

Fenugreek-Psyllium Biopolymer Hydrogel: Prototyping A Novel pH-Responsive, Antioxidant Wound Dressing for Enhanced Healing

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ABSTRACT

Chronic wounds represent a major healthcare challenge worldwide, emphasizing the need for sustainable and multifunctional wound dressings. Hydrogel-based materials maintain moisture and promote tissue regeneration, yet conventional Psyllium husk (*Plantago ovata*) hydrogels lack antimicrobial, antioxidant, and diagnostic properties. In this study, a prototype of a Fenugreek Psyllium biopolymer hydrogel was engineered by integrating fenugreek seed gel (*Trigonella foenum-graecum*) for antimicrobial and anti-inflammatory activity, Indian black carrot extract (*Daucus carota* subsp. *sativus*) for anthocyanin-based pH responsiveness, and Aloe vera gel (*Aloe barbadensis* miller) to enhance hydration and antioxidative capacity. The chromatic response of the hydrogel was evaluated across pH 2-14, fluid retention was measured at 1, 2.5, and 4 hours, and antioxidant activity was quantified using the DCPIP assay. Compared to the Psyllium control, the enhanced hydrogel exhibited distinct pH-dependent color transitions, approximately 33% greater radical-scavenging efficiency, and 60-70% higher fluid absorption. These findings highlight its dual diagnostic and therapeutic functionality, offering a low-cost, biocompatible, and eco-friendly approach for next-generation wound care applications.

KEYWORDS

Antioxidants, Biopolymers, Hydrogel, pH-responsiveness, Sustainable biomaterials, Wound dressing

INTRODUCTION

Hydrogel-based wound dressings have been shown by studies to create a moist microenvironment, facilitate exudate absorption, and facilitate tissue regeneration¹⁰. However, conventional hydrogels, such as those made of Psyllium husk, despite their structural stability, lack antimicrobial activity, pH-responsiveness, and antioxidant, bioactive healing properties⁸, all of which are key to opening applications in advanced wound healing. Synthetic enhancements such as silver nanoparticles may augment wound-healing capability but introduce concerns regarding cytotoxicity, environmental implications, and biocompatibility⁴.

This study seeks to engineer a smart, multifunctional, and sustainable Psyllium hydrogel wound dressing by integrating naturally derived bioactive constituents. Fenugreek seed gel confers antimicrobial and anti-inflammatory properties¹ while reinforcing structural cohesion. Indian black carrot extract, abundant in anthocyanins, enables pH-sensitive chromatic monitoring⁵ for real-time infection detection. Aloe vera gel enhances hydration, promotes fibroblast proliferation, and mitigates oxidative stress⁶, as well as acting as a binder and natural plasticizer for the biopolymer matrix.

Given that wound pH varies between 6.5 and 8.5 in acute wounds and 7.2 and 8.9 in chronic wounds³, a pH-responsive hydrogel provides a preliminary, non-invasive diagnostic mechanism, reducing dependency on frequent and sometimes costly clinical assessments. Furthermore, Psyllium-based hydrogels exhibit inherent biodegradability, non-toxicity, and environmental sustainability, aligning with modern advancements in green, eco-friendly wound care^{7,8}.

By assessing antioxidant potential, pH-responsiveness, and fluid retention, this study aims to formulate a bioengineered hydrogel that effectively integrates therapeutic efficacy with diagnostic accuracy, thereby contributing to the development of next-generation bioactive wound dressings.

METHODS

1. Preparation of Control and Enhanced Psyllium Hydrogels

A Psyllium husk hydrogel was prepared in distilled water at 65 °C. For the enhanced formulation, fenugreek seed mucilage was blended and incorporated for antimicrobial and structural properties. Aloe vera gel was added for hydration and antioxidant activity, and anthocyanin-rich black carrot extract was introduced at 45 °C to allow for pH responsiveness. The hydrogels were set at 30-40 °C in the dark to preserve anthocyanins.

2. pH-Responsive Colorimetric Analysis

Samples were immersed in buffer solutions (pH 2, 4, 8, 14) for 45 min, and chromatic responses were recorded photographically to assess pH sensitivity.

3. Antioxidant Activity Assessment (DCPIP Assay)

Antioxidant potential was quantified using the DCPIP assay, with absorbance measured spectrophotometrically at 600 nm. A greater reduction in absorbance indicated higher radical scavenging activity due to higher antioxidant activity.

4. Fluid Retention Capacity

Samples were incubated in Phosphate Buffered Saline (pH 7.4, 37 °C) for 1, 2.5, and 4 hours. Fluid retention, representing potential exudate absorption capacity, (%) was calculated as:

$$\text{Fluid retention (\%)} = \frac{\text{Final weight} - \text{Initial weight}}{\text{Initial weight}} \times 100$$

RESULTS AND DISCUSSION

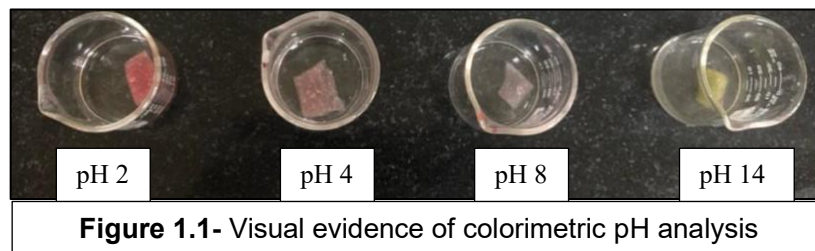


Figure 1.1- Visual evidence of colorimetric pH analysis

The enhanced hydrogel exhibited distinct chromatic transitions across the tested pH range (2–14), unlike the Psyllium control, which showed negligible change. At pH 2, the hydrogel appeared red, shifted to yellowish orange at pH 4, bluish at pH 8, and green at pH 14. This responsiveness highlights the hydrogel's potential for real-time wound monitoring, aiding in early detection of infection and healing progression (**Figure 1.1**). Antioxidant performance, although not illustrated graphically, was quantified via the DCPIP (Dichlorophenolindophenol) assay. The control solution showed the highest absorbance (1.936), the Psyllium-only hydrogel slightly reduced this (1.86), while the enhanced hydrogel consistently demonstrated lower absorbance values across n=3 trials (1.29, 1.31, 1.28). A Tukey's post-hoc test confirmed this reduction was statistically significant compared to the Psyllium-only control ($p < 0.001$). This corresponds to ~33.2% greater radical scavenging efficiency, illustrating the synergistic contributions of fenugreek flavonoids, Aloe vera polyphenols, and black carrot anthocyanins to oxidative stress mitigation².

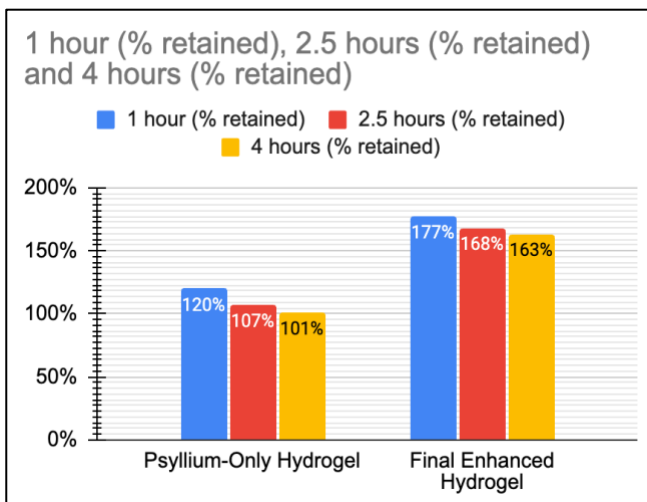


Figure 1.2- Fluid retention comparison



Figure 1.3- A piece of the hydrogel dressing

Fluid retention testing further validated the improvements (**Figure 1.2**). At 1 hour, the enhanced hydrogel absorbed 177% of its initial weight compared to 120% in the control; at 2.5 hours, 168% vs. 107%; and at 4 hours, 163% vs. 101%. These data demonstrate prolonged hydration and exudate absorption, which are critical for tissue regeneration in wound environments.

Overall, the results confirm that the Fenugreek-Psyllium hydrogel integrates diagnostic and therapeutic functions absent in the Psyllium base, supporting its potential as a sustainable, multifunctional wound dressing.

CONCLUSIONS

The enhanced Fenugreek-Psyllium hydrogel outperformed the Psyllium control, demonstrating clear pH-dependent chromatic shifts, ~30% greater radical scavenging, and 60-70% higher fluid absorption. These combined therapeutic and diagnostic properties highlight its potential as a smart wound dressing capable of non-invasive infection monitoring while maintaining sustained hydration for tissue repair. By being derived entirely from low-cost, natural materials, this hydrogel represents a sustainable, biocompatible alternative to synthetic dressings, with special promise for deployment in low-and middle-income country (LMIC) healthcare settings where affordable advanced wound care is critically needed⁷.

Disclaimer: This work is intended for academic and research purposes only and does not constitute medical advice.

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