe-SA: the CDs aqueous solution (5%, w/v) was added to the Fe-SA powder, followed by ultrasonication at room temperature for 30 min to obtain the CDs@Fe-SA composite nanozyme.

2.3 Evaluation of POD-like activity of CD@Fe-SA

The POD-like activity of the CDs@Fe-SA nanozyme was investigated using H₂O₂ and TMB as substrates. Briefly, 150 µL of HAc-NaAc buffer (pH 3.5) was added to a 96-well plate, followed by 20 µL of CDs@Fe-SA solution (Fe-SA dissolved in 1% CDs at 1 mg/mL), 20 µL of H₂O₂ (5 mM), and 20 µL of TMB (5 mM). The reaction was carried out at 30°C for 5 min, and absorption spectra in the range of 400–800 nm were recorded. Under the same conditions, the POD-like activities of CDs (1%) and Fe-SA (1 mg/mL) solutions were also compared.

The steady-state kinetics of the CDs@Fe-SA nanozyme were evaluated by varying the concentration of one substrate while keeping the other fixed. At 30°C, 150 µL of HAc-NaAc buffer (pH 3.5), 20 µL of CDs@Fe-SA (1 mg/mL), 20 µL of H₂O₂ (5 mM), and various concentrations of TMB (1–10 mM) were sequentially added to a 96-well plate. The absorbance at 652 nm was recorded. Under the same conditions, the TMB concentration was fixed at 5 mM, and the H₂O₂ concentration was varied from 1 to 10 mM. The kinetic parameters were calculated using the Michaelis - Menten equation: $v = V_{\max} \times [S] / (K_m + [S])$, where v was the initial reaction rate, $V_{\max}$ was the maximum reaction rate, K_m was the Michaelis constant, and $[S]$ was the substrate concentration.

2.4 High-throughput and on-site detection of acrolein

High-throughput mode: in a 96-well plate, 40 µL of Tris-HCl buffer (pH 9.4), 20 µL of NAC (25 mM), and 20 µL of acrolein (various concentrations) were sequentially added. The mixture was incubated at 40°C for 10 min. Subsequently, 40 µL of this reaction mixture was transferred to a second system containing 150 µL of buffer (pH 3.8), 20 µL of CDs@Fe-SA, 20 µL of H₂O₂ (5 mM), and 20 µL of TMB (5 mM). After incubation at 30°C for 8 min, the absorbance at 652 nm was recorded.

On-site mode: first, 4 µL of CDs@Fe-SA nanozyme was immobilized on a Whatman No. 4 filter paper (10 mm diameter) and dried at 65°C. The dried paper was placed inside the cap of a 5 mL centrifuge tube for later use. In a 2 mL centrifuge tube, 40 µL of Tris-HCl buffer (pH 9.4), 20 µL of NAC (25 mM), and 20 µL of acrylamide (various concentrations) were mixed and incubated at 40°C for 10 min. Then, 40 µL of this mixture was transferred to a 5 mL centrifuge tube containing 50 µL of HAc-NaAc buffer (pH 4), 20 µL of H₂O₂ (5 mM), and 20 µL of TMB (5 mM). The tube was sealed with the cap bearing the dried nanozyme paper and inverted. After reaction at 30°C for 12 min, the cap was placed at a fixed position in a 3D printer light box for imaging. The RGB values of the captured image were analyzed by an intelligent mini-program.

2.5 Actual sample analysis

Each baked food sample (french fries, biscuits, and bread; 0.5 g) was mixed with 10 mL of deionized water and ultrasonicated for 30 min. The mixture was centrifuged at 8000 rpm for 10 min, and the supernatant was filtered through a 0.22 µm membrane filter. The resulting filtrate was used for acrolein determination by the spiked recovery method, following the procedure described in Section 2.4.

3. Results and Discussion

3.1 Characterization of CDs@Fe-SA nanozymes

The characterization and structure of the individual CDs^[22] and Fe-SA^[23] have been thoroughly investigated. The morphology of CDs@Fe-SA was observed by SEM (Fig. 1A). The surface appeared rough, with blurred particle boundaries and an overall irregular shape. In contrast, Fe-SA exhibited a uniform size, smooth surface, and well-defined octahedral morphology (Fig. 1B), consistent with the highly ordered ZIF-8 framework. Upon incorporation of CDs, a surface coating formed on Fe-SA, concealing the originally distinct crystal planes and edges, which ultimately rendered the CDs@Fe-SA particles irregular. EDS elemental mapping (Fig. 1C) revealed a homogeneous distribution of C, N, O, and Fe across the material surface.

FT-IR spectra (Fig. 1D) revealed that high-temperature calcination induced carbonization of Fe-SA, thereby weakening its characteristic absorption bands. Upon incorporation of CDs, new peaks appeared at 3420 cm^{-1} (O-H/N-H) and 1630 cm^{-1} (C = O), enriching the spectral features of the nanozyme. This enhancement is mainly ascribed to the abundant -OH, -COOH, and -NH₂ groups on CDs, which enabled their stable anchoring onto the Fe-SA surface via physical adsorption or interfacial interactions during composite formation. Figure 1E revealed broad amorphous peaks for CDs, whereas Fe-SA displays graphitic carbon peaks and a weak, broad peak at 44° attributable to Fe-N₄ or trace Fe species, confirming the atomically dispersed state of Fe. The CDs@Fe-SA retained the characteristic peaks of both components, verifying the successful integration of CDs into the Fe-SA matrix.

The XPS was employed to investigate the surface chemical states of CDs@Fe-SA (Fig. 1F). The survey spectra confirmed the presence of C, N, O, and Fe, consistent with the constituent CDs and Fe-SA. High-resolution C 1s (Fig. 1G), N 1s (Fig. 1H), and Fe 2p (Fig. 1I) spectra revealed that CDs@Fe-SA retained both the oxygen-containing groups of CDs and the Fe-N_x coordination of Fe-SA, although their characteristic peaks exhibited binding energy shifts of 0.2–0.5 eV. Specifically, the Fe 2p peak shifted to lower binding energy, indicating increased electron density around Fe, while the concurrent shifts in pyridinic N and Fe-N_x N 1s signals confirmed an altered electronic environment for N. These findings suggested that CDs were not physically adsorbed onto Fe-SA but instead formed a composite with interfacial electron transfer.

2. 2. Evaluation of the POD-like activity of CD@Fe-SA

The H₂O₂ oxidation of TMB was a classic system for evaluating the POD-like activity of CD@Fe-SA nanozymes. As shown in Fig. 2A, the prepared CDs@Fe-SA composite exhibits significantly enhanced POD-like activity compared to individual CDs or Fe-SA. To elucidate the mechanism behind this enhancement, BET analysis was conducted to characterize the pore structures (Fig. 2B and Fig. S1). The Table S1 showed that, relative to Fe-SA, the specific surface area of CDs@Fe-SA decreased from 904.8 m²/g to 705.7 m²/g, and the pore volume decreased from 0.803 cm³/g to 0.639 cm³/g. This suggested that CDs self-assemble and load onto the pore surface of the carrier, forming a coating layer. Meanwhile,

the Fe-N₄ monometallic active sites remain stably anchored on the carbon nitride framework. Together, they form a confined structure that synergistically boosts the peroxidase-like activity of CDs@Fe-SA. Furthermore, XPS results reveal shifts in the binding energies of Fe 2p and N 1s, indicating interfacial electron transfer between CDs and Fe-SA. Therefore, this self-assembly strategy establishes a tight interfacial contact, shortens the electron transfer pathway, and enables synergistic catalysis between the active centers of CDs and Fe-SA, ultimately leading to stronger POD-like activity.

The catalytic mechanism of CDs@Fe-SA was further investigated. Electron paramagnetic resonance (EPR) spectroscopy was used to identify reactive oxygen species (ROS) generated in the catalytic system. As shown in Fig. 2C, the characteristic 1:2:2:1 quadruple peaks of DMPO adducts and 1:1:1 triple peaks of TEMP adducts were detected, confirming the generation of •OH and ¹O₂. Quenching assays were then performed to determine the dominant ROS (Fig. 2D). Isopropanol (IPA), p-benzoquinone (pBQ), and tryptophan (Try) were used as selective scavengers for •OH, superoxide anion (O₂^{•-}), and ¹O₂, respectively. The catalytic activity was markedly suppressed by IPA and Try, whereas pBQ showed negligible inhibition, indicating that •OH and ¹O₂ were the major reasons for the catalytic mechanism of CDs@Fe-SA. Furthermore, the effects of pH and temperature on the POD-like activity of CDs@Fe-SA were systematically evaluated using natural horseradish peroxidase (HRP) as a control (Fig. 2E and 2F). The CDs@Fe-SA exhibited excellent tolerance to strongly acidic and high-temperature conditions. Compared with HRP, the CDs@Fe-SA demonstrated superior structural stability and environmental adaptability, effectively overcoming the inherent instability of natural enzymes.

Steady-state kinetic studies were performed on CDs, Fe-SA, and CDs@Fe-SA (Fig. S2). The K_m values of CDs@Fe-SA for H₂O₂ and TMB were 0.522 and 0.892 mM, respectively, which were lower than those of CDs and Fe-SA (Table S2), indicating a higher substrate affinity. Moreover, the maximum reaction rates (V_{max}) for H₂O₂ and TMB reached 6.08 × 10⁻⁶ and 5.31 × 10⁻⁶ M/s, respectively, outperforming the other two nanozymes. These results demonstrate the superior catalytic efficiency and kinetic performance of CDs@Fe-SA, fully reflecting the synergistic enhancement effect resulting from the combination of CDs and Fe-SA.

2.3 Colorimetric detection of acrolein and mechanism

The blue color of the CD@Fe-SA/TMB/H₂O₂/NAC system was significantly intensified upon acrolein addition, with UV-Vis spectroscopy verifying the colorimetric sensing capability (Fig. 3A). Based on our research experience^[24, 25], the potential sensing mechanism of acrolein has been proposed (Fig. 3B). The thiol moiety of NAC scavenges reactive oxygen species generated from H₂O₂ decomposition, thereby suppressing CD@Fe-SA-catalyzed TMB oxidation and yielding a light-blue product. Conversely, acrolein specifically reacts with this thiol group at the β-carbon via a 1,4-Michael addition, forming a stable thioether adduct. This covalent consumption of NAC abolishes its inhibitory effect on the peroxidase-like activity of CD@Fe-SA, restoring TMB oxidation. Consequently, the color depth of the CD@Fe-SA/TMB/H₂O₂/NAC system intensifies progressively with increasing acrolein concentration.

Although GSH was the most common biological thiol, the NAC exhibited better storage stability at room temperature and proved more suitable for acrylic acid sensing, as shown in Fig. 3C.

Optimization of the detection conditions established the optimal parameters (Fig. S3): incubation at pH 9.4 and 40°C for 10 min, followed by reaction at 30°C for 8 min, with 25 mM NAC, 5% (w/v) CDs, and 0.8 mg/mL Fe-SA. Over the linear range of 0.02-1.0 nM, ΔA correlated linearly with acrolein concentration, giving the regression equation $\Delta A = 0.46C + 0.198$ ($R^2 = 0.9988$) and a detection limit of 0.012 nM (Fig. 3D). Additionally, the selectivity was evaluated against potential interferents, including metal cations (K^+ , Na^+ , Ca^{2+} , Al^{3+}), anions (Cl^- , CO_3^{2-} , HCO_3^-), biomolecules (alanine, glutamic acid, glycine, glucose), and common fried-food components (acrylic acid, methacrylic acid, cis-butenedioic acid, hexenal, starch). None of these species caused significant interference in acrolein detection (Fig. 3E and Fig. 3F).

3.5 Machine learning assists in paper-based detecting acrolein

Although the 96-well plate method enables high-throughput detection of acrolein using CDs@Fe-SA, it cannot adequately fulfill the requirements for on-site screening. Therefore, in this study, the CDs@Fe-SA nanozymes were immobilized on filter paper to develop a new portable paper-based colorimetric sensing strategy for acrolein. The effects of filter paper type, CDs@Fe-SA concentration, reaction temperature, buffer pH, and reaction time on acrolein sensing were systematically optimized and examined. Whatman No. 4 filter paper was selected for its minimal coffee ring effect, uniform color, and clear boundaries, providing the most stable and reproducible signal (Fig. S4). High concentrations of CDs@Fe-SA caused a background effect, whereas low concentrations lacked sufficient catalytic activity for sensitive acrolein detection. The optimal color-development conditions were determined as 30 °C, pH 4 and a reaction time of 12 min.

Conventional smartphone-assisted paper-based sensing relies on manual RGB extraction. This practice is inherently subjective, poorly representative of the sampled region, and research efforts of inefficient. A Python-based tool for automatic RGB extraction (accessible *via* QR-code scanning) was designed to improve both data objectivity and processing throughput (Fig. 4A). The tool performs sequential operations: image upload, automatic localization and segmentation of colored areas, extraction of valid pixels, RGB statistical analysis, and data output. Pixel-wise processing was adopted, with abnormal pixels (arising from local CDs@Fe-SA agglomeration, speckles, reflections, or shadows) filtered out according to a uniform criterion. This automation eliminates the subjectivity inherent in manual region selection and value reading, significantly improving data consistency, accuracy, and reproducibility. Ten linear calibration curves were obtained using ten commonly used color difference formulas (Fig. 4B). Considering both the linear range and sensitivity, the R-value was selected as the ordinate against acrolein concentration. The calibration curve exhibited a linear range of 0.3–2.3 mM, with the regression equation $y = -39.57x + 124.7$ ($R^2 = 0.9906$) and a detection limit of 195 μM . Selectivity of the paper-based sensor was evaluated against common interferents (Fig. S5). Color development occurred only in

the presence of acrolein, and coexisting substances caused negligible interference, confirming the high selectivity of the proposed system.

3.6 Detection of acrolein in baked food

This study validated the accuracy of the proposed method for acrolein detection in baked foods *via* spike-and-recovery tests using high-throughput well-plate and on-site paper-based sensors, given that thermal degradation of edible oil triglycerides generates acrolein - a potent carcinogen that attacks proteins, DNA, and antioxidant defenses. Samples of baked goods (e.g., french fries, biscuits, and bread) were pretreated according to Chinese national standards, and the clarified extracts were analyzed. Summarizes the recovery data: the well-plate method yielded 97.0–101.5% (Table S3), while the mobile-phone-assisted paper-based sensor gave 103.3–115.9% (Table S4), with relative standard deviations (RSD) all below 4.67%. Although the paper-based colorimetric approach exhibited marginally higher recoveries and RSDs—likely due to uneven solution penetration into the paper—these values remained within acceptable criteria for detecting hazardous food contaminants. The results confirm that the integrated sensing platform offers reliable accuracy and reproducibility, highlighting its promise for on-site and high-throughput food safety applications.

4. Conclusions

In this study, the CDs were assembled with Fe single-atom *via* a facile self-assembly strategy to fabricate CDs@Fe-SA hybrids nanozymes with enhanced peroxidase-like activity. Based on the Michael addition between acrolein and N-acetylcysteine, a dual application scenarios integrating high-throughput microplate and portable paper-based sensing was developed for acrolein detection. The microplate assay showed a linear range of 20 -1000 μM (LOD = 12.02 μM), while the paper-based sensor gave 0.3-2.3 mM (LOD = 195 μM). Spike recovery tests on fried and baked foods (French fries, biscuits and bread) yielded recoveries of 97.0 - 101.5% for the microplate method and 103.3 - 115.9% for the paper-based sensing, with RSDs below 5%. This dual-mode method holds promise for high throughput and on-site screening of acrolein in food safety monitoring.

Declarations

Declaration of competing interest

The authors confirm the absence of any financial conflicts or personal affiliations that might be perceived as influencing this research.

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Scheme

Scheme 1 is available in the Supplementary Files section.

Figures

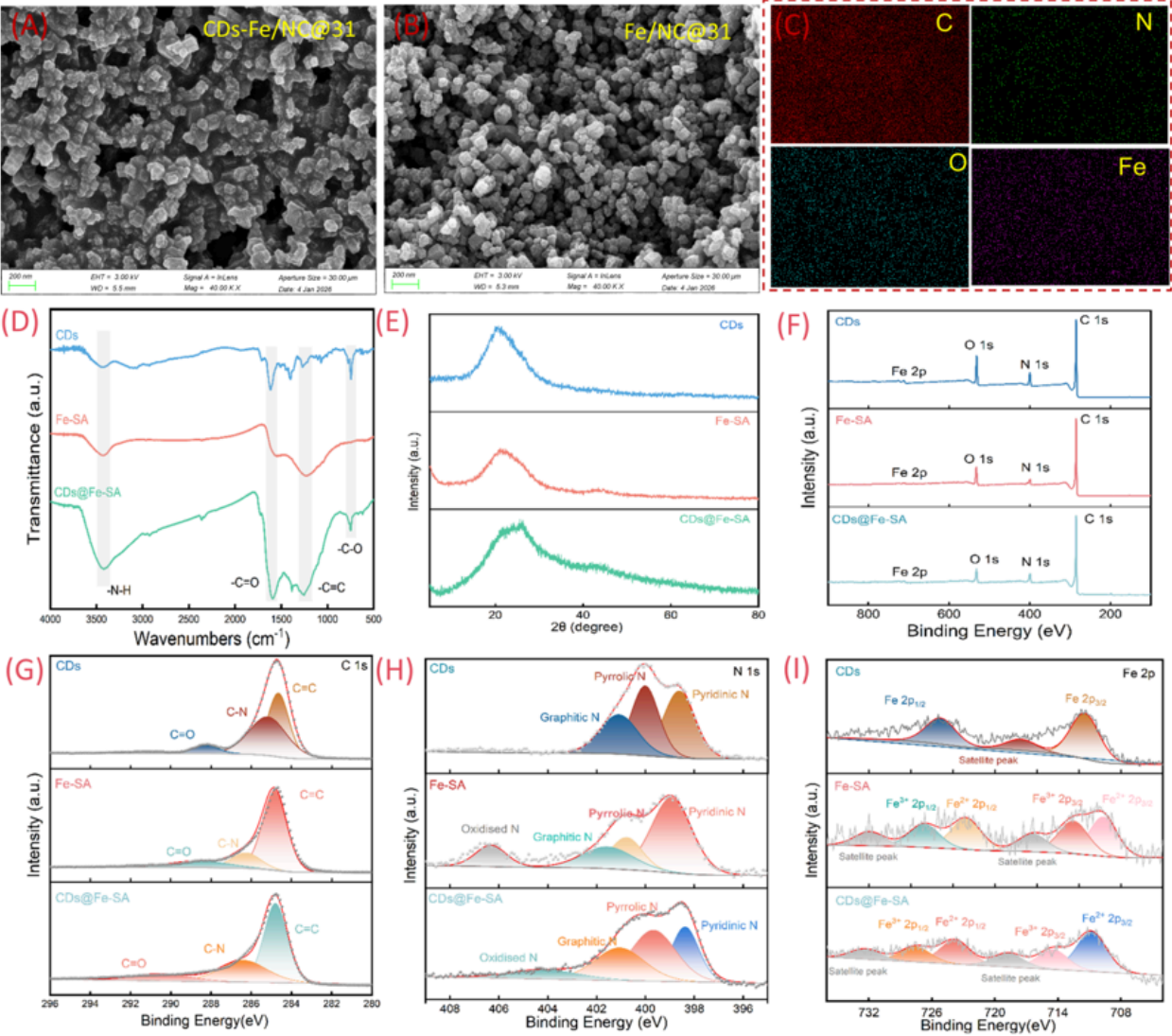


Figure 1

(A) SEM image of CDs@Fe-SA; (B) SEM image of Fe-SA; (C) EDS element mapping of CDs@Fe-SA; Infrared spectra (D) and XRD (E) of CDs, Fe-SA, CDs@Fe-SA; XPS full spectrum of CDs, Fe-SA, CDs@Fe-SA (F); the high-resolution XPS fine spectra of C 1s (G); N 1s (H) and Fe 2p (I).

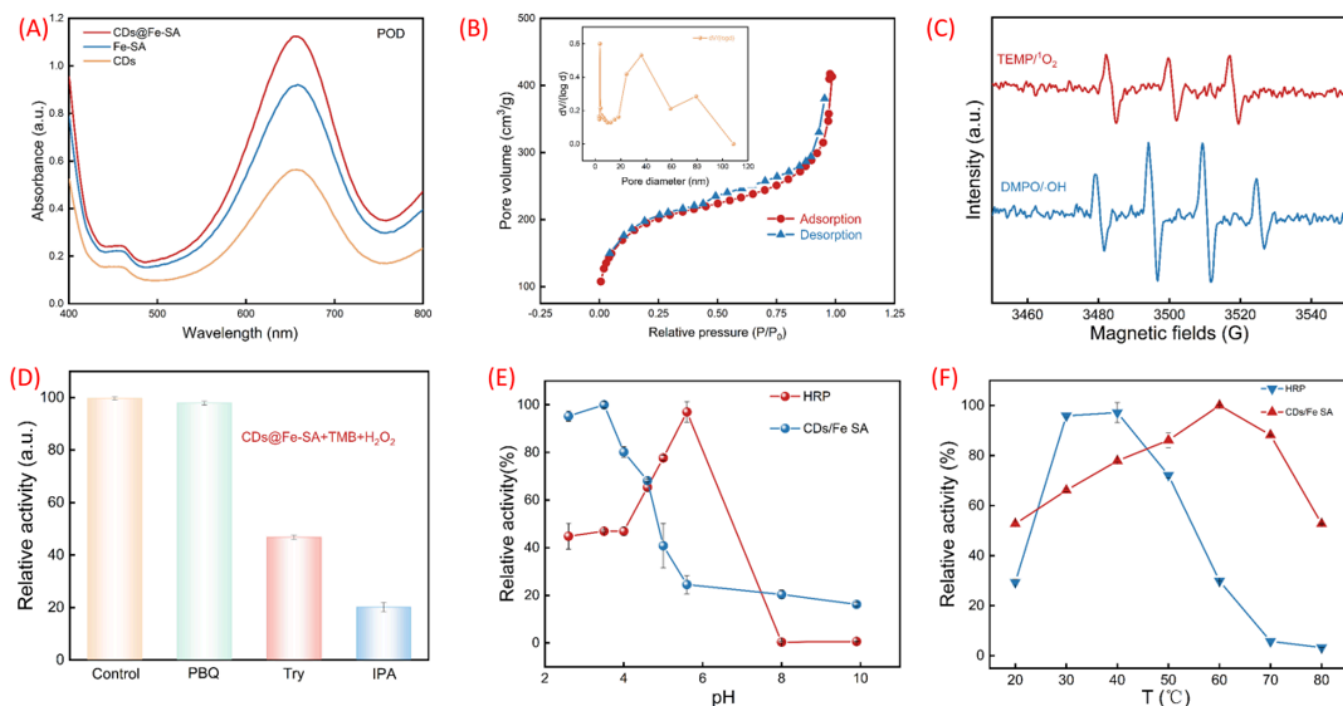


Figure 2

(A) Visible absorption spectra of the three nanozyme; (B) BET test results of CDs@Fe-SA; (C) EPR spectrum of CDs@Fe-SA; (D) Free radical scavenging experiment; (E) The effects of pH (E) and temperature (F) on the CDs@Fe-SA activity.

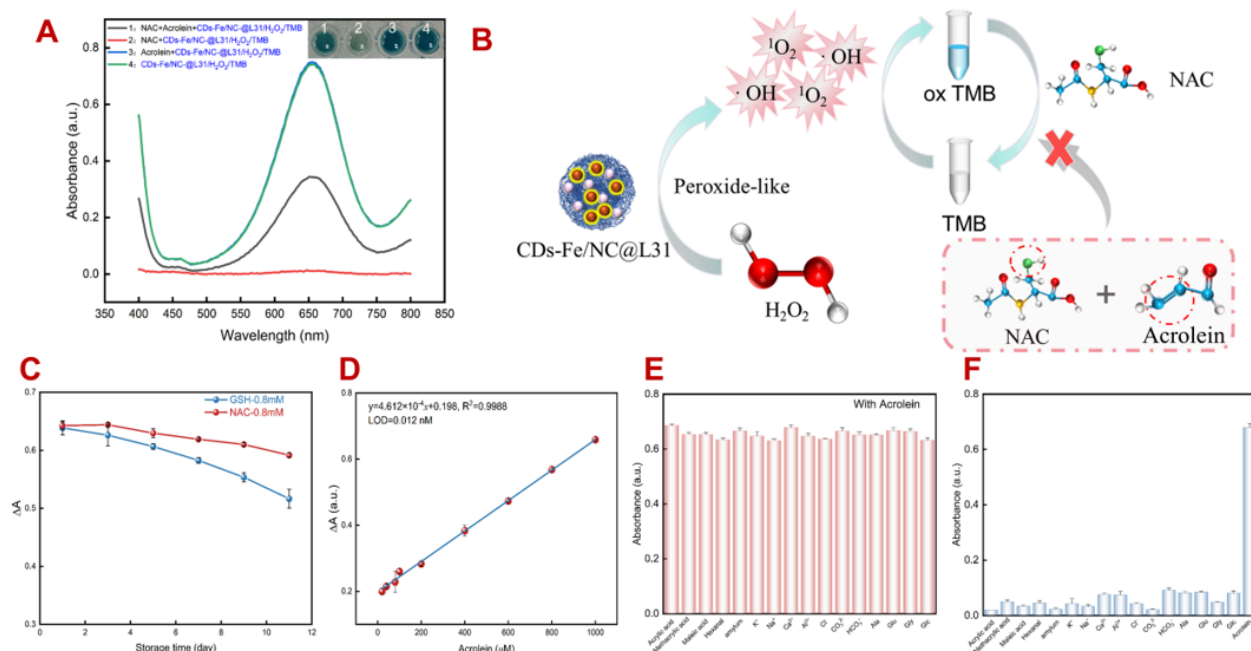


Figure 3

(A) Feasibility experiment for detecting acrolein; (B) Diagram of the reaction mechanism between acrolein and NAC; (C) Comparison of the reduction effects of GSH and NAC; (D) The standard curve for the detection of acrolein by the microplate reader, which $\Delta A = A_1 - A_0$, A_1 is the absorbance at 652nm in the presence of both acrolein and NAC, and A_0 is the absorbance at 652nm in the presence of NAC. (E) Selective experiment; (F) Interference experiment.

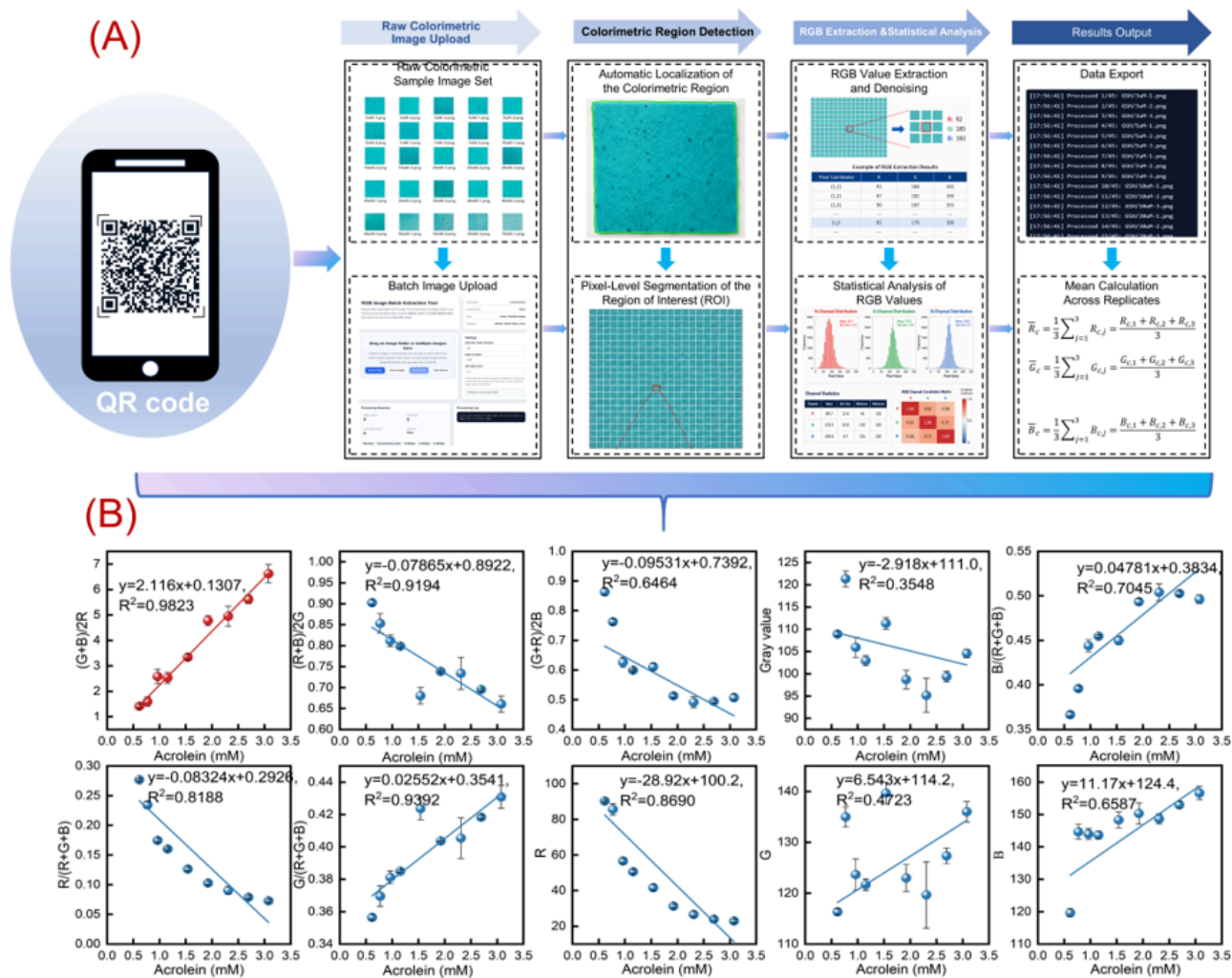


Figure 4

(A) An automatic image recognition and extraction tool based on RGB and written in path programming for uploading images; (B) Response curve of different color difference formulas for paper-based colorimetric sensing to acrolein.

Supplementary Files

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