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Resistance-based CO₂ Detection Using Eco-friendly Tetraethylenepentamine-functionalized Polyvinyl Alcohol Films

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The primary goal of this study is to develop an environmentally friendly carbon-adsorptive film using polyvinyl alcohol (PVA), a nontoxic and eco-friendly material, as the base for the polymer gas adsorption film. By employing tetraethylenepentamine (TEPA) as a functionalizing agent, the PVA polymer film is immersed in a TEPA solution to introduce functional groups capable of adsorbing carbon dioxide (CO₂) onto its surface. Fourier-transform infrared spectroscopy is used to analyze whether the TEPA successfully binds to the PVA film and to confirm the CO₂ adsorption capability of the polymer gas adsorption film. The polymer gas adsorption film is placed in a CO₂ chamber, and the changes in film resistance over different adsorption times are recorded. It is observed that for the first 30 min of adsorption, the relationship between adsorption time and resistance change is described by the equation y = -0.038x + 4.02, whereas after 30 min, the relationship follows y = -0.0023x + 2.52. The results show that CO₂ adsorption reduces the resistance of the polymer gas adsorption film, with the most significant rate of decrease occurring within the first 30 min.

1. Introduction

Since the onset of the Industrial Revolution in the 19th century, global carbon dioxide (CO₂) emissions have been on a steady rise, culminating in a sharp escalation in the late 20th century. This surge has made CO₂ the predominant greenhouse gas, accounting for approximately 65% of total emissions.^(1,2) In 2024 alone, global CO₂ emissions have reached an alarming 41 billion tons, highlighting the urgent need for innovative solutions to mitigate its environmental impact. The accumulation of CO₂ in the atmosphere is directly linked to climate change, contributing to global warming, rising sea levels, and extreme weather events, such as hurricanes, droughts, and floods. These effects underscore the pressing necessity for sustainable approaches to reduce atmospheric CO₂ concentrations.

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To address these challenges, nations worldwide have implemented various carbon reduction policies, including carbon taxes, emissions trading systems, the Paris Agreement, and net-zero emissions commitments.^(3,4) These policies have catalyzed the development and deployment of carbon capture, utilization, and storage (CCUS) technologies, which aim to sequester CO_2 in different forms. CCUS not only provides a pathway to reduce CO_2 levels in the atmosphere but also offers opportunities to repurpose CO_2 into valuable products, thereby promoting a circular carbon economy.^(5,6)

Simultaneously, the public awareness of CO_2 's detrimental effects on both the environment and the human health has grown, increasing the demand for reliable CO_2 monitoring devices. High concentrations of CO_2 can cause respiratory problems, cognitive impairment, and other health complications in humans. Consequently, CO_2 sensors have become essential in public spaces, such as offices, schools, hospitals, and industrial settings, to ensure air quality and monitor compliance with safety standards.⁽⁷⁾ According to recent market analyses, the global CO_2 sensor market was valued at \$270 million in 2023 and is projected to grow at a compound annual growth rate of 7.6%, reaching \$557.7 million by 2031.⁽⁸⁾

To meet the dual objectives of reducing atmospheric CO_2 and improving monitoring capabilities, in this study, we focused on the development of an environmentally friendly polymer CO_2 adsorption film. The shift toward this material is driven by its renewability, low environmental footprint, and ability to integrate seamlessly with emerging green technologies. This film is based on polyvinyl alcohol (PVA), a nontoxic, biodegradable, and sustainable polymer material that demonstrates outstanding performance in sensor device applications.^(9–14)

Tetraethylenepentamine (TEPA) is employed as a functionalizing agent to enhance the CO_2 adsorption properties of the PVA film.⁽³⁾ The principle behind this film lies in the chemical interaction between CO_2 and water, which leads to the hydrolysis of CO_2 into carbonate and hydrogen ions. This reaction modifies the film surface properties, inducing a measurable change in its electrical resistance, which can be used as a basis for CO_2 detection.⁽¹⁵⁾ The dispersion, mechanical enhancement, and precise control of optical properties in nanomaterial systems are pivotal for creating highly efficient sensing materials.^(16–18) These principles form the foundation for designing our PVA composite aimed at CO_2 adsorption detection.

The primary objective of this study is to develop an environmentally friendly carbonadsorptive film using PVA functionalized with TEPA. This film is designed to detect CO_2 through changes in its electrical resistance, offering a low-cost, eco-friendly alternative for CO_2 monitoring applications. Additionally, we provide a detailed analysis of the performance of the film in terms of resistance changes over different adsorption times, offering valuable insights into the kinetics of CO_2 adsorption. By advancing the development of sustainable CO_2 adsorption materials, we contribute to the growing field of green sensor technology, aligning with global efforts to combat climate change.

2. Materials and Methods

2.1 Materials

PVA (molecular weight 89000–98000, 99+% hydrolyzed) was purchased from Sigma-Aldrich (USA). TEPA (reagent grade, 98%) was procured from Alfa Aesar (USA). Ethanol (anhydrous, \geq 99.5%) and deionized (DI) water were used as solvents. All chemicals were used as received without further purification.

2.2 Sample preparation

The TEPA-functionalized PVA film was prepared in two main steps. First, a 10 wt% PVA solution was made by dissolving 1 g of PVA in 9 g of DI water while stirring continuously at 120 °C and 240 rpm for 1 h. The resulting solution was poured into a container, sealed with an airtight membrane, and stored in a freezer at 7 °C for 6 h. Then, the container was transferred to a freeze dryer and allowed to dry for 1 day to fabricate the polymer film.

Next, we prepared a 1 wt% solution of TEPA in ethanol by stirring at 60 °C and 120 rpm for 30 min. We immersed the polymer film into the prepared TEPA solution and subsequently placed it in an oven set at 60 °C for 30 min to produce the film.

Finally, we placed the polymer into a carbon dioxide chamber, added 1 ml of DI water to the chamber, and used a digital multimeter to record the changes in film resistance at various CO₂ adsorption durations.

2.3 Fourier-transform infrared spectroscopy (FTIR) analysis

FTIR analysis was conducted to confirm the successful functionalization of the PVA film with TEPA and to verify the CO₂ adsorption capability of the film. The samples, including the pristine PVA film, TEPA, PVA-TEPA film before CO₂ adsorption, and PVA-TEPA film after CO₂ adsorption, were prepared by cutting them into uniform sizes. The FTIR spectra were obtained using a PerkinElmer Spectrum Two FTIR spectrometer. The analysis was performed in the wavenumber range of $4000-500 \text{ cm}^{-1}$.

2.4 CO₂ adsorption test

The CO₂ adsorption properties of the films were evaluated using a custom-designed CO₂ chamber. The chamber allowed the precise control of CO₂ concentration and humidity level. The functionalized polymer film was placed inside the chamber, and 1 ml of deionized (DI) water was added to the system to facilitate the reaction between CO₂ and the film. Resistance changes in the polymer film were measured using a digital multimeter at regular intervals up to 60 min. The data were analyzed to determine the relationship between CO₂ adsorption duration and resistance changes, highlighting the most significant reductions during the initial 30 min.

2.5 Electrical test

The conductivity of the films was assessed using a simple light bulb circuit setup. Four configurations were tested: non-CO₂-adsorbed PVA film without DI water, CO₂-adsorbed PVA film without DI water, non-CO₂-adsorbed PVA film with DI water, and CO₂-adsorbed PVA film with DI water. In each configuration, the film was used as the resistor in the circuit. The brightness of the light bulb was observed as an indicator of the film resistance.

3. Results and Discussion

The surface of the polymer films showed distinct visual changes post-functionalization. As shown in Fig. 1, (a) the pristine PVA film appeared colorless and translucent, whereas (b) the TEPA-functionalized PVA film exhibited a yellowish hue.

FTIR analysis was performed to confirm whether TEPA successfully attached to the surface of the polymer film and to verify if the functionalized polymer film could adsorb carbon dioxide. As shown in Fig. 2(a), by comparing the FTIR spectra of the PVA film and TEPA, the



Fig. 1. (Color online) Photographs of (a) PVA and (b) functionalized PVA film samples.



Fig. 2. (Color online) FTIR curves of (a) PVA and TEPA and (b) PVA-TEPA film.

characteristic absorption peaks of each material can be observed. In Fig. 2(b), the FTIR spectrum of PVA-TEPA shows the characteristic peaks of both materials and also reveals a new absorption peak between 1500 and 1550 cm⁻¹. This peak corresponds to the N–O bond, indicating that the amine group of TEPA has interacted with the hydroxyl groups on the PVA surface, confirming that TEPA has successfully attached to the PVA film.⁽¹⁹⁾

As shown in Fig. 3, the FTIR spectrum of the PVA-TEPA film after CO₂ adsorption shows significantly higher peak intensities at 3000–2840 and 1126 cm⁻¹ than that of the nonadsorbed sample. These absorption peaks correspond to C–H bonds, indicating the presence of hydrogen bonding interactions between CO₂ and the PVA-TEPA film. Additionally, the absorption peak at 1740–1720 cm⁻¹, corresponding to the C=O bond, shows increased intensity in the adsorbed sample, suggesting the presence of CO₂ on the surface and further confirming the successful adsorption of CO₂. As shown in Fig. 4, CO₂ adsorption causes a measurable decrease in the electrical resistance of the TEPA-functionalized PVA film, with the most significant reduction



Fig. 3. (Color online) FTIR curves of PVA-TEPA before and after CO₂ adsorption.



Fig. 4. (Color online) Stimulus-response diagram of CO2 adsorption on PVA films.

occurring within the first 30 min. This behavior is attributed to the hydrolysis of adsorbed CO_2 in the presence of water, which generates carbonate (CO_3^{2-}) and hydrogen (H⁺) ions. These ions enhance the ionic conductivity of the film, resulting in a pronounced drop in resistance. As CO_2 adsorption continues, the number of available functional groups on the polymer surface becomes limited, leading to a gradual saturation effect. Consequently, the rate of resistance decrease decreases after 30 min.

The electrical test of the polymer films was further validated using a simple light bulb circuit, as depicted in Fig. 5. For the (a) non-CO₂-adsorbed films without DI water and (b) CO₂-adsorbed films without DI water, the light bulb remained off, indicating that the film resistance was too high to allow sufficient current to pass through the circuit.

However, a notable change was observed upon the addition of DI water to the films. Both (c) nonadsorbed and (d) CO₂-adsorbed films became conductive, allowing current to flow and lighting the bulb. The introduction of DI water facilitated ion mobility within the films, likely due to the dissociation of residual groups or the hydration of surface functionalities, reducing resistance.^(20,21) Among the tested configurations, the CO₂-adsorbed film with DI water exhibited the brightest glow, indicating the lowest resistance under this condition.

The significant reduction in resistance observed during the electrical conductivity tests is directly linked to the chemical interactions between CO_2 and water on the surface of the TEPA-functionalized PVA film. FTIR analysis revealed that CO_2 adsorption leads to the formation of carbonate (CO_3^{2-}) and hydrogen (H⁺) ions, as evidenced by the increased peak intensities at 3000–2840 and 1126 cm⁻¹, along with the new peak at 1740–1720 cm⁻¹ corresponding to carbonate species. These chemical modifications, caused by the reaction of adsorbed CO_2 with water through hydrolysis, generate ionic species that enhance the ionic conductivity of the film.⁽²²⁾

The visual results from the light bulb circuit also offer an intuitive demonstration of the film properties, making it a powerful tool for conceptual validation and educational purposes. In future investigations, we will explore the quantitative relationship among ion concentration, resistance, and light intensity, providing deeper insights into the electrical behavior of the film and further optimizing its performance for practical applications.



Fig. 5. (Color online) Circuit diagram of simple light bulb circuit with (a) non-CO₂-adsorbed PVA film without DI water, (b) CO₂-adsorbed PVA film without DI water, (c) non-CO₂-adsorbed PVA film with DI water, and (d) CO₂-adsorbed PVA film with DI water as resistor.

4. Conclusion

In this study, we used PVA as a substrate to fabricate a polymer gas adsorption film, which not only has carbon sequestration capabilities but also exhibits environmentally friendly characteristics. The experimental results showed that the adsorption process leads to changes in the physical properties of the samples. The CO₂ adsorbed on the film reacts with water to form carbonate and hydrogen ions, resulting in a decrease in the resistance of the polymer gas adsorption film. However, owing to the limitation of the total adsorption capacity, the most significant changes occur within the first 30 min of adsorption. This experiment demonstrated the potential for developing gas adsorption technologies and the feasibility of product recovery and reuse after adsorption.

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