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Label-Free Detection of Sialic Acid Using Oxidase-Mimicking Co/2Fe MOF via Optical Behavior of Liquid Crystals

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Abstract

Sialic acid (SA) is an essential component of glycoproteins and glycolipids within cellular membranes and plays a pivotal role in various physiological and pathological processes. In this study, we synthesized a metal-organic framework (MOF), Co/2Fe, which was employed for the detection of SA using a stearic acid-doped liquid crystal (LC)-based sensing platform. When applied to SA detection, NANA-aldolase catalyzes the conversion of free SA into pyruvate, which is then transformed into H_2O_2 by the oxidase-mimicking Co/2Fe bimetallic MOF. The substitution of SA with H_2O_2 induces a pH shift that triggers the deprotonation of stearic acid to stearate, leading to the reorientation of the LC at the aqueous/LC interface. This orientational transition can be observed using a polarized optical microscope. We found that SA can be quantitatively assessed within a linear range of 1.5–400 μM , with a detection limit of 0.17 μM . Furthermore, the proposed sensing platform demonstrated high sensitivity and selectivity for the detection of SA in human serum samples. This study highlights the effectiveness of the MOF strategy and introduces a novel approach for SA detection.

Keywords: Co/2Fe MOF, sialic acid, liquid crystals, biosensors, pH-dependent absorption

1. Introduction

Sialic acid (SA), a monosaccharide comprising nine carbon atoms, plays critical roles in various physiological and pathological processes in humans. Located as terminal residues of glycoproteins and glycolipids, they act as ligands for numerous cell receptors [1]. Its distribution across the cell surface notably affects cellular dynamics, adhesion, and signaling pathways. Thus, quantitative measurement of SA concentrations in biological samples has become increasingly important in biomedical research, particularly for the early diagnosis of cancer, neurological disorders, and infectious diseases [2]. For example, changes in the sialylation of glycoproteins have been observed in several epithelial cancers, frequently serving as indicators of tumor progression and metastasis [3-5]. Consequently, quantitative evaluation of SA has emerged as an essential diagnostic tool for the early detection of various cancers, cardiovascular diseases, and diabetes [6, 7].

Metal-organic frameworks (MOFs), frequently known as porous coordination polymers, are a groundbreaking category of materials with considerable applications in catalysis. These crystalline formations arise from the self-assembly of metal ions or clusters along with organic ligands, showcasing elevated surface areas, tunable porosity, and diverse chemical characteristics [8-11]. One particularly significant application of MOFs is in the development of biosensors that harness their unique properties for the detection and monitoring of biological analytes. The large surface area and robustness of these MOFs enable the effective immobilization of biomolecules, including enzymes, making them ideal for the detection of various biological targets such as glucose, proteins, and nucleic acids [12, 13]. Notably, the bimetallic Co/2Fe MOF, which integrates cobalt

(Co²⁺) and iron (Fe³⁺) ions, shows great promise for biosensor applications because of its enhanced electrochemical properties [14]. The redox activity of cobalt (Co) and iron (Fe), both transition metals, is crucial for electrochemical biosensors that depend on electron transfer to generate signals [15]. The presence of Co and Fe augments the catalytic efficiency, thereby enhancing the sensitivity and response time of the biosensors. For instance, in glucose sensing applications, Co/2Fe MOF-based platforms can successfully immobilize glucose oxidase, and the redox reactivity of metals promotes glucose oxidation, producing an electrochemical signal. The combination of high conductivity and stability in MOFs, along with their proficiency in facilitating electron transfer, highlights their potential as materials for biosensors in medical diagnostics and environmental monitoring [16-18].

Liquid crystals (LCs) are materials that exhibit properties between those of crystalline solids and isotropic liquids. They have garnered considerable interest from researchers in various fields, including biology and medicine. These materials can exist in phases that transition between the liquid and solid states, displaying increased sensitivity to external factors such as temperature, pressure, electric fields, and molecular interactions [19-22]. This heightened sensitivity stems from the anisotropic nature of LCs, where environmental changes can lead to shifts in the molecular orientation, resulting in noticeable variations in their optical properties [23-25]. These attributes make LCs advantageous for the development of advanced biosensing technologies.

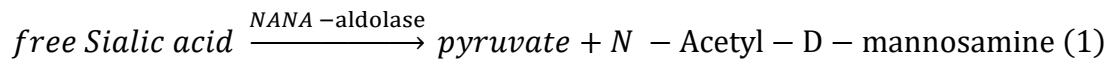
Liquid crystal-based sensors present an appealing framework for detecting a range of biological and chemical entities, largely owing to the unique optical features of LCs. A notable superiority of these sensors is their capability to promote label-free sensing. Unlike traditional sensing platforms, such as fluorescent or electrochemical sensors, which often require labeling or modification of target molecules, potentially complicating detection processes and altering the natural behavior of

these targets, LC-based sensors allow for direct observation of interactions between analytes and the sensor surface through changes in the orientation of LCs [26-29]. This method provides a simple and intuitive detection mechanism.

Moreover, LC-based sensors exhibit significant versatility in response to a variety of stimuli, making them suitable for diverse applications, including the sensing of proteins, DNA, bacteria, and environmental pollutant [30-33]. This adaptability is particularly beneficial in biosensing, where LCs can be integrated with functionalized surfaces to enhance the specificity and selectivity for target analytes. For example, when detecting biomolecules such as proteins or nucleic acids, the LC layer can be immobilized on a substrate coated with specific recognition components such as antibodies or aptamers [34, 35]. The binding of the target molecule to these recognition components disrupts the bonds within the LCs, leading to an observable optical change under polarized light microscopy. In addition, LC-based sensors enable rapid detection with straightforward readouts, eliminating the need for complex instrumentation. Their low cost, ease of fabrication, and ability to operate without a power source distinguish them from other sensor types, such as electrochemical or optical sensors, making them particularly suitable for *in situ* testing and environmental monitoring [36-38]. Furthermore, the real-time and reversible responses of LCs to target binding facilitate the dynamic monitoring of analyte concentrations, which is advantageous for applications that require continuous or repeated measurements. These assays have demonstrated successful applications in sensing of diverse targets, including pathogens in clinical diagnostics, heavy metals in water quality monitoring, and volatile organic compounds in air pollution control [31, 39-41]. Ongoing research aims to enhance the stability, sensitivity, and functionalization of LC materials, thereby expanding their application in the medical and

environmental fields and establishing LC-based sensors as invaluable tools in contemporary analytical science.

In the current study, a synthetic oxidase enzyme, which mimics the bimetallic MOF structure of Co/2Fe, along with the NANA-aldolase enzyme, was immobilized on gold transmission electron microscopy (TEM) grids. In this context, free SA in an aqueous solution is expected to transform, as indicated by the following reactions [14]:



It is assumed that the replacement of SA in the solution by hydrogen peroxide (H₂O₂) will lead to a significant change in the pH value. As SA is removed and replaced by the much weaker acid H₂O₂, the net result is a local reduction in acidity and a corresponding increase in pH, particularly at the LC–aqueous interface. To transduce this pH change into an optical signal, stearic acid-doped LCs were used under the polarized optical microscope (POM). After the development of the SA biosensor, the experimental parameters were systematically optimized. In addition, the specificity and reliability of the sensor were evaluated.

2. Materials and methods

The information about materials and methods used for this LC-based assay is presented in Supplementary Information.

3. Results and discussions

3.1 Detection strategies for SA detection

The detection strategy for SA used in the proposed assay is based on the pH-sensitive properties of stearic acid. When stearic acid is spiked in 5CB LCs, the optical response of the system is determined by the pH of the aqueous phase. At the studied concentration (0.5 wt%), stearic acid is likely molecularly dispersed in the 5CB matrix rather than forming reverse micelles. The stearic acid interacts with the LC environment via van der Waals forces through its hydrophobic tail, and through dipole interactions or hydrogen bonding between its carboxylic headgroup and the nitrile group of 5CB. Upon contact with the aqueous phase, stearic acid molecules tend to accumulate at the LC–water interface, where changes in pH modulate their protonation state. This interfacial behavior alters the anchoring of the LCs, thereby producing the observed optical texture transitions.

In the presence of free SA, NANA aldolase catalyzes the conversion of SA to pyruvate and N-acetyl-d-mannosamine, as described in the Introduction. Subsequently, Co/2Fe bimetallic MOFs with oxidase-like activity catalyze the oxidation of pyruvate to acetyl phosphate and H_2O_2 . Notably, the principal factor responsible for the observed increase in pH is not the formation of H_2O_2 —which is only weakly acidic—but rather the enzymatic depletion of sialic acid. Given that sialic acid is a strong acid ($\text{pK}_a \approx 2.6$), its enzymatic removal decreases the total acidic content of the buffered solution, effectively leading to a shift in local pH toward neutrality.

To systematically assess the contribution of each component to the pH shift, four experimental conditions were compared in Figure S1: (i) buffered solutions containing increasing concentrations of SA; (ii) solutions containing increasing concentrations of H_2O_2 ; (iii) SA solutions pre-adjusted

to pH 6.0 and incubated with a bare (non-functionalized) TEM grid; and (iv) SA solutions pre-adjusted to pH 6.0 and incubated with the modified TEM grid bearing immobilized aldolase and MOFs.

The results indicate that: (1) SA induces significant acidification of the medium in a concentration-dependent manner; (2) H₂O₂, although weakly acidic, causes only negligible changes in pH over the tested range; (3) incubation with the bare TEM grid after pH adjustment causes no substantial change, confirming that the grid itself does not alter the chemical environment; and (4) incubation with the modified grid leads to a measurable increase in pH, consistent with enzymatic consumption of SA (**Figure S1**). These findings confirm that the increase in interfacial pH is driven by the removal of free SA from the system, not by the presence of H₂O₂ or physical interactions with the substrate. This enzymatically induced pH elevation promotes the deprotonation of stearic acid (pK_a $\approx$ 4.8), resulting in the formation of stearate anions. The increase in interfacial negative charge subsequently perturbs the anchoring of mesogens at the aqueous–LC interface, thereby generating a detectable optical response (**Scheme 1**).

3.2 Characterization of Bimetallic Co/2Fe MOF Structure

The bimetallic Co/2Fe MOF exhibits a cubic architecture with Co and Fe atoms in the core and coordinated with benzene-1,3,5-tricarboxylic acid (BTC) as the organic ligand. Scanning electron microscopy (SEM) images (Fig. 1a) show the well-defined formation of Co/2Fe MOF crystals with regular polygonal and cubic surfaces corresponding to the Co and Fe constituents, respectively. Figure 1b illustrates the spatial distribution of Co and Fe atoms within the Co/2Fe MOF framework. Energy dispersive X-ray spectroscopy (EDS) analysis, shown in Fig. 1c, confirmed the elemental composition of the synthesized material and revealed weight percentages

of 55.28% carbon, 45.68% oxygen, 0.69% cobalt and 3.05% Fe, with corresponding atomic percentages of 76.62% C, 22.52% O, 0.35% Co and 0.51% Fe.

The crystalline structure of the Co/2Fe MOF was analyzed by powder X-ray diffraction (XRD) in the 2θ range of 0° - 50° . As shown in Fig. 1d, the diffraction pattern contains prominent peaks at 2θ values of 6.18° , 9.69° , 13.09° , 19.52° , 26.39° and 39.97° , which are in agreement with previously published data [14, 15]. In particular, the peaks at 9.69° , 13.09° and 19.52° correspond to the cubic structure of iron, while the peaks at 26.39° and 39.97° are due to the cubic structure of cobalt.

The Fourier transform infrared (FTIR) spectrum of the Co/2Fe MOF (Fig. 1e) further confirms the structural composition. Important absorption bands were observed at 3410, 1368 and 1615 cm^{-1} , corresponding to hydrogen-bonded O–H groups, $-(\text{C}=\text{O})\text{OH}$ groups and H–O–H groups, respectively. These bands were consistently observed in all samples. A weak absorption band at 3063 cm^{-1} indicates the stretching vibrations of the aromatic ring ($-\text{CH}$)_{ar} and confirms the presence of BTC ligands within the MOF structure [15, 42]. The FTIR spectrum also shows aromatic ring stretching bands ranging from 1600–1605 to 700–800 cm^{-1} , with weaker and narrower bands at 1065–1083 cm^{-1} and 750–782 cm^{-1} , corresponding to the $\gamma(\text{C}-\text{H})$ and $\delta(\text{C}-\text{H})$ vibrations of the aromatic rings, respectively. In particular, the absence of two distinct peaks at 761 and 713 cm^{-1} indicates a complete deprotonation of the carboxyl groups in the BTC ligand. In addition, a medium strength band at 538–557 cm^{-1} is assigned to the M–O vibrations, confirming the successful formation of the bimetallic MOF.

3.3 Established the pH Conditions for Aassay

We investigated the critical pH transition of stearic acid-doped LCs to establish a baseline pH for all aqueous solutions used in subsequent experiments. Stearic acid-doped LC films were incubated

in phosphate buffer (PB) solutions with varying pH values for one hour at room temperature. As shown in Fig. 2, exposure to PB buffer at pH 5.5 and 6.0 resulted in bright optical textures, indicative of a planar alignment of the LC molecules at the aqueous/LC interface. In contrast, as the pH increased from 6.3 to 6.6, a transition from bright to dark textures was observed, signifying a shift from planar to isotropic anchoring. At pH 7.0, the optical image appeared completely dark.

The observed pH-dependent behavior suggests that PB buffer at pH 5.5 does not sufficiently deprotonate stearic acid at the aqueous/LC interface, as the LC films maintained a planar orientation, producing a bright optical texture under POM. Conversely, at pH 7.0, the dark optical image indicated the complete deprotonation of stearic acid and its subsequent adsorption at the interface, promoting a perpendicular (homeotropic) orientation of the LC. It is important to note that while the pKa of stearic acid in water is approximately 4.5, this value does not directly apply to stearic acid doped in the 5CB matrix. In our system, stearic acid is initially dispersed in the LC phase and only becomes active at the LC–aqueous interface. The interfacial protonation behavior is influenced by the local environment, which differs significantly from bulk aqueous conditions. Therefore, the LC anchoring transition observed here is not solely a function of bulk pH crossing the pKa threshold, but rather a consequence of localized interfacial reorganization triggered by subtle pH changes. This phenomenon has also been reported in other LC-based sensing studies, where minor shifts in interfacial pH can induce cooperative reorientation of mesogens[43].

Based on these results, pH 6.0 was determined to be the critical transition point for stearic acid-doped LCs. Consequently, the pH of all experimental solutions was precisely adjusted to this value to ensure consistency in experimental conditions.

3.4 Sensing Performance of the LC-Based Assay for Stearic Acid

The sensor performance of the LC-based assay for SA was evaluated by assessing the optical response of the LC upon exposure to different concentrations of SA. As previously described, the combination of NANA aldolase and Co/2Fe MOF catalyzes the conversion of free SA to H₂O₂, resulting in an increase in pH. This pH increase promotes the adsorption of stearic acid at the aqueous/LC interface, triggering a homeotropic alignment of the LCs and resulting in dark optical images.

SA concentrations from 0.5 to 1000 μ M were investigated, and the responses of the LCs were recorded after a 1-hour incubation at 37 °C. The resulting optical images are shown in Fig. 3. At SA concentrations below 1.5 μ M, bright optical structures were observed, indicating insufficient pH increase to facilitate the adsorption of stearic acid at the interface. As the SA concentration increased from 2 to 400 μ M, the optical textures transitioned from light to progressively darker, corresponding to the increasing SA concentration. Beyond 400 μ M, the optical images reached a saturation point, reflecting a complete pH shift triggered by the catalytic activity of NANA aldolase and Co/2Fe MOF, which fully promoted the adsorption of stearic acid.

The limit of detection (LOD) of the biosensor was determined by analyzing the relationship between the SA concentration and the grayscale intensity of the optical images. The LC response to different SA concentrations was investigated using NANA aldolase and Co/2Fe MOF-functionalized TEM grids. Each concentration was tested in three independent experiments using separate TEM grids. For each grid, grayscale intensity was measured over 32 grid squares, yielding a total of 96 data points per concentration. This sampling strategy ensured reliable statistical representation while demonstrating the homogeneity of the optical response across the sensing platform. The relatively small standard deviations reflect this consistency and suggest that fewer

sampling points may still yield reproducible results in future applications.

The correlation between the grayscale intensity and the logarithm of the SA concentration is shown in Fig. 4. For SA concentrations between 1.5 and 400 μM , a linear relationship was observed, yielding a regression equation of $y = 23.97x + 25.45$ with a high correlation coefficient ($R^2 = 0.998$). At concentrations below 1.5 μM or above 400 μM , the response showed minimal variation, indicating the limits of the effective detection range of the sensor. Although the sialic acid is present in bulk solution, the sensor response is determined by interfacial processes. In our design, the LC–aqueous interfacial area is fixed due to the defined geometry of the TEM grid and consistent aqueous volume ($\sim 200\ \mu\text{L}$) across all wells. As a result, the amount of enzymatic product generated and its effect on local pH is localized to the interface, where optical changes in LC orientation occur. Even if the bulk volume were increased, the LC signal would remain governed by local events at the grid surface, not by the total solution volume.

Although the estimated bulk pH change at the LOD of 0.17 μM SA is relatively small (likely <0.1 pH units), the LC-based sensor is highly sensitive to interfacial effects. The LC–aqueous interface acts as an amplification platform where minor changes in protonation state of stearic acid—especially at the interface—can lead to significant disruptions in LC alignment. These changes are optically observable, enabling detection of extremely low SA concentrations through amplified mesogen reorientation. This ultrasensitive interfacial behavior accounts for the observable optical shift at low SA levels, even when the bulk solution pH appears nearly unchanged.

Based on the regression analysis and standard deviation calculations, the LOD of the sensor was determined to be 0.17 μM , with a linear operating range of 1.5 to 400 μM . Comparisons with previously reported methods (Table 1) show that the proposed sensor has a competitive LOD and a robust linear detection range. These results confirm the reliability and efficiency of the sensor in

quantifying SA levels, making it a practical tool for the diagnosis of conditions associated with elevated SA concentrations.

3.5 Specificity Evaluation of the SA Detection Assay

To further validate the feasibility of SA detection, the specificity of the proposed assay was evaluated by analyzing the optical response of stearic acid-doped LCs after the reaction of SA with NANA aldolase and Co/2Fe MOF immobilized on a TEM grid. Potential interferents, including Ca^{2+} , Cl^- , Na^+ , NH_4^+ , uric acid, ascorbic acid, cysteine, glucose, fructose, and acetophenone, were introduced to evaluate the selectivity of the sensor. The optical images of the LCs were taken after 1 hour of incubation and the corresponding grayscale intensities were measured, as summarized in Fig. 5.

The results showed that the bright optical structures of the LCs remained largely unchanged in the presence of these potential interferents. However, the introduction of SA led to a significant darkening of the optical images. The grayscale intensities of the LCs exposed to the interfering solutions were significantly lower than those observed for the SA solution (Fig. 5). This observation is attributed to the fact that the interfering substances are unable to be catalytically converted by the NANA aldolase, preventing the reaction sequence that converts SA to H_2O_2 . As a result, the pH at the aqueous/LC interface remained stable and no significant perturbation of LC alignment occurred. In contrast, the presence of SA initiated the catalytic activity of NANA aldolase and Co/2Fe MOF, leading to the production of H_2O_2 , a pH shift and the subsequent desorption of stearic acid. This process facilitated the reorientation of the LCs from a planar to a homeotropic orientation, resulting in the dark optical response.

These results confirm that the combined action of NANA aldolase and Co/2Fe MOF specifically catalyzes the conversion of SA to H_2O_2 , a critical step in the assay mechanism. Consequently, the stearic acid-doped LC sensors in combination with NANA aldolase and Co/2Fe MOF showed excellent specificity for SA detection and effectively discriminated SA from a range of potential interferents.

3.6 Detection of SA in Human Serum Samples

Based on the experimental results, the TEM grid immobilized with NANA aldolase and Co/2Fe MOF showed remarkable analytical performance in detecting SA in real samples. To evaluate the practical applicability of the proposed sensor, it was used to quantify the SA concentration in human serum samples.

The results summarized in Table 2 show recovery values between 95.20% and 103.10%, with the relative standard deviation (RSD) consistently below 2.26% ($n=3$). The measured SA concentration in human serum was approximately 1.65 mM, calculated as the mean detected concentration multiplied by the dilution factor. This value aligns well with the total sialic acid (TSA) concentration typically found in human serum (1.5–2.5 mM), which primarily reflects protein-bound sialic acid. In serum, sialic acid is commonly attached to glycoproteins such as transferrin, haptoglobin, alpha-1-acid glycoprotein, and immunoglobulins. While our current detection strategy targets free sialic acid, the experimental setup involved the use of serum samples spiked with known concentrations of free SA, providing a reliable proof-of-concept for detection in biological matrices. Future work will focus on enzymatic or chemical hydrolysis to release protein-bound SA for total sialic acid analysis. These results emphasize the potential of the proposed sensor for practical SA detection, especially in clinical applications. The high recovery

rates and low RSD values indicate robust reproducibility, while the compatibility with serum samples emphasizes its applicability in real-world diagnostics.

4. Conclusion

In this study, we designed and synthesized an LC-based sensor using a Co/2Fe MOF for the detection of SA. The proposed sensor showed exceptional sensitivity and specificity for the detection of SA. The detection mechanism is based on the catalytic activity of NANA aldolase, which converts free SA into pyruvate. This intermediate is subsequently oxidized to H_2O_2 the Co/2Fe MOF mimicking the oxidase. The replacement of SA with H_2O_2 leads to a pH shift that facilitates the deprotonation of stearic acid to stearate, which triggers the reorientation of LC at the aqueous/LC interface. The integration of NANA aldolase and Co/2Fe MOF proved to be highly specific in interference tests and effectively discriminated SA from potential interferents. In addition, the sensor showed excellent analytical performance in detecting SA in human serum samples, with recoveries ranging from 95.20% to 103.10% and detected concentrations in good agreement with known physiological levels. With the successful application of MOFs in LC-based sensing, this study highlights the efficacy of the MOF strategy and presents a new, reliable approach for SA detection. The results suggest that this sensor holds promise for practical applications, particularly in clinical and diagnostic contexts.

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Compliance with ethical standards

The authors declare they have no potential conflicts of interest related to the publication of this article.

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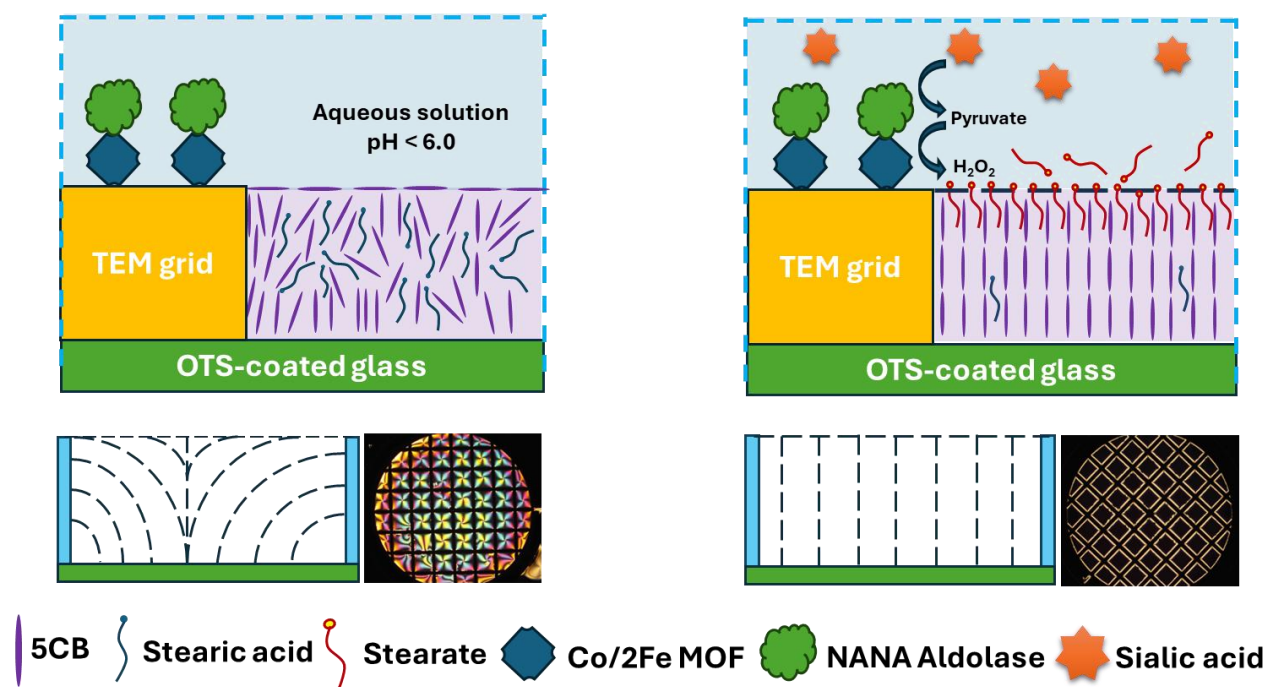
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Table 1. Comparison of different methods for sialic acid detection.

Method	Material	Sample	Linear range	LOD	Ref.
Colorimetry	4-MPBA-AuNPs	Human serum	80–2000 μM	68 μM	[44]
Colorimetry	3-APBA-AuNPs	Human saliva	150–1000 μM	60 μM	[45]
Electrochemistry	PABA/ERGO/GC	Human serum	2–1380 μM	0.8 μM	[46]
Electrochemistry	NANA-aldolase/pyruvate oxidase	Human serum	3500 μM	10 μM	[47]
Fluorescence	boronic-acid/CDs	Human serum	80–4000 μM	54 μM	[48]
Fluorescence	BA-FITC@rGO	Human serum	500–5000 μM	44 μM	[49]
Fluorescence	UiO-CPBA	Human serum	1–100 μM	0.15 μM	[50]
SERS	cit-Ag-NPs	Saliva	-	-	[51]
SERS	Au NPs/ITO	Human serum	0.25-1.5 μM	0.12 μM	[52]
SERS	Ag NPs	-	-	0.1 μM	[53]
Liquid crystal	Co/2Fe MOF and NANA-aldolase	Human serum	1.5–400 μM	0.17 μM	This work

Table 2. Determination of sialic acid in human serum samples.

Sample	Detected	Added	Found	Recovery	RSD
	(μM)	(μM)	(μM)	(%)	(%, $n = 3$)
1	15.64	10	25.32	96.8	2.11
		50	66.26	101.24	1.62
		100	117.03	101.39	0.67
2	17.42	10	26.94	95.2	1.79
		50	67.34	99.84	1.48
		100	119.68	102.26	0.86
3	16.56	10	26.87	103.1	2.26
		50	64.97	96.82	1.64
		100	114.98	98.42	0.91



Scheme 1. A schematic illustration of the sensing mechanism using stearic acid-doped liquid crystals, which is integrated with TEM grid functionalized NANA-aldolase and Co/2Fe MOF for the detection of sialic acid.

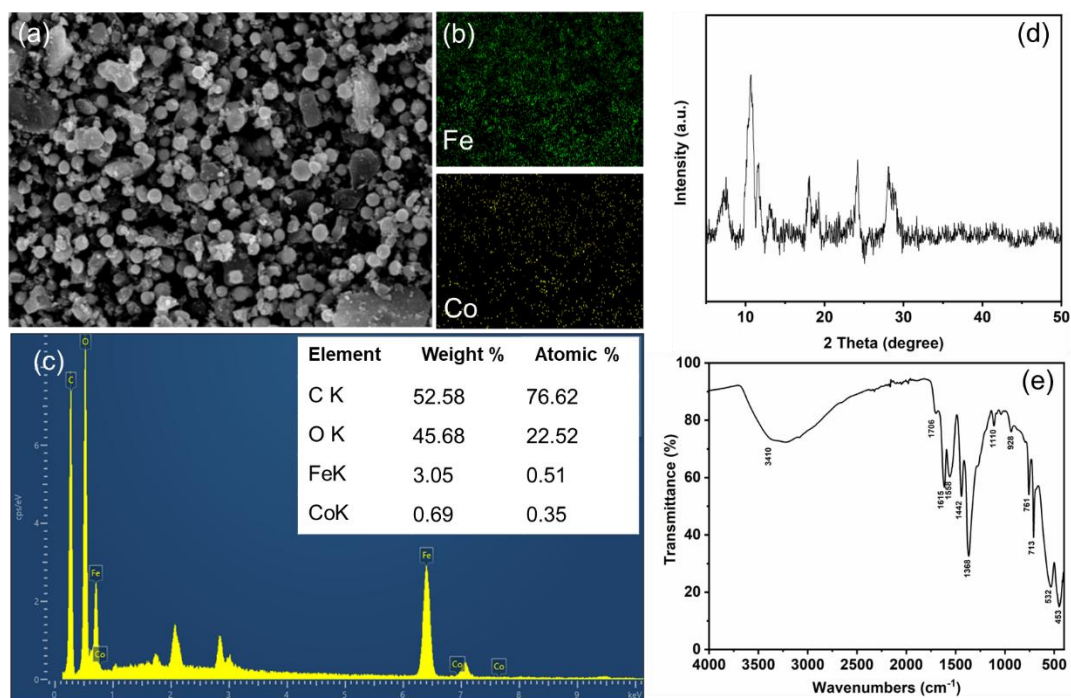


Figure 1. Results of the analyses: (a) SEM image, (b) SEM mapping image, (c) EDS, (d) XRD spectra, and (e) FTIR spectrum of the bimetallic Co/2Fe MOF

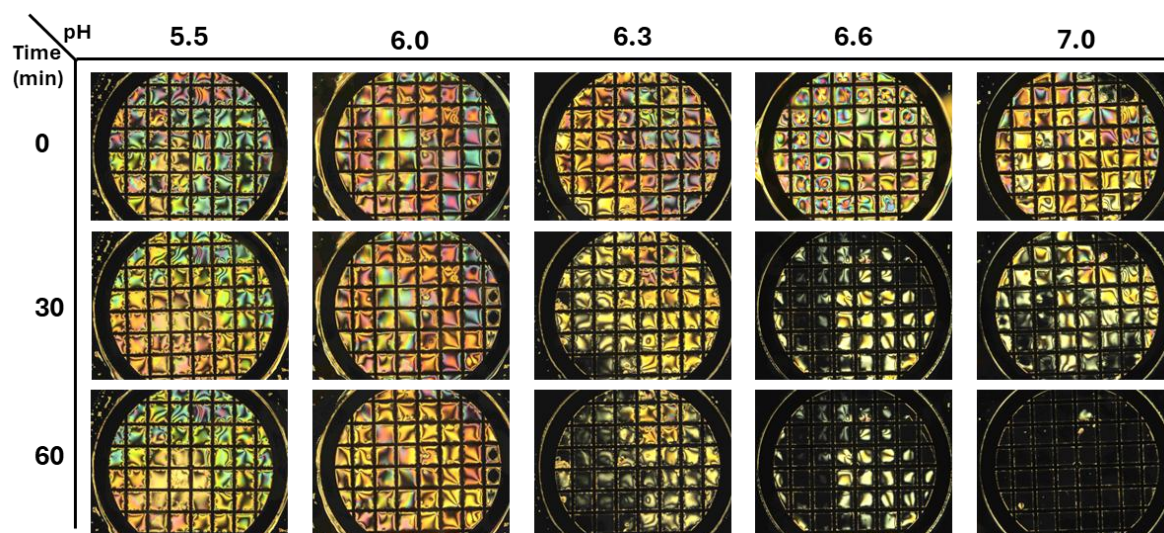


Figure 2. Polarization microscopy images obtained from a functionalized TEM grid filled with stearic acid-doped liquid crystals incubated in PB buffer solutions at pH 5.5–7.0. The optical response was monitored over a period of 60 min, with images captured at 0, 30, and 60 min.

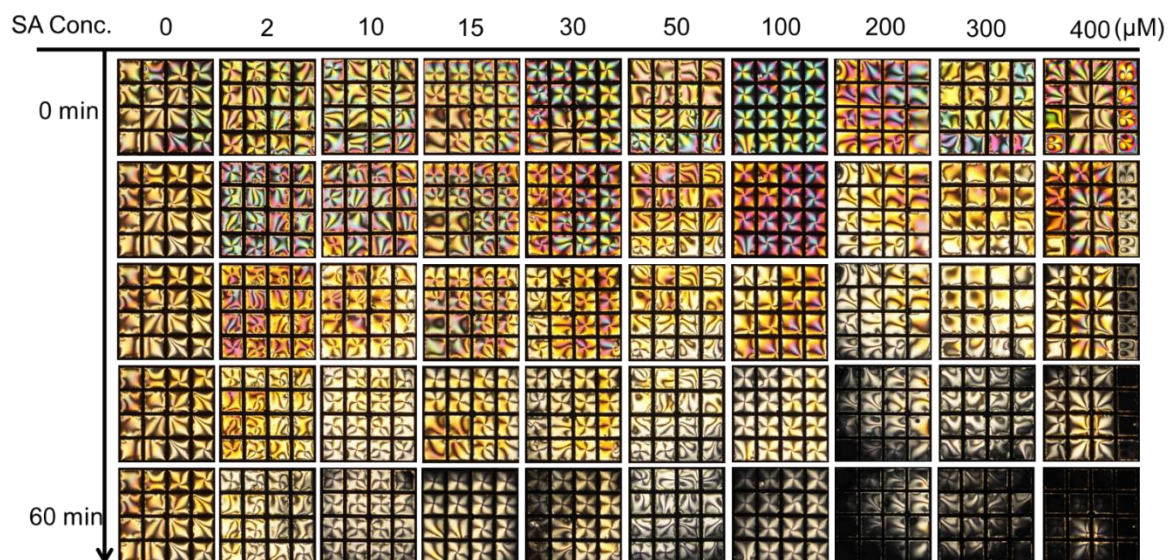


Figure 3. Optical response of stearic acid-doped liquid crystals after incubation with varying concentrations of sialic acid on a functionalized TEM grid for 1 h. Each grid hole is 285 μm in diameter.

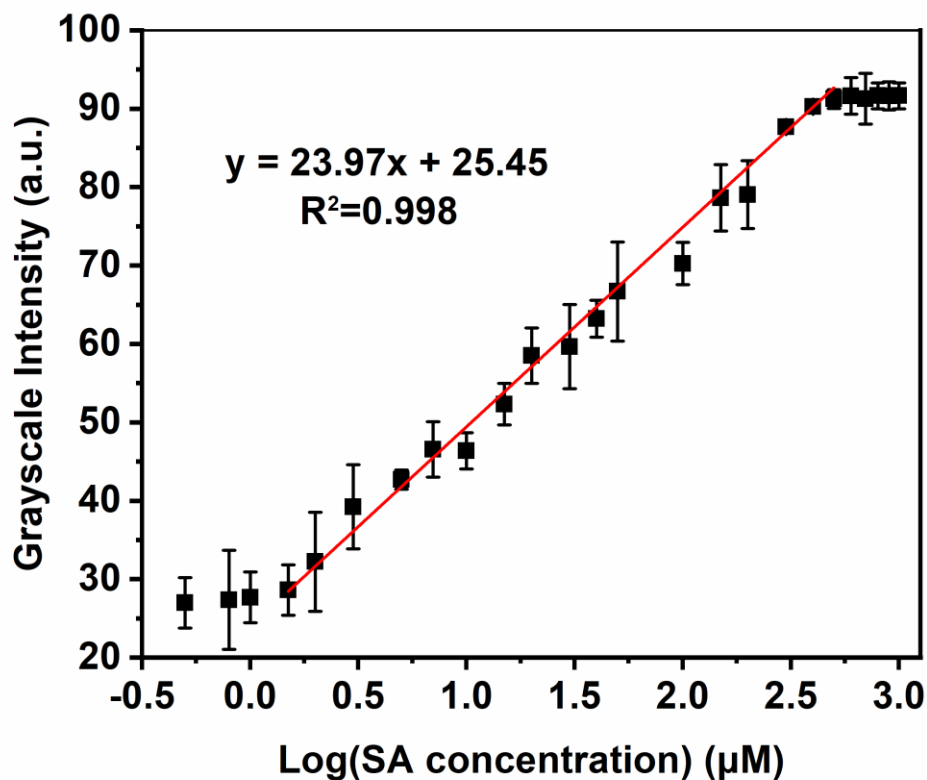


Figure 4. Graph illustrating the relationship between the intensity of the optical image and the logarithmic concentration of sialic acid, spanning from 0.5 to 1000 μM . The red line represents the linear correlation between the grayscale intensity of the optical image and logarithmic SA concentration, specifically within the range of 1.5–400 μM . Each grid hole is 285 μm in diameter.

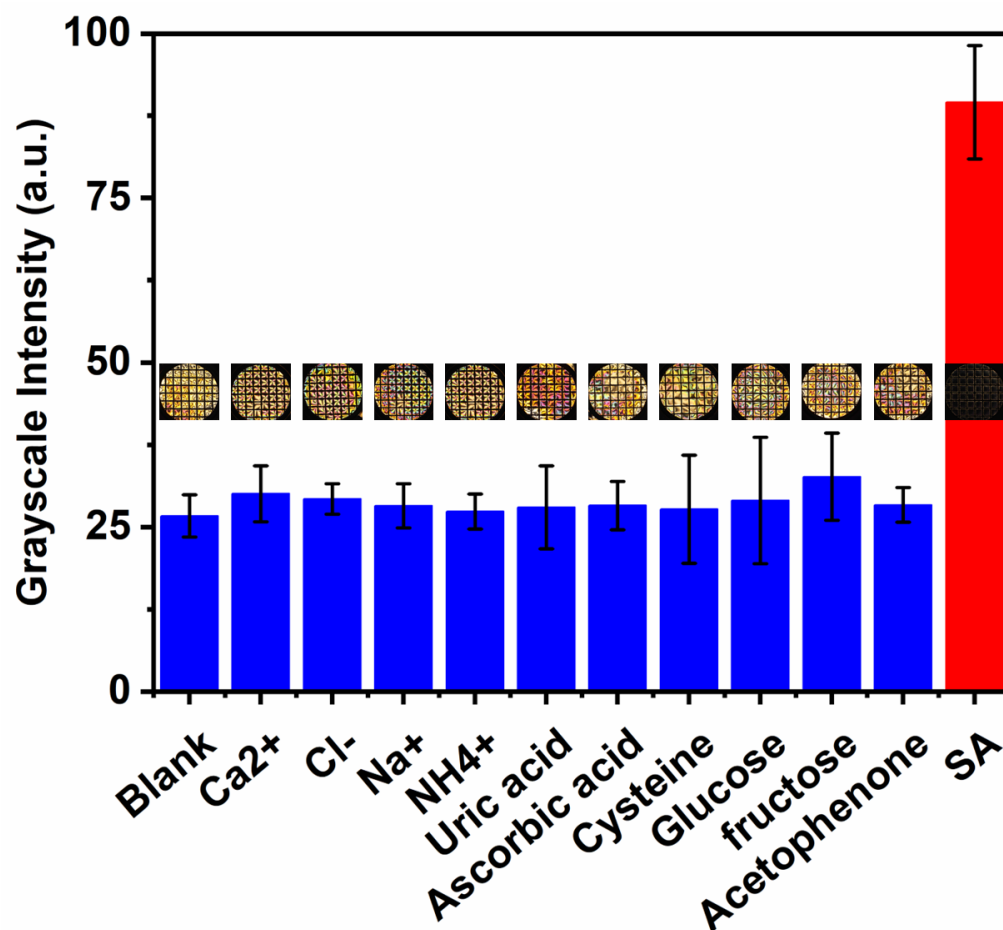


Figure 5. The mean intensity of liquid crystals optical images following a 1-h incubation period within a functionalized TEM grid containing stearic acid-doped LCs with SA, Ca²⁺, Cl⁻, Na⁺, NH₄⁺, uric acid, ascorbic acid, cysteine, glucose, fructose, and acetophenone. Each grid hole is 285 μ m in diameter.