GLUXSYSTEM: REAL-TIME MONITORING OF DIABETIC WOUNDS USING AN APP-IOT INTEGRATED HYDROGEL PATCH

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Abstract

Introduction: Diabetes mellitus is a metabolic disorder associated with severe complications, including diabetic foot ulcers (DFU). The World Health Organization estimates that more than 830 million people worldwide are affected. DFU remains a leading cause of infection, amputation, and mortality, largely due to delayed detection of changes in the wound microenvironment. **Objective:** This study presents a theoretical design and conceptual framework for GLUXSYSTEM, an intelligent hydrogel-based patch integrating pH and glucose sensing with an application–IoT platform for non-invasive monitoring of diabetic wounds. **Methods:** The proposed sensing mechanisms are derived from established biochemical principles. pH sensing is conceptualized using a chitosan hydrogel containing glycerol and Bromothymol Blue (BTB), in which colorimetric changes result from pH-dependent protonation of the indicator. Glucose sensing is modeled using a PEGDA–APBA hydrogel embedded in a photonic crystal, in which glucose binding induces hydrogel swelling and structural color shifts. The system architecture envisions optical signal capture via a smartphone application for cloud-based data interpretation. **Results:** As a design-based study, the system is projected to produce distinguishable colorimetric responses corresponding to wound conditions. Based on the underlying chemical models, pH changes from acidic to alkaline would generate yellow-to-blue transitions, while increasing glucose concentration would produce structural color shifts from blue to purple and pink. These theoretical responses are consistent with reported associations between elevated pH/glucose levels and DFU severity. **Conclusion:** GLUXSYSTEM offers a conceptual, non-invasive approach to wound monitoring. While this study focuses on the design and integration framework, it provides a necessary foundation for future experimental validation and the development of accessible digital solutions in diabetic wound care.

Keywords: Colorimetric pH, glucose sensors, Diabetic Foot Ulcer, hydrogel patch, smart biomedical sensor system.

Introduction

Diabetes mellitus remains a major global health burden, affecting more than 830 million people worldwide. Beyond metabolic and cardiovascular complications, diabetes frequently leads to skin and soft tissue disorders, particularly diabetic foot ulcers (DFU). DFU is a severe complication associated with infection, delayed healing, high amputation rates, and increased morbidity and mortality. The wound microenvironment plays a critical role in healing; elevated glucose levels, alkaline pH, excessive exudate, and bacterial colonization can significantly impair tissue regeneration. However, wound assessment in current clinical practice still relies largely on visual inspection and subjective evaluation, which may delay the detection of infection or poor healing. This highlights the need for objective, real-time, and user-friendly wound monitoring solutions.

Recent advances in smart wound dressings have identified hydrogels as promising materials due to their tissue-like structure, moisture retention capacity, exudate absorption, and compatibility with sensing elements. Although hydrogel-based sensors for monitoring wound parameters such as pH and glucose have been widely studied, many systems remain limited to laboratory settings and face challenges related to stability, accuracy, and digital integration. pH and glucose are critical biomarkers in diabetic wounds, as chronic ulcers typically demonstrate alkaline pH and elevated glucose levels, both of which promote bacterial growth and impair healing. Simultaneous monitoring of these parameters enables a more comprehensive evaluation of wound status and early identification of infection or delayed healing.

To address these challenges, this study proposes a smart hydrogel-based patch that integrates pH and glucose sensing and is supported by a smartphone application. The patch is designed to maintain a moist wound environment, absorb exudate, and incorporate colorimetric sensors whose optical changes are captured by a smartphone camera. The processed data can then be transmitted through an Internet of Things (IoT)-enabled platform to healthcare providers, enabling non-invasive, accessible, and continuous wound monitoring. This integrated approach aims to facilitate timely clinical intervention, reduce severe complications, and ultimately mitigate the medical and socioeconomic burden of DFU.

Materials and Methods

Conceptual Methodology: pH Sensing Module

The pH sensing module is conceptualized as a non-invasive colorimetric patch integrating a pH-responsive chitosan hydrogel matrix with Bromothymol Blue (BTB) as the optical indicator. This design framework leverages chitosan's inherent biocompatibility and antibacterial properties to support theoretical interactions with wound environments while maintaining structural integrity for patch-based applications. The module is presented as a material and sensing concept rather than an experimentally validated device, focusing primarily on the theoretical signal transduction mechanism and its relevance to wound monitoring.

The proposed sensing principle is based on reversible protonation and deprotonation of functional groups within the modeled chitosan hydrogel in response to environmental pH changes. Sodium hydroxide (NaOH) is incorporated to facilitate ionic interactions within the polymer network and condition the matrix for pH-responsive behavior. BTB embedded in the hydrogel is expected to undergo molecular-state transitions in response to changes in hydronium ion concentration, resulting in visible color changes. These transitions are described as shifting from yellow under acidic conditions to blue under alkaline conditions, forming the theoretical basis for qualitative colorimetric detection.

To support mechanical compliance and effective interaction with wound fluids, a hybrid fabrication strategy combining ionic gelation and cryogelation is proposed. Glycerol is included as a plasticizer to reduce brittleness and improve flexibility, enabling the envisioned patch to better conform to irregular skin surfaces. Cryogelation is intended to generate an interconnected porous structure that promotes fluid uptake and facilitates uniform color development. BTB is envisioned to be incorporated through absorption into the porous matrix and subsequently stabilized to minimize dye migration during theoretical exposure to wound exudates.

The operating range of the pH sensing module is designed to span physiologically relevant acidic to alkaline conditions associated with wound healing and infection states. Under this model, acidic environments are represented by a yellow color response, near-neutral conditions by an intermediate green tone, and alkaline environments by a blue response. For future digital health integration, these visually distinguishable color states are envisioned to be converted to RGB data via image acquisition, providing a conceptual foundation for pH interpretation models in subsequent system development stages.

Conceptual Methodology: Glucose Sensor Module

The glucose-sensing module within GLUXSYSTEM is presented as a conceptual, non-enzymatic optical sensor design that integrates a photonic crystal structure with a glucose-responsive poly (ethylene glycol) diacrylate (PEGDA) hydrogel functionalized with 4-aminophenylboronic acid (APBA). This architectural design is based on established photonic crystal–hydrogel theory, in which the interaction with glucose is modeled to induce hydrogel swelling and generate a visible structural color change. The sensing module is envisioned as a material framework in which glucose recognition relies on the reversible chemical interaction between APBA and glucose molecules; this interaction is expected to alter the hydrogel network and promote volumetric swelling. Within this conceptual system, integrating a photonic crystal lattice enables mechanical swelling to modulate the structure's optical behavior, resulting in a color shift that reflects relative changes in glucose levels without the metabolic limitations of traditional enzymes.

The photonic component is proposed as an ordered porous framework, such as an inverse opal configuration, designed to support the formation of structural color. Colloidal templating is proposed as the theoretical pathway for constructing the photonic scaffold, followed by the incorporation of the PEGDA–APBA hydrogel to enable responsive optical modulation. This glucose-sensing framework is intended to operate across a physiological concentration range relevant to diabetic wound monitoring, where lower glucose levels are theoretically associated with cooler color tones (e.g., blue) and higher levels are projected to produce warmer color shifts (e.g., pink). These relative color transitions are envisioned as the primary data input for the GLUXSYSTEM application, providing a theoretical foundation for the IoT and cloud-based visualization pipeline.

Structural Integration Concept: Substrate and Patch Assembly

The assembly of the flexible, dual-functional sensor patch is proposed as a conceptual integration of two independently modeled hydrogel matrices: a chitosan-gelatin framework for pH detection and a polyacrylamide (PAAm)-APBA structure for glucose monitoring. The design architecture begins with the selection of an inert, flexible, and biocompatible substrate, such as a polydimethylsiloxane (PDMS) or polyurethane polymer film, which serves as the structural foundation. In this envisioned configuration, the pH and glucose sensor matrices are arranged side-by-side. To ensure mechanical stability, the design uses medical-grade adhesives, such as silicone adhesive tape, to attach the sensing elements to the base substrate.

This spatial configuration is strategically designed to prevent signal interference between the two sensing modalities, theoretically enabling isolated and simultaneous visual monitoring of glucose and pH on a single integrated platform. This precise assembly framework is intended to ensure the independent functionality of each hydrogel while maintaining the overall mechanical integrity of the device. By organizing the components in this manner, the system architecture provides a foundation for non-invasive monitoring, enabling the capture and interpretation of two distinct optical signals without cross-contamination of chemical responses.

Conceptual IoT Architecture and Mobile Application Design Framework

The proposed GLUXSYSTEM is structured as a multi-layered design framework that integrates responsive biomaterials with an IoT-enabled digital ecosystem for remote wound management. At the sensing level, the architecture uses a hydrogel patch that serves as a biochemical interface, translating glucose and pH fluctuations into observable optical changes. This conceptual model proposes a mobile application as the primary gateway for data acquisition, where image-based inputs are captured and pre-processed. By framing the mobile interface as an edge-processing tool, the design prioritizes usability and responsiveness, ensuring that qualitative optical information is prepared for digital translation in a clear, intuitive format for the end-user.

The broader system architecture is envisioned to utilize a cloud-based backend to facilitate data handling, long-term visualization, and system scalability. Within this proposed framework, data acquired from the sensing interface is transmitted to cloud resources, establishing a streamlined flow of information from the point of care to a centralized analytical platform. This design is intended to bridge the gap between patient-level monitoring and professional clinical oversight, enabling healthcare stakeholders to access remotely interpreted outputs. Furthermore, the framework integrates supportive features such as educational modules and self-care guidance, positioning the platform not merely as a tracking tool but as a conceptual foundation for a comprehensive, recovery-oriented patient awareness system.

The proposed analytical framework addresses the inherent challenges of smartphone-based colorimetric biosensing, including ambient lighting fluctuations and hardware-specific color biases, by introducing a conceptual illumination normalization protocol. This design envisions a white-reference correction step to standardize raw image data before secondary analysis. Following normalization, the system is designed to translate visual data into the CIELAB (L*a*b*) color space, selected for its perceptual uniformity and device independence. Within this framework, the L*, a*, and b* components are treated as the primary feature set for quantifying colorimetric shifts, providing a stable mathematical basis for correlating visual changes in the hydrogel with specific biomarker variations.

To facilitate spatially resolved monitoring, the system architecture incorporates a conceptual image-segmentation strategy to identify active sensing regions across the hydrogel surface. This approach defines multiple regions of interest (ROIs), enabling the system to extract representative L*a*b* values from distinct pH- and glucose-sensing zones based on the patch's physical layout. These extracted features are intended to be processed through regression-based machine learning models designed to interpret non-linear colorimetric responses. Under this proposed model, complex training is envisioned as a cloud-level function, while real-time inference is intended to generate on-device spatial biomarker maps. These outputs are conceptualized as false-color overlays that provide users with an intuitive visual representation of the wound's physiological status.

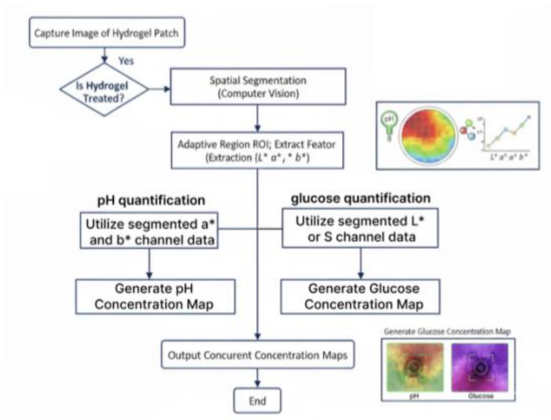

Figure 1. Automated Spatially Resolved Image Flowchart

The GLUXSYSTEM framework is conceptually designed to leverage IoT technology to bridge the gap between smart hydrogel interfaces and remote digital infrastructure. In this proposed architecture, the hydrogel patches function as passive visual sensors, with the mobile application serving as the primary gateway for data acquisition. The design outlines a guided user workflow for image capture, intended to translate the patch's colorimetric signals into digital datasets. These data packets—encompassing qualitative indicators of wound status, glucose levels, and pH states—are envisioned for transmission to a cloud-based environment via secure communication protocols. This tiered connectivity model is specifically designed to prioritize data integrity and privacy throughout the transfer process from the point of care to the analytical backend.

For long-term clinical utility, the framework proposes a structured cloud database designed to serve as a longitudinal digital record for wound monitoring. This centralized storage system is intended to facilitate the tracking of wound progression over time, providing a comprehensive history for both patients and clinicians. To maintain a secure and scalable environment, the design incorporates a proposed Application Programming Interface (API) layer. This intermediary layer is conceptualized to manage all data exchange, ensuring controlled communication between the mobile front-end and the cloud database while preventing direct exposure of the underlying data structures. This architectural approach aims to create a robust, secure, and interoperable system that supports clinical decision-making within a digital health ecosystem.

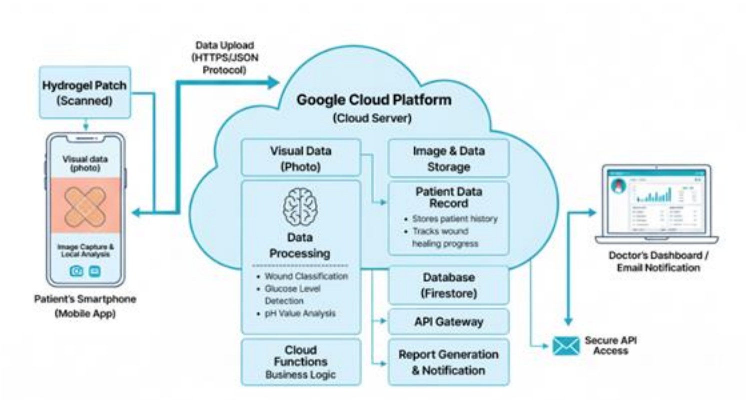

Figure 2. Data Flow of Smart Hydrogel Patch for Glucose and pH Monitoring

At the interface level, the framework envisions a dedicated dashboard and notification mechanism designed for healthcare providers to review processed diagnostic data. This conceptual interface is intended to facilitate clear visualization of wound progression, providing a structured digital environment that enhances clinical awareness and supports timely interventions. Within the GLUXSYSTEM concept, the integrated IoT architecture serves as a bridge for continuous connectivity, supporting remote monitoring and evidence-based decision-making by establishing a seamless information loop between patients and medical professionals.

Results

Based on the proposed sensing design, the performance of the pH-responsive hydrogel patch is interpreted at a conceptual level. The expected colorimetric behavior is consistent with the intrinsic response characteristics of the BTB–chitosan system. Under near-neutral conditions (approximately pH 7), the patch is envisioned to maintain its baseline appearance, representing a physiologically stable wound environment. When exposed to acidic conditions (around pH 4), a visible shift toward yellow is expected, whereas alkaline conditions (approximately pH 10), commonly associated with infected or chronic wounds, result in a blue color response. These distinct color states illustrate the intended capability of the patch to qualitatively differentiate wound pH conditions by visual inspection.

Table 1. Wagner's Classification of Diabetic Foot Ulcers

Type	Depth	pH	Glucose
Grade 1	Superficial wound limited to the epidermis	pH tends to shift toward neutral or mildly alkaline (>6.5), often associated with exposed tissue and early bacterial presence	Elevated blood glucose levels (>200 mg/dL) are commonly reported and may impair early healing processes
Grade 2	Wound extends to deeper soft tissues without bone involvement	pH is frequently reported to increase to alkaline ranges (≈7.1–8.9), creating an environment favorable for bacterial growth	Poorly controlled hyperglycemia (>200 mg/dL) is commonly observed and contributes to delayed healing
Grade 3	Wound reaches bone or joint, often accompanied by severe infection	pH is typically reported at higher alkaline levels (>8.0), indicating advanced infection	Very high and uncontrolled glucose levels (>250 mg/dL) are frequently associated with disease progression
Grade 4 - 5	Partial or complete gangrene of the foot	Highly alkaline wound environments are commonly reported, supporting anaerobic bacterial activity and tissue necrosis	Persistently elevated glucose levels (>300 mg/dL) are often observed in severe cases and correlate with vascular damage

Similarly, the glucose-sensing concept is based on established photonic crystal–hydrogel response mechanisms reported in the literature and aligns with the GLUXSYSTEM demonstration range of 0–25 mM glucose. The PEGDA–APBA photonic crystal sensor is conceptually expected to exhibit progressive structural color shifts as glucose concentration increases. Low glucose levels are represented by a blue appearance, intermediate levels by a purple transition, and higher glucose levels by a pink color. This gradual color progression is intended to provide an intuitive visual gradient that supports smartphone-based patch scanning and application-level interpretation within the GLUXSYSTEM framework.

In general, pH and glucose levels are closely correlated with the severity of diabetic wounds. In general, the higher the wound grade (severity), the worse the pH and glucose levels, reflecting an environment that is not conducive to healing.

In addition to developing patch materials, this research integrates an app-based support system that displays glucose and pH levels through a simple visual interface and transmits data to the cloud via IoT. This integration is intended to support wound monitoring through a dedicated dashboard. Beyond monitoring, the application concept includes basic information on diabetic wound care and lifestyle guidance to improve patient awareness and encourage independent preventive actions alongside medical treatment.

Discussion

The optical response of the pH-sensing patch is conceptually governed by the halochromic behavior of BTB within the chitosan matrix. Reversible protonation and deprotonation are expected to produce visible color shifts, with yellow indicating acidic conditions and blue representing alkaline environments. This behavior is consistent with clinical observations, which show that a transition toward alkaline pH is commonly associated with chronic infection in diabetic wounds. Immobilization of the indicator within a biocompatible hydrogel scaffold enables non-invasive, visually interpretable monitoring without the need for invasive sampling.

From a system perspective, the pH-sensing concept offers advantages such as low material cost, a simple visual readout, and chitosan's antibacterial properties. However, the approach remains semi-quantitative, as accurate pH interpretation relies on digital color analysis. Practical factors, including environmental contamination, single-use operations, and the diffusion of wound exudate within the matrix, warrant consideration for future optimization.

The glucose-sensing mechanism is conceptually based on reversible interactions between APBA functional groups and glucose molecules, which are expected to induce hydrogel swelling when integrated with a photonic crystal structure. This volumetric change is anticipated to alter optical properties and generate a structural color shift. Within the

GLUXSYSTEM framework, this glucose-dependent response is positioned as a complementary indicator that can be interpreted alongside pH trends using smartphone-based imaging.

The primary strength of the glucose-sensing concept lies in its non-invasive, visually intuitive nature, which supports application-based colorimetric analysis. Nevertheless, further experimental validation is required to assess stability, repeatability, and reliability under complex wound conditions. Similarly, at the application level, system performance may be influenced by camera quality, lighting conditions, and data security considerations. Addressing these aspects through improved image processing, validation, and secure data handling will be important for future system development.

Conclusions

This work presents a conceptual design of an integrated hydrogel-based sensing system for diabetic wound monitoring, combining pH and glucose-responsive colorimetric patches with smartphone-based analysis and IoT connectivity. By leveraging biocompatible hydrogel materials and optical sensing principles, the proposed system enables non-invasive and visually interpretable assessment of key wound biomarkers associated with infection risk and healing progression.

The integration of application-level image processing, machine learning–assisted interpretation, and cloud-based data management positions GLUXSYSTEM as a potential digital health support platform for both patients and healthcare professionals. Although the current work is design-oriented and lacks experimental validation, it establishes a structured framework for future development. Further laboratory testing and clinical evaluation are required to assess quantitative performance, robustness, and real-world applicability. Overall, the proposed concept highlights the potential of combining smart biomaterials with mobile and IoT technologies to improve the accessibility and effectiveness of diabetic wound monitoring.

Competing Interests

There is no conflict of interest to declare.

Acknowledgments

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Generative AI Declaration

In the development of this manuscript, the author(s) made use of Gemini 3.0 to support grammatical refinement and language polishing. All outputs were carefully reviewed, revised, and refined by the author(s), who take full responsibility for the accuracy, originality, and integrity of the final published version.

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