DYNAMICS OF METHYLENE BLUE DIFFUSION THROUGH A LAYERED MEMBRANE FROM GELATIN AND POLYPROPYLENE NONWOVEN TEXTILE

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Abstract

In this contribution, we examine the diffusion dynamics of methylene blue dye through a layered membrane, constructed with a specific count of nonwoven polypropylene textiles and intervening layers of gelatin hydrogel. The hydrogel ostensibly functions as the diffusion medium, while the nonwoven textile provides structural reinforcement. Due to the large pore structure inherent to polypropylene, the membrane displays minimal dye adsorption. Our research discovered the unusual nature of the dye's diffusion process, revealing a distinct, characteristic concentration profile of methylene blue within the membrane, which is notably inhomogeneous. Using UV-VIS spectroscopy in conjunction with image analysis techniques, we provide an analysis of the temporal progression of dye permeation through the gelatin layers. This examination has led to the identification of a fascinating mechanism governing methylene blue diffusion. These insights substantially augment our understanding of dye diffusion processes within gel matrices and stand to influence the advancement of gel-based application design, including but not limited to sensor technologies and other devices necessitating controlled substance release or absorption mechanisms. Furthermore, the significance of our findings reverberates beyond the immediate study, bearing broad implications for the comprehension of diffusion dynamics within gel substrates on a more comprehensive scale.

Keywords: Diffusion, layered, membrane, applications, modeling

1. INTRODUCTION

Numerous methods exist for drug delivery, but achieving consistent and extended release remains a challenge due to the "burst effect" [1,2]. This issue necessitates frequent dosing and can lead to complications. Developing materials to address this problem is crucial. Current research focuses on "smart hydrogels" that respond to stimuli for controlled drug release but still grapples with the burst effect [3,4]. Researchers are exploring various avenues to mitigate this challenge, including altering preparation methods, modifying carrier matrix composition, and adjusting layer configurations. Hydrogels are vital in targeted drug delivery, resembling the extracellular matrix. Effective artificial matrices must mimic the ECM's characteristics [5] and support cell growth while facilitating nutrient transfer and metabolic waste removal.

One of the strategies involves creating a layered material [6]. This approach offers numerous possibilities, such as the use of a gradient of concentration of active compound. In this article, we present the most basic version, where the design of the layered material comprises alternating layers of polypropylene nonwoven fabric and a gelatin layer. We investigate the diffusion of substances from a reservoir solution of methylene blue into a pure solvent through this membrane. Even in this uncomplicated setup, the diffusion mechanism proves to be intriguing, and we present it in the contribution.

Gelatine serves as a versatile drug carrier, particularly in hydrogels, with its suitability depending on drug properties and therapeutic goals [7]. Monitoring both carrier and drug properties is essential for effective therapeutic outcomes, maintaining the drug's concentration within a therapeutic range while avoiding toxicity.

Layered materials are promising for controlled drug release, primarily responding to external stimuli [8, 9], such as pH changes or enzymatic triggers. Gelatine remains a versatile drug carrier, offering adaptability in various forms, from micro and nanoparticles to hydrogels. However, its appropriateness depends on specific drug attributes and therapeutic objectives, allowing tailored selection of materials to achieve desired drug release profiles. Layered materials are a growing area of research for controlled drug release, offering precise control over material structure. They primarily function based on external stimuli, such as changes in environmental pH, ionic strength, or responses to light and temperature fluctuations.

With combination of gelatin and nonwoven fabric one can design interesting materials. It is a step where the nanotextile will propose even more interesting possibility of settings.

2. MATERIALS AND METHODS

The effective diffusion coefficient was determined by diffusion cell and by analyzing the solution by UV-VIS spectra of methylene blue, as it traversed a specially prepared membrane into the receiving cell. A gelatine concentration of 3% (w/w) was chosen due to its layering property, where the polymer remained sufficiently robust, and there was no separation between the layers. We created membranes using non-woven fabric (polypropylene) impregnated with a 3% (w/w) gelatine polymer solution, with varying layer counts: 2, 4, 8, 16, and 32.

To construct these layered materials, 8×8 cm sections of non-woven fabric were combined. The resulting membranes (with 8, 16, and 32 layers) were left to air dry for 24 hours before being cut into shapes matching diffusion cells (PermeGear, Inc.) with a 5 cm diameter.

The prepared materials were inserted between diffusion cells. The receiving cells were filled with 60 cm^3 of distilled water, and the source cell contained 60 ml of methylene blue with a concentration of 0.04 $g \cdot dm^{-3}$. These assembled diffusion cells were placed on a magnetic stirrer operating at 250 rpm at room temperature. Samples were collected at intervals to monitor the rate of dye permeation.

Initially, it was necessary assess the absorbance of the methylene blue calibration series. This calibration set was meticulously prepared, comprising concentrations ranging from 0.001 to 0.04 $g \cdot dm^{-3}$. Subsequently, the UV-VIS spectrometer (specifically, the Hitachi U-3900H Spectrophotometer) was employed to scrutinize this calibration series over a wavelength range spanning 900 to 300 nm. This analysis yielded absorption spectra, which showcased the methylene blue's absorption peak at 665 nm.

Figure 1 Measurement of the diffusion coefficient on side-bi-side cells with a membrane consisting of 8 layers of non-woven fabric connected by 3% (w/w) gelatine hydrogel after 8 hours

The material, was positioned in a manner like the previously mentioned materials, positioned between the diffusion cells. In this experimental setup, the source cell contained a solution of methylene blue at a concentration of 0.04 $g \cdot dm^{-3}$, while the receiving cell was filled with distilled water (**Figure 1**). It took

approximately 3 hours for the methylene blue dye to permeate this membrane. At this juncture, the first sample collection, comprising 3 cm³, was executed and subsequently analyzed using a UV-VIS spectrometer. The subsequent sampling event occurred 8 hours after the commencement of the measurement, with the final sample taken after 24 hours had elapsed.

3. RESULTS AND DISCUSSION

A 2-layer, 0.0125 mm thick membrane was placed between diffusion cells. Methylene blue penetration was observed within a minute, and samples were analyzed with a UV-VIS spectrometer. Subsequent samples were collected at 1, 2, and 3-hour marks.

The 4-layer, 0.025 mm membrane allowed dye penetration after 2 hours, and similar analysis intervals were maintained.

The 8-layer, 0.05 mm thick membrane displayed methylene blue penetration after 3 hours, with samples analyzed after 8 and 24 hours. The material retained dye during drying.

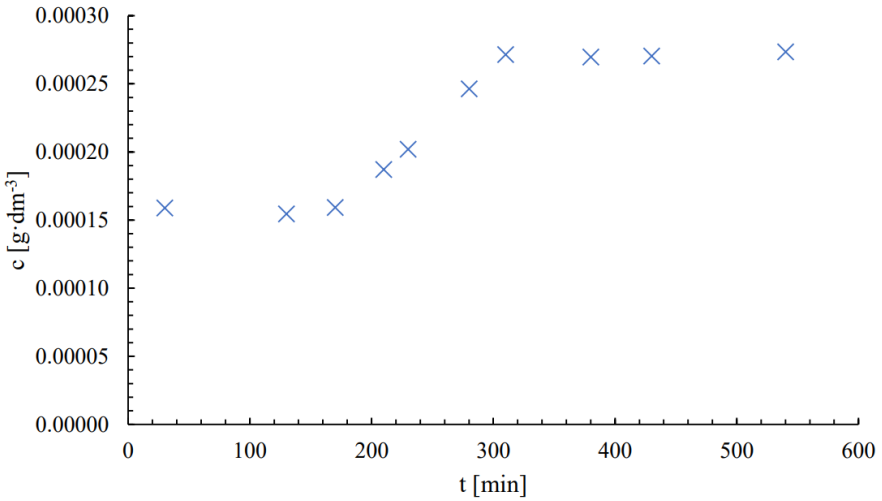

Figure 2 Dependence of the concentration of methylene blue released from the 8-layered material on time

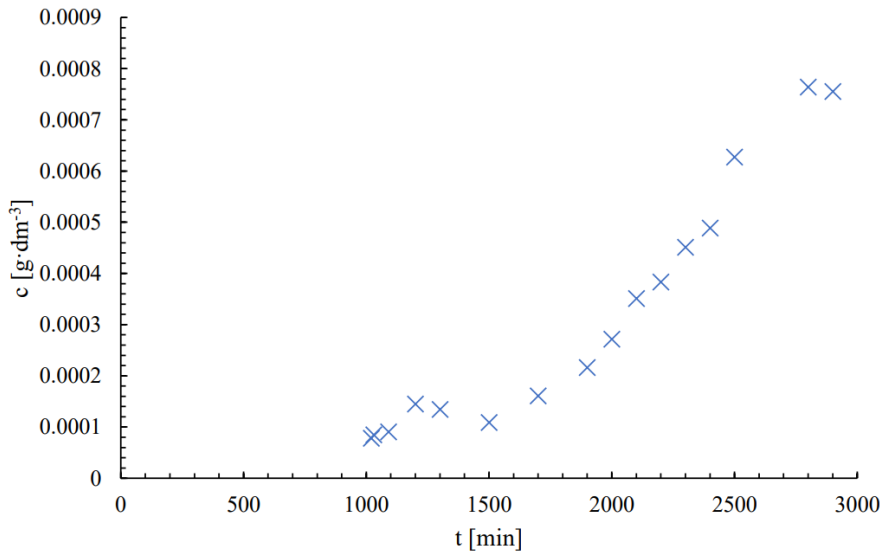

Figure 3 Dependence of the concentration of methylene blue released from the 32-layered material on time

The 16-layer membrane, observed for 36 hours, did not reach equilibrium but allowed for effective diffusion coefficient determination. After drying, methylene blue formed pathways through the hydrogel, retaining a concentration of 0.012 g·dm^{-3}, making it ideal for controlled dye release applications.

A 32-layer material showed interest. Initial dye penetration into the receiving cell occurred after 8 hours, with exceptionally low dye concentration. First samples were collected at this point, and additional 3 ml samples from both cells were collected 24 hours later. Remarkably, this material started releasing dye around 1600 minutes into the experiment, maintaining a linear release rate until about 2500 minutes, beyond which the curve started to bend, indicating most of the dye had been expelled.

The effective diffusion coefficient was subsequently determined by analyzing the linear segments of the methylene blue concentration-time relationships (**Figure 4a**) [10]. By measuring the concentration of solutions in both cells at different time intervals, it can then provide a relationship for calculating the diffusion coefficient:

$$\varepsilon D_{eff} = \left(\frac{dn}{dt}\right) \cdot \left(\frac{l}{\Delta c_{10}}\right) \quad (1)$$

where D_{eff} is the effective diffusion coefficient of the solute in the solvent, ε is the partition coefficient, (dn/dt) is the concentration gradient, l is the thickness of the membrane and Δc_{10} is difference of concentration in source cell and in receiving cell.

In the case of materials featuring a gradient, we once again determined the effective diffusion coefficient for each material, as shown in **Figure 4b**. It's important to acknowledge that the release values in these measurements did not start from zero. This variation may be attributed to potential inconsistencies in the vessel insulation, potentially allowing external light to influence the measurements, especially given daily fluctuations. This explains the absence of bars for the 2-layer and 4-layer materials in **Figure 4b**.

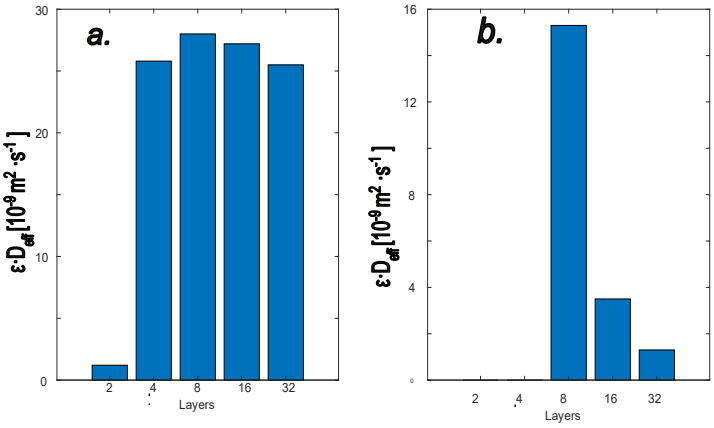

Figure 4 Effective diffusion coefficients for various layered materials: a. Derived from the first linear segment of the material. b. Derived from the second linear region (the second linear region was not observed in the materials with 2 and 4 layers, as shown in Figure b)

As we can observe, the diffusion in the initial interval is quite consistent across all samples, with the exception of the 2-layer materials, where the diffusion was notably rapid, making precise measurement challenging. However, in the second time interval, the diffusion patterns diverged significantly. The first samples with 2 and 4 layers did not exhibit a second linear region, indicating that the entire diffusion process occurred predominantly in the initial region. The highest diffusion rate in the second linear region was observed in the 8-layer materials, with a subsequent decrease in diffusion observed in the 32-layered materials.

4. CONCLUSION

Selected layered materials were made from gelatin and nonwoven fabric as our sample material to investigate the diffusion of methylene blue through these membranes. Materials were designed with different layer counts, ranging from two to thirty-two layers, aiming to determine the effective diffusion coefficient. Methylene blue was consistently observed in all layered materials, potentially due to interactions with gelatin, which has implications for drug delivery, necessitating dose adjustments. We noted a gradual reduction in the diffusion

rate as the number of layers increased, with materials containing more than four layers exhibiting relatively constant diffusion coefficients. This observation is likely because the dye was already present within the materials, resulting in the earlier capture of initial dye concentrations. Importantly, the release curves did not exhibit the typical bending associated with a burst effect, indicating progress towards more efficient drug delivery materials. The diffusion process likely involves two mechanisms. The first mechanism corresponds to standard diffusion through hydrogels. The second mechanism is more complex and is not observed when the sample is thin, consisting of 2-4 layers. In 8-layer samples, the diffusion mechanism is relatively fast, while in 16 and 32-layer samples, it becomes relatively slow. The mechanism probably reflects the diffusion of hydrogels inside the membrane. When the methylene blue is relatively strongly bounded to the hydrogels and it moves together with hydrogel.

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