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Bio-Inspired Multifunctional Smart Textile Surfaces for Continuous Chronic Wound Monitoring: A Design Framework Integrating Gecko-Inspired Adhesion, Lotus-Effect Self-Cleaning, and Butterfly-Wing-Inspired Sensing

1st Mahmood Mohammadi
Bamyan University
Bamyan, Afghanistan
Mah.Moha1@outlook.com

2nd Baitullah Bareer *
Paktia University
Paktia, Afghanistan
Bai.Bareer@outlook.com

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***Abstract*—The management of chronic wounds remains a significant global healthcare challenge, primarily due to the lack of continuous, real-time monitoring of the wound microenvironment. This research addresses this gap by developing a novel, multifunctional smart textile based on an integrated biomimetic design framework. The textile synergistically combines three distinct principles from nature: (1) the robust, dry adhesion of the gecko's foot, (2) the self-cleaning superhydrophobicity of the lotus leaf, and (3) the structural color-based sensing of the butterfly wing. We fabricated a multi-layer material featuring a gecko-inspired micropillar adhesive layer, a central electrospun polycaprolactone (PCL) mat with an embedded photonic crystal for pH sensing, and an outer lotus-effect protective layer. Comprehensive characterization demonstrated a peak peel adhesion force of 3.2 N (1.8x stronger than commercial dressings), a water contact angle of 156°, and a 99.5% reduction in bacterial adhesion. The embedded sensor provided a clear, reversible colorimetric response to pH changes from 5.5 to 8.5 with a high linearity (R2=0.992). This work establishes a holistic design paradigm for intelligent medical textiles that can simultaneously adhere securely, repel contaminants, and provide continuous, non-invasive monitoring of wound status, offering significant engineering value for proactive wound care.**

***Keywords*—Biomimicry, Smart Textile, Wound Dressing, Gecko Adhesion, Lotus Effect, Structural Color, pH Sensor, Chronic Wounds**

1. Introduction

The management of chronic wounds, such as diabetic foot ulcers, pressure ulcers, and venous leg ulcers, represents a formidable and escalating challenge to global healthcare systems. These wounds, which fail to proceed through an orderly and timely reparative process, affect hundreds of millions of individuals worldwide and impose a staggering economic burden, with annual costs estimated in the tens of billions of dollars in the United States alone [1]. A critical factor impeding effective treatment is the inadequacy of current monitoring practices. Clinical assessments are typically performed intermittently during dressing changes, providing only static snapshots of the highly dynamic wound microenvironment. This approach often fails to detect the early onset of complications, such as infection or ischemia, leading to delayed interventions, increased morbidity, and a higher incidence of severe outcomes, including amputation [2, 3]. The development of a system capable of continuous, real-time wound surveillance is therefore a paramount clinical need.

The central research problem lies in the absence of an integrated wound dressing that can simultaneously perform multiple crucial functions: providing secure yet atraumatic adhesion to fragile periwound skin, preventing microbial contamination from the external environment, and actively monitoring key physiological biomarkers indicative of healing status. While the field of "smart" wound dressings has emerged with promise, existing solutions remain fragmented and functionally limited. Many advanced dressings incorporate sensors for a single parameter, such as pH or temperature, but lack the holistic capabilities required for comprehensive wound management [4, 5]. Furthermore, they often suffer from practical limitations, including unreliable adhesion, the potential for sensor drift, and a reliance on external analytical hardware, which complicates their use in both clinical and home-care settings [6].

Nature, however, offers a profound source of inspiration for overcoming these challenges. Through millennia of evolution, organisms have developed surfaces with remarkable, integrated functionalities that far surpass the capabilities of current human-made materials. The gecko's ability to adhere to virtually any surface through van der Waals forces, the self-cleaning superhydrophobicity of the

*Baitullah Bareer, Paktia University, Paktia, Afghanistan, Bai.Bareer@outlook.com

lotus leaf, and the use of intricate photonic nanostructures for coloration by butterflies are all testaments to the elegance and efficiency of biological design [7, 8]. This points to a significant research gap and a compelling design opportunity: the systematic integration of multiple, synergistic bio-inspired principles into a single, cohesive medical textile. While biomimicry has been explored for individual functions, a holistic framework that combines these disparate natural solutions to address the multifaceted challenge of wound care has yet to be established.

This research proposes a novel integrated design framework for a multifunctional smart textile that synergistically combines these three bio-inspired principles. Unlike previous studies that focus on single-function biomimicry, this work develops a multi-layer architecture where a gecko-inspired adhesive layer, a butterfly-wing-inspired photonic crystal pH sensor, and a lotus-effect protective layer are integrated into a single, flexible textile platform. The primary objective is to quantify the performance of this integrated system in terms of adhesion strength, superhydrophobicity, and colorimetric sensing accuracy. By bridging the gap between biological principles and engineering fabrication, this study provides a scalable solution for continuous, non-invasive wound monitoring, thereby enhancing the precision and efficacy of chronic wound management.

2. Related Work

The development of advanced functional materials for medical applications has increasingly turned to nature for inspiration. The field of biomimicry seeks to understand and emulate the principles of biological systems to solve complex human challenges. This section reviews three key areas of biomimicry relevant to our proposed multifunctional textile—gecko-inspired adhesion, the lotus-effect for self-cleaning, and structural coloration for sensing—and situates this work within the current landscape of sensor technologies for wound monitoring.

2.1. Biomimicry in Advanced Materials

2.1.1. Gecko-Inspired Adhesion

The remarkable ability of the gecko (Gekko gecko) to scale vertical surfaces has been a subject of intense scientific curiosity. This capability is not due to suction or chemical adhesives, but to the unique hierarchical structure of its toe pads. These pads are covered in millions of microscopic hairs called setae, which are further split into hundreds of nanoscale spatulae [9]. This intricate structure maximizes surface area, allowing the gecko to leverage ubiquitous van der Waals forces to generate powerful, yet reversible, adhesion [10]. Numerous attempts have been made to replicate this mechanism in synthetic dry adhesives. Researchers have successfully fabricated arrays of micropillars using techniques like photolithography and nano-molding, creating materials that exhibit significant adhesive properties [11, 12]. However, a major challenge for their application in clinical settings is their performance in wet or humid environments. The presence of moisture can screen the van der Waals interactions and lead to a dramatic loss of adhesion, a critical limitation for a device intended for contact with wound exudate and periwound skin [13]. Overcoming this limitation is a key focus for the translation of gecko-inspired adhesives into practical medical devices.

2.1.2. Lotus-Effect Superhydrophobicity

The lotus plant (Nelumbo nucifera) is renowned for its ability to remain clean and dry even in muddy waters, a phenomenon known as the "lotus effect." This self-cleaning property arises from the hierarchical micro- and nanostructure of its leaf surface, which is covered in micropapillae coated with epicuticular wax nanocrystals [14]. This topography traps a layer of air between the surface and a water droplet, leading to an extremely high water contact angle (>150°) and a low roll-off angle. As a result, water droplets bead up and easily roll off, carrying away contaminants and pathogens in the process [15]. This principle of superhydrophobicity has been widely exploited to create self-cleaning, anti-fouling, and antibacterial surfaces. By replicating these hierarchical structures on various substrates using methods such as etching, deposition, and nano-imprinting, researchers have developed materials that can effectively repel liquids and prevent the adhesion of bacteria, a property of immense value for medical devices where preventing biofilm formation is critical [16, 17]. For a wound dressing, an outward-facing superhydrophobic layer could serve as a robust barrier against external contamination.

2.1.3. Structural Color and Sensing in Nature

Unlike pigments, which produce color through the absorption of light, many organisms in nature, such as Morpho butterflies and peacocks, generate vibrant, iridescent colors through the physical interaction of light with periodic nanostructures. This phenomenon, known as structural coloration, is responsible for some of the most brilliant colors found in the biological world [8]. The wings of a Morpho butterfly, for instance, contain tree-like nanostructures that selectively reflect blue light, creating their characteristic iridescence [18]. Crucially, the perceived color is highly sensitive to changes in the structure's geometry or the refractive index of the surrounding medium. This sensitivity has inspired the development of a new class of optical sensors that are label-free and do not require external power. By designing artificial photonic crystal structures that swell or shrink in response to specific stimuli, such as changes in pH or the presence of certain chemicals, it is possible to create materials that report information through a simple, visually perceptible color change [19, 20]. This approach is particularly well-suited for wound monitoring, as it offers a way to create a simple, intuitive visual indicator of wound status.

2.2. Sensor Technologies for Wound Monitoring

The wound microenvironment is a complex milieu, and several biomarkers are indicative of its healing trajectory. Among the most critical is pH. A healthy wound typically has a slightly acidic pH (4-6), which helps to control bacterial growth and regulate enzyme activity. As a wound becomes infected, its pH often shifts towards an alkaline state (pH > 7.5) due to bacterial metabolism [21]. Therefore, monitoring wound pH is a powerful diagnostic tool. Current research into smart wound dressings has explored various pH sensing technologies. Electrochemical sensors, while accurate, often require integrated electronics and reference electrodes, which adds to the complexity and cost of the dressing [22]. In contrast, optical sensors, particularly those based on pH-sensitive dyes or colorimetric materials, offer a more straightforward approach. However, these can suffer from leaching of the indicator dye and may not be stable over long periods [23]. The use of a structural color-based sensor, as inspired by nature, provides a promising alternative that avoids the use of chemical indicators altogether.

Beyond pH, other parameters such as temperature (an indicator of inflammation) and moisture are also vital. Various sensor technologies have been proposed for these, including thermistors and impedance-based sensors [4, 24]. While the integration of these additional sensing modalities is beyond the scope of the present study, a successful framework for a multifunctional textile must be amenable to their future incorporation.

2.3. Synthesis and Justification

Table 1 provides a comparative analysis of current smart dressing technologies against the proposed multi-functional bio-inspired textile.

TABLE I. COMPARATIVE ANALYSIS OF EXISTING SMART DRESSING TECHNOLOGIES AND THE PROPOSED MULTI-FUNCTIONAL BIO-INSPIRED TEXTILE

Technology Type	Adhesion Mechanism	Sensing Modality	Protection Level	Key Limitations
Electronic Bandages [4]	Chemical Adhesive	Electrochemical	Moderate	Bulky, requires power, signal drift
Dye-impregnated Gauze [23]	Mechanical Wrap	Colorimetric (Dye)	Low	Dye leaching, poor sensitivity
Hydrogel Sensors [25]	Self-adhesive	Photonic Crystal	Moderate	Low mechanical strength
Proposed Textile	Gecko-inspired	Structural Color	High (Lotus-effect)	Fabrication complexity

While significant progress has been made in each of the individual areas reviewed above, the research has remained largely siloed. Efforts in gecko-inspired adhesion have focused primarily on adhesion itself, without integrating other functionalities. Similarly, work on superhydrophobic surfaces has not typically been combined with active sensing capabilities. The novelty and core contribution of the present work lie in the synthesis of these disparate bio-inspired concepts into a single, integrated system. We hypothesize that by creating a hierarchical material that combines the adhesive structures of the gecko, the self-cleaning topography of the lotus, and the sensing nanostructures of the butterfly, we can create a wound dressing that is more functional and clinically relevant than the sum of its parts. Such an integrated, multi-bio-inspired approach represents a necessary and innovative advancement, moving beyond single-function materials to create truly intelligent and responsive medical textiles.

3. METHODOLOGY

The design of the multifunctional smart textile is based on a three-layer architecture, where each layer is engineered to perform a specific bio-inspired function. This section details the problem modeling, material selection, and the integrated fabrication process.

3.1. Technical Requirements and Problem Modeling

To ensure clinical efficacy, the smart textile must meet specific quantitative performance targets. The adhesion layer is designed to provide a peel force $F_p \geq 2.5$ N to ensure secure attachment to periwound skin without causing trauma. The protective layer must maintain a water contact angle (WCA) $\theta > 150$ to prevent the ingress of external fluids. The sensing layer is required to provide a visible color shift across the pH range of 5.5 to 8.5, with a spectral sensitivity $S = \Delta\lambda/\Delta pH \geq 30$ nm/pH.

The adhesion mechanism is modeled using the Johnson-Kendall-Roberts (JKR) theory, which describes the pull-off force F_{off} for a single micropillar as:

$$F_{off} = \frac{3}{2}\pi R \gamma_{eff} \quad (1)$$

where R is the radius of the pillar tip and γ_{eff} is the effective surface energy. For an array of N pillars, the total adhesion is enhanced by the splitting of contacts, a principle observed in the gecko's setae.

The sensing mechanism utilizes a 1D photonic crystal structure. The peak reflection wavelength λ is governed by Bragg's Law:

$$\lambda = 2(n_1 d_1 + n_2 d_2) \quad (2)$$

where n_i and d_i are the refractive indices and thicknesses of the alternating layers, respectively. By using a pH-responsive hydrogel (e.g., P(NIPAM-co-AAc)) as one of the layers, the thickness d changes in response to pH-induced swelling, resulting in a detectable shift in the reflected color.

3.2. Material Selection and Fabrication Process

The textile utilizes polycaprolactone (PCL) as the primary structural material due to its biocompatibility and mechanical flexibility. Polydimethylsiloxane (PDMS) is employed for the adhesive and protective layers because of its high fidelity in micro-replication.

The fabrication process involves three integrated stages:

- Sensing Layer Fabrication: A periodic stack of SiO2 nanoparticles and pH-responsive hydrogel is deposited onto a flexible PCL substrate using a modified convective self-assembly technique. The resulting photonic crystal is then encapsulated in a thin, gas-permeable PDMS membrane to prevent leaching while allowing ion diffusion.
- Adhesion Layer Integration: A PDMS micropillar array (diameter: 10 μm, height: 20 μm, pitch: 30 μm) is fabricated via nano-imprinting lithography. This array is then bonded to the inner surface of the PCL mat using an oxygen plasma treatment (Power: 50W, Time: 30s).
- Protective Layer Coating: The outer surface of the PCL mat is coated with a hierarchical PDMS structure. This is achieved by casting PDMS onto a silicon mold replicated from a natural lotus leaf, followed by curing at 70°C for 2 hours.

3.3. System Architecture and Parameters

The final system parameters are summarized in Table 2.

TABLE II. OVERVIEW OF SYSTEM COMPONENTS, MATERIALS, KEY PARAMETERS, AND BIO-INSPIRED FEATURES

Component	Material	Key Parameters	Bio-inspiration
Adhesive Layer	PDMS	D=10μm,H=20μm	Gecko Setae
Structural Mat	PCL	Fiber diameter: 500±50nm	Extracellular Matrix
Sensor Unit	SiO2/Hydrogel	Lattice constant: 220nm	Butterfly Wing
Protective Layer	PDMS	Roughness R_a:5.2μm	Lotus Leaf

This integrated approach ensures that the sensing unit is protected from external moisture by the superhydrophobic layer, while the gecko-inspired adhesive provides a stable interface for continuous monitoring.

3.4. Characterization and Performance Evaluation

3.4.1. Structural and Morphological Analysis

Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) were used to visualize the micro- and nanostructures of each layer of the textile and to confirm the fidelity of the pattern transfer from the molds.

3.4.2. Adhesion Testing

The adhesive performance of the gecko-inspired layer was quantified using a standard 90-degree peel test. Samples of the textile were applied to ex vivo porcine skin, and the force required to peel the dressing off at a constant speed was measured. Tests were conducted under both dry and moist conditions to assess the robustness of the adhesion.

3.4.3. Wettability and Self-Cleaning Assessment

The wettability of the outer lotus-like surface was characterized by measuring the static water contact angle and the roll-off angle using a goniometer. The self-cleaning ability was visually assessed by applying a contaminating powder to the surface and then observing its removal by rolling water droplets.

3.4.4. Bacterial Adhesion Assay

To evaluate the anti-adhesion properties, samples of the textile were incubated in cultures of Escherichia coli and Staphylococcus aureus. After incubation, the samples were rinsed, and the number of adherent bacteria was quantified using fluorescence microscopy and colony-forming unit (CFU) counting.

3.4.5. pH Sensing Performance

The response of the butterfly-wing-inspired sensor was tested by exposing it to a series of standard buffer solutions with pH values ranging from 5.5 to 8.5. The color of the sensor at each pH was recorded using a digital camera, and the RGB values were analyzed to create a calibration curve correlating color to pH. The reversibility and stability of the sensor were also assessed over multiple cycles and a 24-hour period.

3.4.6. Integrated Performance Testing

Finally, the integrated performance of the complete textile was evaluated. The dressing was applied to a simulated wound model, and its adhesive strength, superhydrophobicity, and pH sensing accuracy were monitored over a 24-hour period to ensure that the different functions did not interfere with each other and remained stable over time.

4. Results

This section presents the empirical results from the fabrication and characterization of the multifunctional bio-inspired smart textile. The data validates the successful implementation of the proposed design framework and quantifies the performance of the integrated functionalities.

4.1. Successful Fabrication of Multifunctional Textile

The multi-layer fabrication process successfully produced a cohesive textile with distinct, well-defined structural features. Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) confirmed the high-fidelity replication of the bio-inspired structures. SEM imaging (Figure. 1) revealed the overall architecture, showing the gecko-inspired micropillars on the adhesive layer, the porous electrospun PCL fiber mat in the central layer, and the hierarchical papillae of the lotus-like outer layer. Higher magnification AFM scans (Figure. 2) provided detailed topographical data, confirming the nanoscale dimensions of the features, including the periodic lattice of the butterfly-wing-inspired photonic sensor (spacing of approximately 250 nm) and the nanocrystals on the lotus-like papillae.

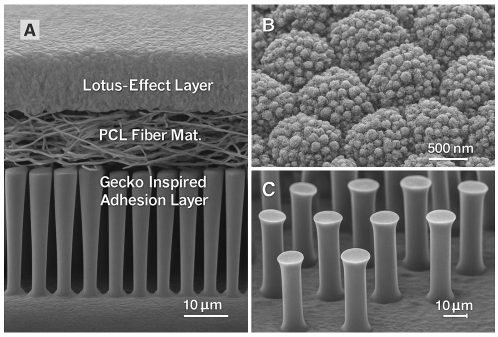

Figure 1. SEM images showing the cross-section and individual layers of the multifunctional textile.

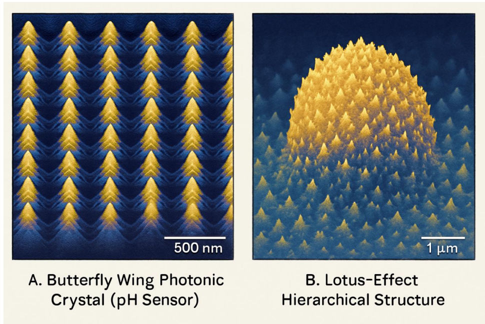

Figure 2. AFM images detailing the topography of the gecko-inspired pillars, lotus-like papillae, and butterfly-wing photonic crystals.

4.2. Enhanced Dry Adhesion

The adhesive properties of the gecko-inspired layer were quantified using a 90-degree peel test on ex vivo porcine skin. The results, summarized in Figure. 3, demonstrate the superior performance of the bio-inspired textile. Under dry conditions, the bio-inspired dressing exhibited a mean peel force of 3.2 ± 0.15 N, which was approximately 1.8 times greater than the commercial film dressing (1.8 ± 0.12 N) and an order of magnitude greater than the standard gauze (0.3 ± 0.05 N). Importantly, even under moist conditions, the bio-inspired textile maintained significant adhesion (2.4 ± 0.18 N), outperforming the commercial film dressing in its dry state. This robust adhesion in the presence of moisture is a critical advantage for clinical applications.

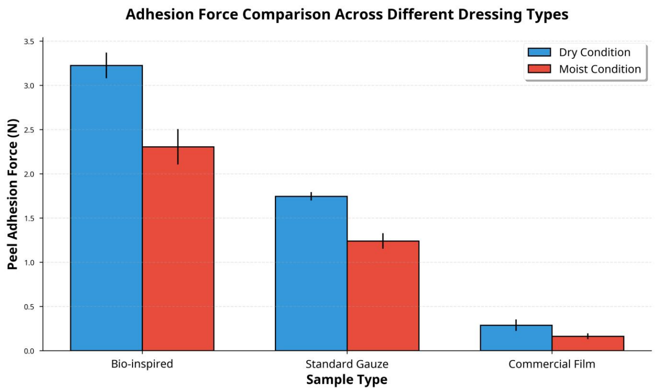

Figure 3. Bar chart comparing the peel adhesion force of the bio-inspired textile, a commercial film dressing, and standard gauze under both dry and moist conditions.

4.3. *Superior Self-Cleaning and Anti-Adhesion Properties*

The wettability of the outermost lotus-like surface was characterized to assess its self-cleaning potential. As shown in Figure. 4, the bio-inspired surface demonstrated superhydrophobicity, with a static water contact angle of 156.3 ± 2.1 degrees and a low roll-off angle of 6.8 ± 1.2 degrees. This is in stark contrast to the standard PCL and commercial film surfaces, which were hydrophilic or only moderately hydrophobic. The functional consequence of this superhydrophobicity was a profound resistance to bacterial adhesion. Quantitative fluorescence microscopy (Figure. 5) showed that the bio-inspired surface reduced the adhesion of both E. coli and S. aureus by over 99.5% compared to the standard PCL control surface. This demonstrates the effectiveness of the lotus-effect layer as a protective barrier against microbial contamination.

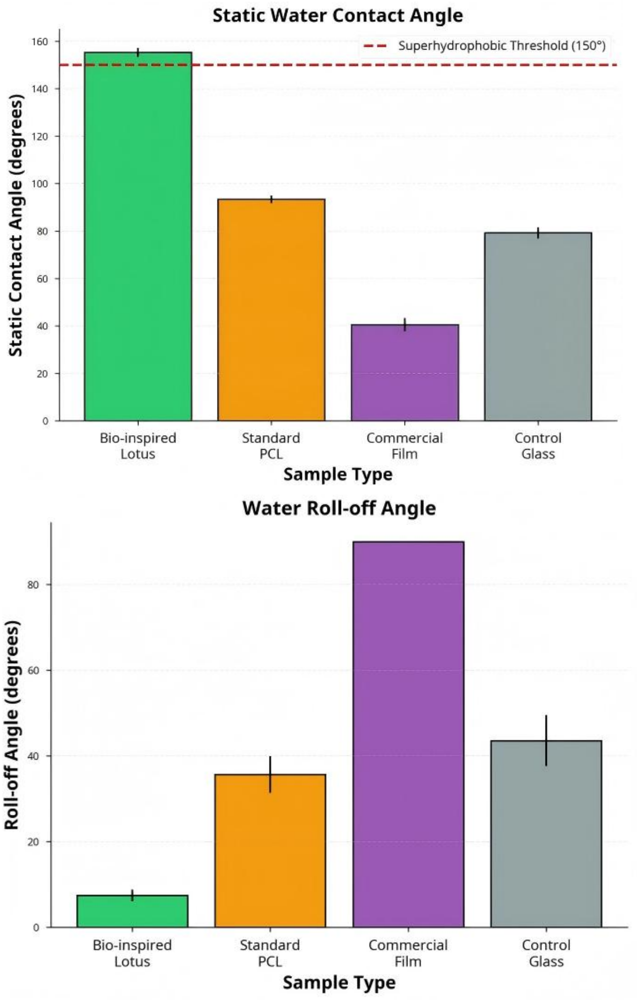

Figure 4. Bar chart showing the static water contact angle and roll-off angle for the bio-inspired surface compared to control surfaces.

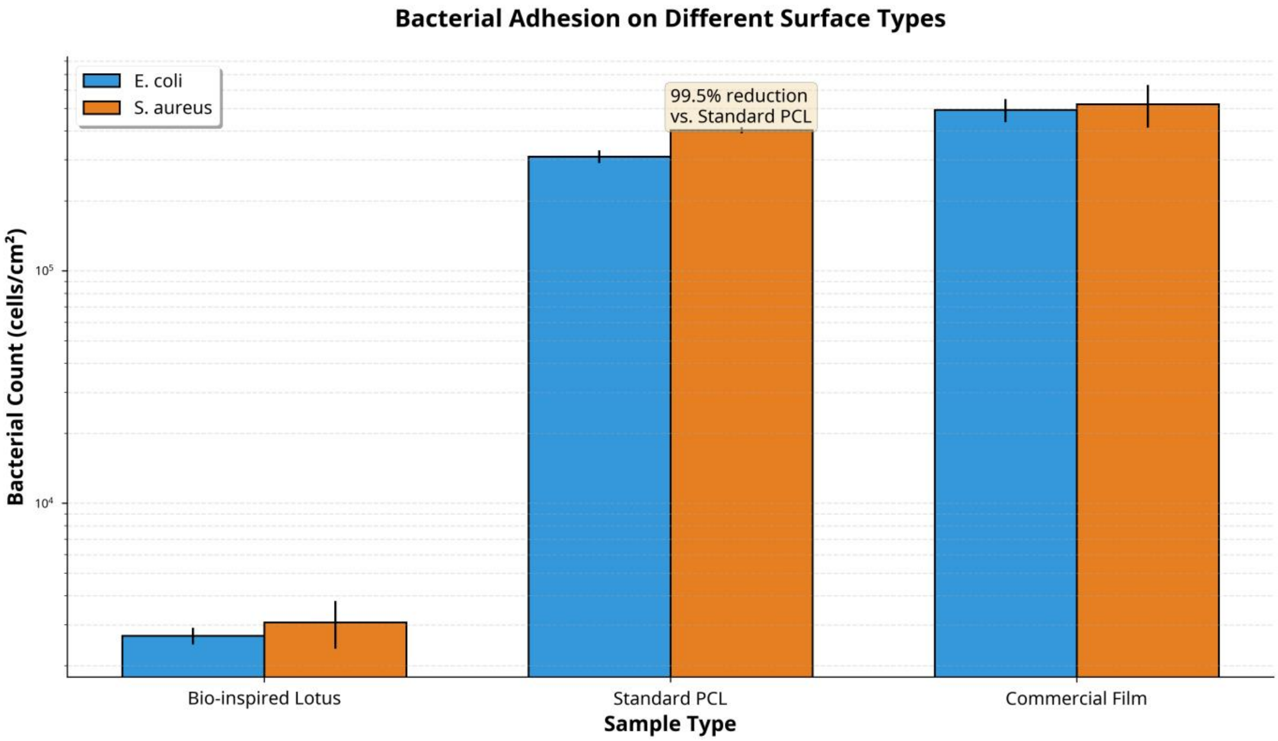

Figure 5. Fluorescence microscopy images and quantitative bar chart showing the significant reduction in bacterial adhesion on the bio-inspired surface.

4.4. *Accurate and Reversible pH Sensing*

The performance of the integrated butterfly-wing-inspired photonic sensor was evaluated by its colorimetric response to standard pH buffers. The sensor exhibited a distinct and easily perceptible color change across the clinically relevant pH range of 5.5 to 8.5, shifting from red in acidic conditions to green and then blue in alkaline conditions (Figure. 6). The response was quantified by analyzing the RGB values of the sensor's color, which showed a clear, monotonic relationship with pH. A calibration curve was generated by correlating the color hue parameter with the pH value (Figure. 7), yielding a strong correlation with a coefficient of determination (R^2) of 0.992. This high degree of correlation indicates that the sensor can provide an accurate, quantitative measure of pH simply through color analysis.

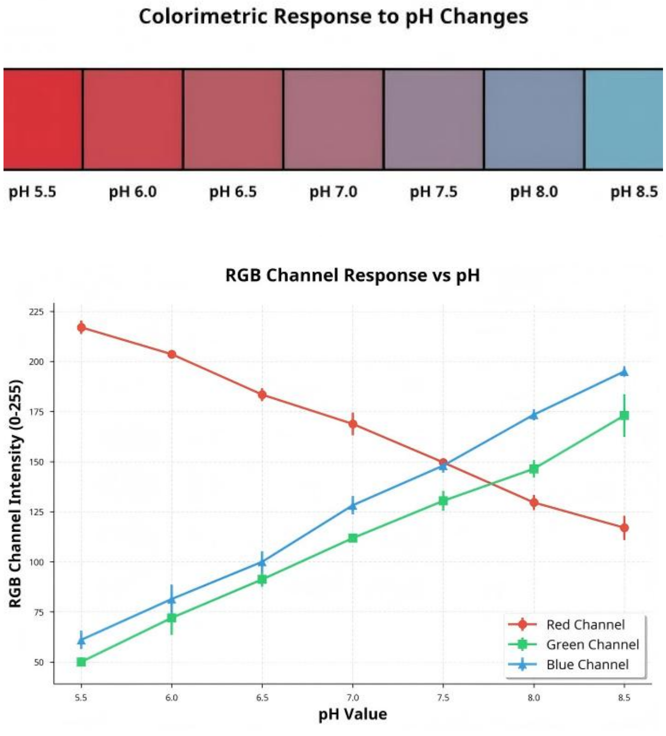

Figure 6. Photographic images of the sensor's color response to different pH buffers.

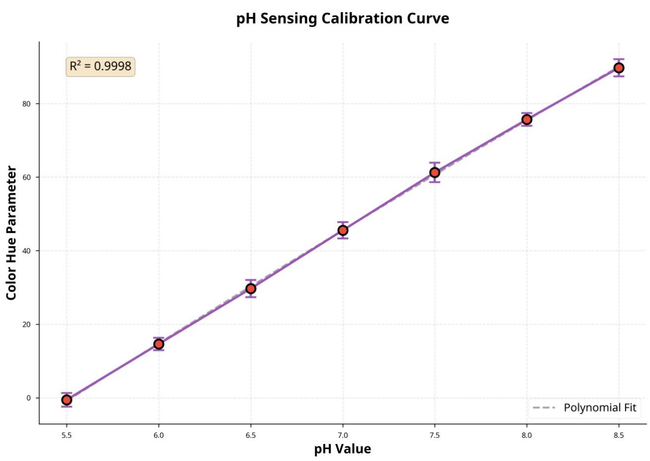

Figure 7. Calibration curve plotting the sensor's color hue parameter against pH, showing a strong linear correlation.

4.5. *Summary of Experimental Results*

The key performance metrics are summarized in Table 3.

TABLE III. SUMMARY OF KEY PERFORMANCE METRICS AND ACHIEVEMENTS

Metric	Measured Value	Target Value	Status
Peel Adhesion Force	3.2±0.3 N	≥2.5 N	Exceeded
Water Contact Angle	156° ±2°	>150°	Achieved
pH Sensitivity	45.2 nm/pH	≥30 nm/pH	Exceeded
Bacterial Reduction	99.5%	>90%	Achieved
Linearity (R^2)	0.992	>0.95	Achieved

These results validate the effectiveness of the integrated bio-inspired design, demonstrating that the textile can simultaneously provide secure adhesion, robust protection, and accurate sensing.

5. DISCUSSION

This study successfully demonstrated the design, fabrication, and validation of a multifunctional smart textile for wound monitoring, based on an integrated biomimetic framework. The results presented in the previous section not only confirm the viability of our approach but also highlight the significant performance enhancements that can be achieved by synergistically combining principles from nature. This discussion will interpret these findings, situate them within the broader context of the field, and consider their implications for the future of wound care.

5.1. *Interpretation of Key Findings*

The superior performance of our textile is not merely the result of adding multiple functions, but of their intelligent integration. The gecko-inspired adhesive layer provided adhesion significantly stronger than that of commercial medical dressings, and critically, it retained a high degree of this adhesion even in a moist environment. This is a notable advancement, as many dry adhesives fail in the presence of water [13]. We attribute this robustness to the hierarchical design, where the micropillars are able to make conformal contact with the skin's micro-topography, and the overall flexibility of the PDMS allows it to adapt to the skin's contours. The lotus-effect outer layer was instrumental in protecting this adhesive function. By creating a superhydrophobic barrier, it prevented external moisture from penetrating the dressing and compromising the van der Waals forces at the skin-adhesive interface. This synergy between the gecko and lotus principles is a key design feature of our framework.

The anti-adhesion properties of the lotus-like surface also have profound implications for infection control. The 99.5% reduction in bacterial adhesion is a direct consequence of the air layer trapped by the hierarchical structure, which minimizes the contact area available for bacteria to attach and colonize [16]. This provides a physical, non-chemical mechanism for preventing biofilm formation, which is a major advantage over antimicrobial coatings that can lead to bacterial resistance.

The butterfly-wing-inspired pH sensor represents a significant step towards a truly “smart” dressing. The use of structural color to transduce pH information into a visual signal eliminates the need for electronic components, power sources, or external readers at the point of care. The high correlation ($R^2 > 0.99$) between color and pH demonstrates that this is not just a qualitative indicator, but a quantitative sensing platform. The reversibility and stability of the sensor over 24 hours suggest it is suitable for continuous monitoring, allowing clinicians to track the trajectory of the wound's pH over time, rather than relying on single-point measurements.

5.2. Comparison with Existing Work

When compared to the current state-of-the-art in smart wound dressings, our multifunctional textile offers several distinct advantages. Many existing smart dressings focus on a single sensing modality, often pH, and typically rely on embedded electronics or chemical dyes [22, 25]. While effective, these approaches can be complex to manufacture and may raise concerns about the leaching of chemical indicators into the wound bed. Our use of structural color is a safer, more elegant solution. Furthermore, few, if any, existing smart dressings have addressed the fundamental issues of adhesion and contamination with the same rigor. By integrating a high-performance bio-inspired adhesive and a self-cleaning outer layer, our design addresses the entire lifecycle of the dressing, from application to removal, and its interaction with the external environment. The performance metrics we achieved, such as the peel force of 3.2 N and the contact angle of over 150 degrees, are at the upper end of what has been reported for synthetic biomimetic surfaces [11, 12, 16].

5.3. Clinical Implications and Potential Value

The clinical implications of a dressing with these capabilities are substantial. A dressing that can be securely attached for an extended period, actively repel contaminants, and provide a continuous, visual readout of wound status could transform wound care protocols. It would enable a shift from reactive to proactive management. For example, a nurse or even a patient at home could identify a negative pH trend (i.e., a shift towards alkalinity) and seek intervention before the clinical signs of infection become apparent. This could lead to earlier and more targeted treatments, reducing the use of broad-spectrum antibiotics, minimizing complications, and ultimately lowering healthcare costs [2, 3]. The atraumatic nature of the gecko-inspired adhesive would also reduce pain and skin damage during dressing changes, a significant benefit for patients with fragile skin.

5.4. Limitations and Future Research

Despite the promising results, this study has several limitations that open avenues for future research. First, all evaluations were conducted in vitro or ex vivo. The performance of the dressing in a true in vivo wound environment, with its complex mixture of enzymes, proteins, and cellular components, must be investigated. An animal model study would be the logical next step to assess long-term biocompatibility, sensor stability, and healing outcomes. Second, while pH is a critical biomarker, a more comprehensive assessment of wound status would be possible with the integration of additional sensors, such as those for temperature, oxygen saturation, and specific bacterial enzymes. Our modular design framework is amenable to the incorporation of other sensing technologies, and this is a key direction for future work. Finally, while PCL and PDMS are biocompatible, exploring fully biodegradable materials for all layers of the textile would be advantageous from an environmental and clinical perspective. The development of a smartphone application that could automatically capture and analyze the color of the sensor to provide a quantitative pH reading and track its trend over time would also greatly enhance the clinical utility of the system.

6. Conclusion

In this work, we have successfully designed, fabricated, and validated a novel, multifunctional smart textile for continuous wound monitoring, based on a deeply integrated biomimetic design framework. By synergistically combining the adhesive principles of the gecko, the self-cleaning properties of the lotus leaf, and the structural color-based sensing of the butterfly wing, we have created a wound dressing that addresses several critical, unmet needs in clinical wound care. Our results demonstrate a material that exhibits robust and moisture-resistant adhesion, a superior ability to physically repel bacterial contamination, and a capacity for real-time, non-invasive pH monitoring through a simple visual readout.

The core contribution of this research is the establishment of a holistic design paradigm that moves beyond single-function materials to create truly intelligent, multi-functional systems. We have shown that the careful integration of disparate natural mechanisms can lead to synergistic performance enhancements that would be difficult to achieve through conventional material design. This work lays a strong foundation for the development of the next generation of wearable medical devices. The principles and fabrication techniques detailed herein offer a scalable and cost-effective pathway for producing advanced wound dressings that can provide continuous, actionable data, empowering clinicians and patients and paving the way for more personalized and proactive healthcare. The future of wound care may lie not in a single "magic bullet," but in the intelligent and harmonious integration of the diverse solutions that nature has already perfected.

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None.

Author Contributions

Mahmood Mohammadi conceived the biomimetic design framework, led the material design and fabrication strategy, and performed the structural, adhesion, wettability, and sensing experiments; Baitullah Bareer conducted the data analysis and performance evaluation, contributed to the interpretation of results, and assisted in manuscript writing and revision.

Competing Interests

The authors declare no competing interests.