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Wearable Colorimetric Sensor for Hydrogen Sulfide Detection

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Colorimetric gas sensors are gaining increasing attention as simple, low-cost, and rapid tools for on-site detection. In this work, a flexible colorimetric sensor for hydrogen sulfide (H_2S) detection was developed based on electrospun polylactic acid (PLA) nanofibers functionalized with bromocresol green (BCG). The PLA/BCG nanofibers exhibited a uniform morphology with an average diameter of approximately 250 nm, and the incorporation of the dye did not significantly alter the structural or chemical properties of the polymer matrix. The sensor showed a distinct, concentration-dependent response to sulfide species, first validated in aqueous Na_2S solutions and subsequently confirmed in gas-phase experiments. Under the tested conditions, the sensor was able to visually detect H_2S at concentrations as low as 100 ppb, exhibiting a rapid response within approximately 1.5 s. The membrane also demonstrated good long-term stability, retaining its initial color for at least five months under ambient laboratory conditions. The proposed system combines flexibility, rapid response, and long-term stability, making it a promising platform for wearable applications and environmental monitoring.

1. Introduction

Colorimetric gas sensors have emerged as powerful analytical tools due to their simplicity, rapid response, low cost, and the possibility of direct naked-eye detection. Unlike conventional analytical techniques that require complex instrumentation and controlled laboratory conditions, colorimetric systems enable straightforward, portable, and on-site monitoring, making them particularly attractive for environmental and biomedical applications (Cirillo et al., 2025). In recent years, considerable research efforts have been devoted to enhancing their sensitivity, selectivity, and stability through the incorporation of responsive dyes into functional matrices such as gels, nanofibers, and polymeric substrates. Nanostructured materials have attracted growing interest due to their high surface area, tunable porosity, and ability to promote fast analyte diffusion, all of which contribute to improved sensing performance (Sarno et al., 2018). At the same time, the rapid development of wearable and flexible technologies has opened new opportunities for the design of next-generation sensing platforms. Wearable sensors, capable of conforming to the human body while maintaining mechanical durability, flexibility, and comfort, are increasingly investigated for applications in health monitoring, human–computer interaction, and soft robotics (Dong et al., 2025). Within this framework, flexible colorimetric gas sensors represent a promising strategy for real-time and in situ monitoring of both physiological and environmental parameters (Wang et al., 2024). Their integration into stretchable and breathable materials enables continuous detection while preserving user mobility and comfort, thus supporting the advancement of personalized healthcare systems and intelligent wearable technologies. Moreover, the use of lightweight and disposable materials further enhances their suitability for large-scale and low-cost deployment. Among biologically relevant gaseous molecules, hydrogen sulfide (H_2S) has attracted increasing attention. Traditionally considered a toxic and environmentally hazardous gas, H_2S is now recognized as the third endogenous gasotransmitter, together with nitric oxide (NO) and carbon monoxide (CO) (Zheng et al., 2018; Choi et al., 2016). Endogenously produced H_2S plays a crucial role in several physiological and pathological processes, including the regulation of insulin signaling, modulation of inflammatory responses, neuromodulation, and relaxation of vascular smooth muscles (Dufton et al., 2012).

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Altered H_2S levels have been associated with various diseases, such as cardiovascular disorders, neurodegenerative conditions, and cancer, highlighting the importance of reliable detection under physiological conditions. However, its high volatility, rapid metabolism, and low steady-state concentrations in biological systems make accurate monitoring particularly challenging, especially in real-time and non-invasive scenarios. In this work, we report the development of a bromocresol green (BCG)-based wearable colorimetric sensor for hydrogen sulfide detection. The sensing platform is designed as an adhesive and stretchable patch consisting of electrospun polylactic acid (PLA) nanofibers deposited onto a nonwoven fabric substrate, combining mechanical flexibility with optical responsiveness. The use of electrospinning enables the fabrication of a highly porous and interconnected nanofibrous network, which enhances gas diffusion and interaction with the sensing dye. The proposed system demonstrates promising sensing capability toward H_2S and may be employed both for industrial gas-leak monitoring and wearable real-time sensing applications. These findings further support the development of flexible colorimetric platforms as practical and scalable tools for H_2S detection.

2. Experimental

2.1 Materials

Bromocresol green, polylactic acid (PLA), N,N-dimethylformamide (DMF), chloroform, and all other chemicals were purchased from Sigma-Aldrich. All reagents were of analytical grade and used as received.

2.2 Preparation of electrospun colorimetric sensor

PLA nanofibers were fabricated by electrospinning using a laboratory-scale electrospinner. Briefly, 0.55 g of PLA was dissolved in 2.32 mL of N,N-dimethylformamide (DMF), followed by the addition of 6.87 mL of chloroform. The resulting solution was magnetically stirred at 80 °C until complete dissolution of the polymer to obtain a homogeneous solution. The solution was then transferred into a syringe and electrospun under an applied voltage of 25 kV, with a tip-to-collector distance of 20 cm.
The process was carried out for 3 h to obtain PLA nanofibers with uniform morphology. PLA/BCG nanofibers were prepared under identical electrospinning conditions (Figure 1), incorporating bromocresol green (BCG) at 2 wt% relative to PLA. The dye was added to the PLA–DMF solution prior to chloroform addition to ensure complete dissolution and homogeneous distribution within the polymer matrix before electrospinning.

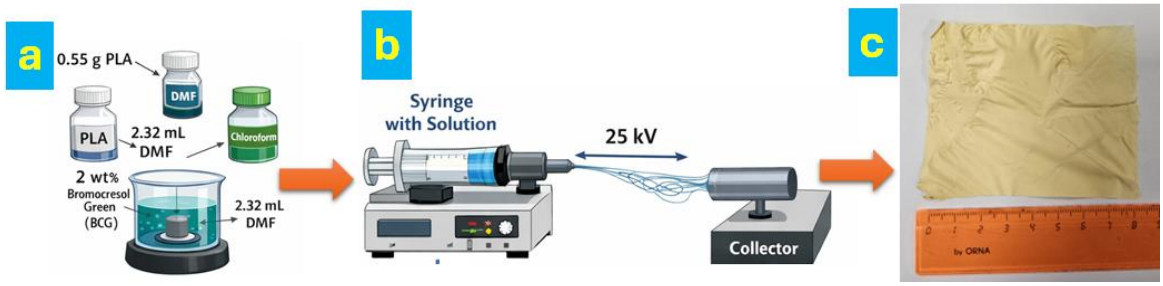

Figure 1: Colorimetric sensor preparation (a); electrostatic spinning colorimetric sensor (b); and PLA/BCG nanofibers (c)

2.3 Colorimetric detection

Hydrogen sulfide (H_2S) was generated at room temperature by reacting an aqueous sodium sulfide (Na_2S) solution with hydrochloric acid (HCl) in a 500 mL reaction vessel. An appropriate amount of Na_2S, corresponding to a target H_2S concentration of 100 ppb, was placed in a small vial. The vial was positioned inside a crystallization dish containing 70 mL of HCl. The reactor was initially purged with nitrogen for 30 min to ensure a homogeneous and oxygen-free internal atmosphere. The gas flow was then stopped, and the vial containing the Na_2S solution was released into the acidic solution, thereby initiating the reaction shown in Equation (1).

$$Na_2S\,(aq) + 2\,HCl\,(aq) \rightarrow H_2S\,(g) + 2\,NaCl\,(aq) \quad (1)$$

2.4 Characterization

The morphology of the samples at different stages of preparation was analyzed using scanning electron microscopy (SEM) combined with energy-dispersive X-ray spectroscopy (EDX). The analysis was performed using a TESCAN VEGA LMH microscope (230 V). FT-IR spectra were recorded using a Nicolet iS50 spectrometer. A reflection spectrophotometer (New Lab) was used to measure the color parameters.

3. Results and discussion

The SEM images shown in Figure 2 illustrate the morphology of electrospun PLA nanofibers in the absence (Figures 2a and 2b) and in the presence of bromocresol green (Figures 2c and 2d). A comparative analysis revealed no significant morphological differences between the two samples at the investigated dye concentration, indicating that the incorporation of bromocresol green did not adversely affect the electrospinning process.

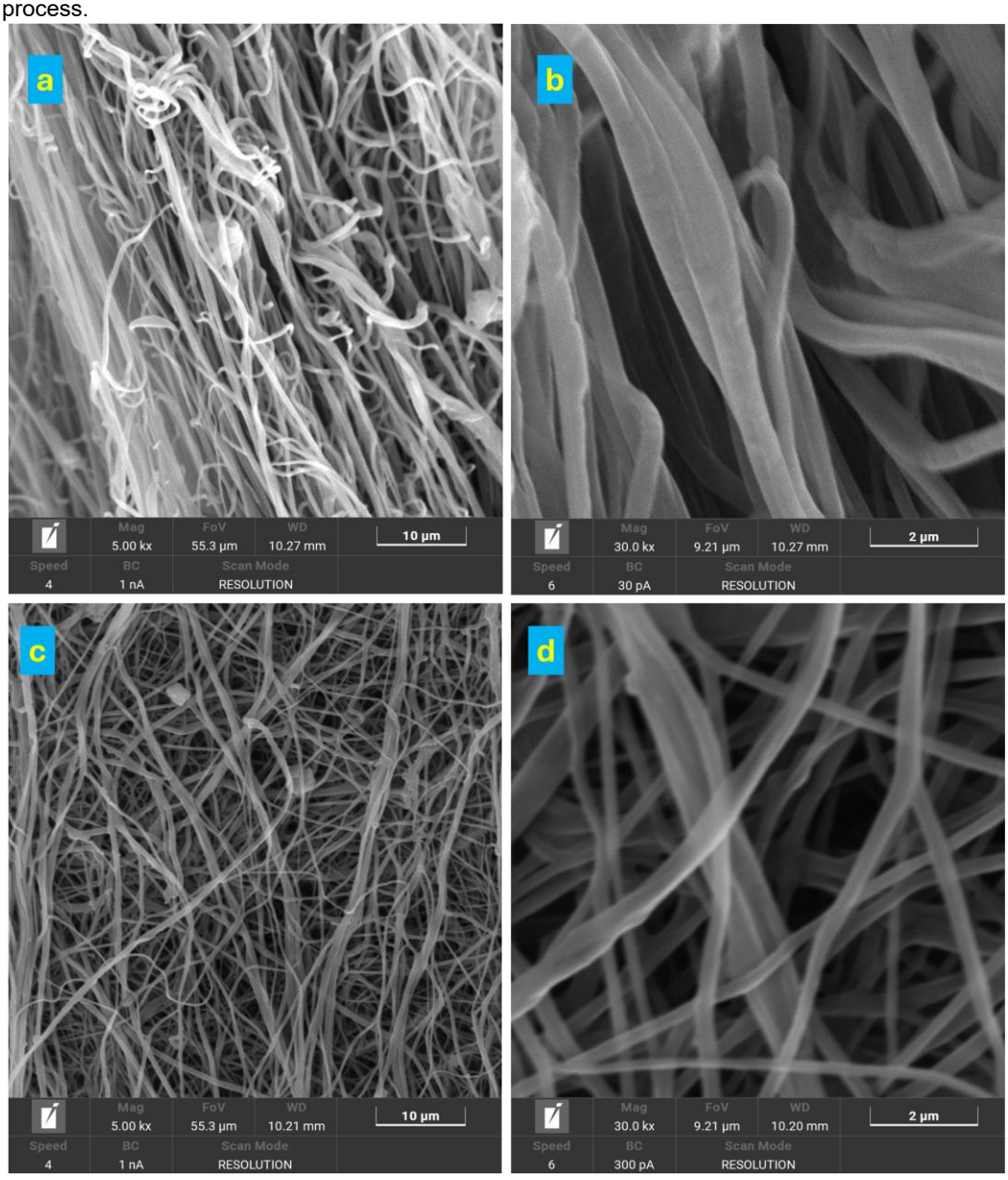

Figure 2: SEM micrographs of electrospun nanofibers: neat PLA (a,b) and PLA/bromocresol green (PLA/BCG) (c,d).

In both cases, the nanofibers appeared continuous, uniform, and free of visible defects. The fibers exhibited a smooth surface and a relatively homogeneous diameter distribution, with some variability typical of electrospun systems. The average fiber diameter was approximately 250 nm, suggesting that the addition of the dye did not significantly alter the rheological properties of the solution or the stability of the electrospinning jet. The observed morphology also indicates a good dispersion of bromocresol green within the polymer matrix.

The absence of visible defects and bead-like structures confirms that the selected electrospinning conditions enabled the formation of uniform nanofibrous membranes suitable for sensing applications. To investigate

potential interactions between the components, FT-IR analysis was performed on both PLA nanofibers and PLA/BCG nanofibers (Figure 3).

For neat PLA nanofibers, the FTIR spectrum exhibits the characteristic absorption bands of the polymer. In particular, the peak around 2946 cm^{-1} is attributed to the stretching vibrations of CH_3 groups (Vargas-Villagran, et al., 2014), while the band at approximately 1748 cm^{-1} (a typical feature of PLA) corresponds to the stretching vibration of the carbonyl (C=O) group. Additionally, the peak at around 1182 cm^{-1} is associated with the stretching vibrations of the C–O–C bonds along the polymer backbone (Min et al., 2021), confirming the typical chemical structure of PLA (Cirillo et al., 2024). In the case of PLA/BCG nanofibers, the FT-IR spectrum is overall similar to that of neat PLA, indicating that the incorporation of bromocresol green does not significantly alter the chemical structure of the polymer. Furthermore, slight variations in peak intensity or position may be ascribed to intermolecular interactions, such as hydrogen bonding, between PLA and bromocresol green.

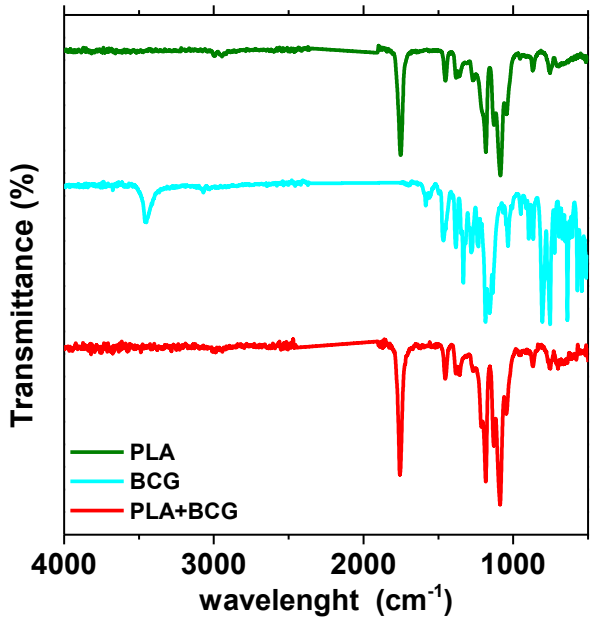

Figure 3: FT-IR spectra of PLA nanofiber, BCG, and PLA/BCG nanofiber.

3.1 Mechanical flexibility and wearable potential

Qualitative bending tests were performed by manually flexing the PLA nanofibrous membrane around a curved surface (e.g., the arm) for up to 50 cycles. No visible mechanical damage or structural failure was observed, indicating good flexibility and mechanical integrity. This behavior confirms that the nanofibrous membrane can conform to curved surfaces without compromising its structure. These results support the potential applicability of the sensor in wearable configurations, although further studies are required to fully assess its performance under real operating conditions.

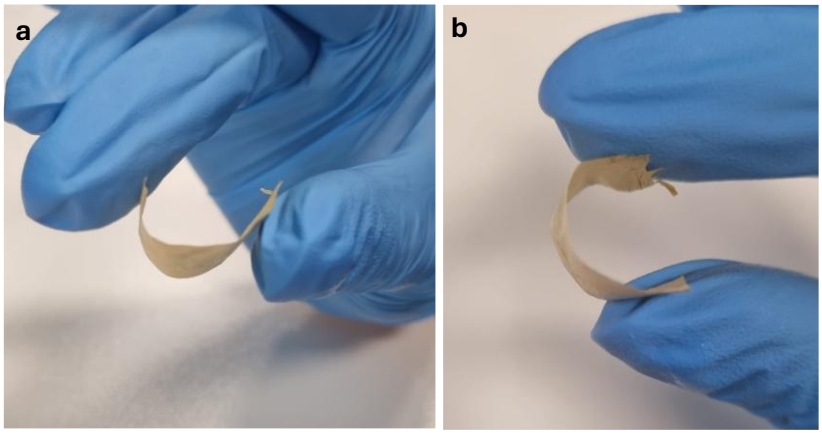

Figure 4: Photographs of the PLA/BCG nanofibrous membrane during manual bending.

3.2 Detection of S^{2-} (aq)

To validate the sensing concept, the performance of the PLA/BCG nanofiber-based sensor was first investigated in the liquid phase using aqueous sulfide (Na_2S) solutions and subsequently extended to gas-phase detection. This preliminary step allowed for a controlled evaluation of the sensor response under well-defined conditions. The PLA/BCG nanofibers exhibited a distinct, concentration-dependent colorimetric response to sulfide species, confirming their sensitivity toward sulfur-containing analytes. Figure 5 presents the response of the PLA/BCG nanofiber sensor upon exposure to a fixed volume (100 µL) of Na_2S solutions at different concentrations. The results are expressed in terms of "gas-phase equivalents," a parameter that represents the amount of Na_2S required to generate a corresponding concentration of H_2S in a reference gas volume of 500 mL. This approach enables a direct and meaningful correlation between liquid-phase testing and the sensor's expected behavior under gas-phase conditions.

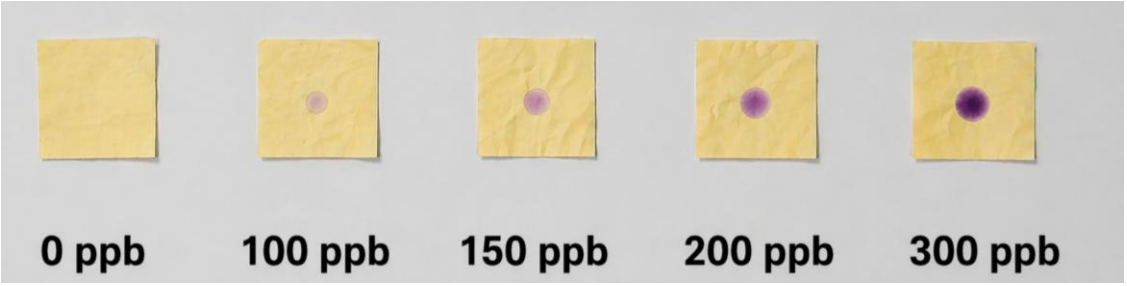

Figure 5: Colorimetric response of PLA/BCG nanofiber probes upon exposure to increasing "gas-phase equivalent" concentrations of aqueous Na_2S.

3.3 H_2S gas detection

To evaluate the gas-sensing performance of the PLA/BCG nanofiber sensor, a preliminary blank test was carried out in the absence of the analyte to exclude any non-specific response. Under these conditions, no visible color change was observed, confirming the stability of the sensing system. Hydrogen sulfide (H_2S) was generated in situ at room temperature through the reaction between an aqueous Na_2S solution and HCl within a closed reactor. A controlled amount of Na_2S was used to achieve the desired H_2S concentration.

Under the tested conditions, the sensor was visually able to detect H_2S at concentrations as low as 100 ppb.The detection limit was defined as the lowest H_2S concentration that produced a clearly distinguishable and reproducible color variation with respect to the blank sample under identical experimental conditions. In the present study, 100 ppb represented the minimum concentration at which a visible color change could be consistently observed by naked-eye inspection.

Moreover, a visible color change was observed within approximately 1.5 s of exposure, indicating a rapid response. The membrane retained its initial color under ambient laboratory conditions for at least five months in the absence of the analyte, suggesting good long-term stability. Upon exposure to the generated H_2S, the PLA/BCG nanofiber sensor exhibited a distinct color change, as shown in Figure 6. The observed colorimetric response is attributed to the acid–base interaction between hydrogen sulfide and bromocresol green embedded within the PLA matrix, leading to a change in the protonation state of the dye and a corresponding variation in its optical properties.

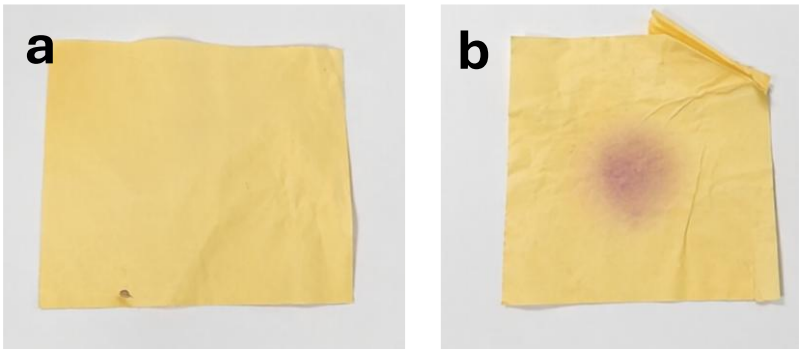

Figure 6: Colorimetric response of PLA/BCG nanofiber probes in the absence and presence of Na_2S.

4. Conclusions

In this study, a flexible colorimetric sensor based on electrospun PLA/BCG nanofibers was developed for hydrogen sulfide (H_2S) detection. The presence of bromocresol green within the polymer matrix enabled a clear and immediate color change upon exposure to sulfide species and H_2S, confirming the effectiveness of the sensing approach. SEM analysis showed that the addition of the dye did not significantly affect the morphology of the fibers, which remained uniform, smooth, and free of defects, with an average diameter of about 250 nm. FT-IR results confirmed the successful incorporation of BCG into the PLA matrix without significant changes in the chemical structure, suggesting only minor interactions between the components.

The sensing behavior was first evaluated in solution using Na_2S, showing a concentration-dependent response, and subsequently confirmed in gas-phase experiments. Under the adopted experimental conditions, the sensor was able to visually detect H_2S at concentrations as low as 100 ppb, exhibiting a rapid response within approximately 1.5 s. The membrane also demonstrated good long-term stability, retaining its initial color for at least five months under ambient laboratory conditions. These results indicate that PLA/BCG nanofibers represent a simple and cost-effective platform for H_2S detection. The flexibility of the material, combined with rapid response and long-term stability, makes the system suitable for wearable applications and rapid environmental monitoring.

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