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Review Paper

Smart dressings and wearable technology: A new era in wound management

Sara Hassani[1], Mohadeseh Pakroo[1], Yasaman Ghafarzadeh[2], Mina Sadat Naderi[3*], Seyed Mehdi Tabaie[4]

1. *Department of Biology, Science and Research Branch, Islamic Azad University, Tehran, Iran*
2. *Faculty of Pharmacy and Pharmaceutical Sciences, Tehran Medical Sciences, Islamic Azad University, Tehran, Iran*
3. *Department of Biology, NT.C., Islamic Azad University, Tehran, Iran*
4. *Department of Medical Laser, Medical Laser Research Center, Yara Institute, Academic Center for Education Culture and Research (ACECR), Tehran, Iran*

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ABSTRACT

Healing a skin wound is an impressive reflection of the body's intricate cellular processes. The repair process is driven by a dynamic interaction among cells, growth factors, and cytokines, working in harmony to close the wound and restore tissue integrity. However, the most significant challenges often arise from the limitations of existing treatment and management methods, which can hinder efficient repair and recovery. These obstacles have inspired advancements in wound care, emphasizing approaches that align more closely with the body's natural healing capabilities. The limitations of traditional wound management have driven the development of innovative wound dressings, which offer improved accuracy, sensitivity, long-term stability, and environmental resilience. These advanced dressings provide clinicians with real-time insights into wound status, enabling them to make prompt and precise treatment decisions that support tissue repair and regeneration. Despite promising advancements, the complexity of wound healing and the challenges of working in challenging environments necessitate further enhancements in sensor performance. This review underscores the potential of intelligent wearable sensors and material innovations in revolutionizing wound management, highlighting the need for personalized treatment approaches to optimize efficiency and minimize risks during the healing process. To support this analysis, a comprehensive review of papers published in the last fifteen years from databases such as Google Scholar, PubMed, and Elsevier has been conducted. The findings emphasize the importance of multidisciplinary research in advancing wound care, offering new avenues for effective patient management and public health monitoring. By integrating wearable sensors and wireless transmission technologies, these comprehensive wound dressings facilitate remote monitoring, early diagnosis, and timely on-demand drug delivery. The investigation of various physicochemical markers—such as temperature, pH, humidity, and inflammatory factors—enables the early detection of wound conditions.

Corresponding Author (s):
Mina Sadat Naderi, PhD
Address: *Department of Biology, NT.C. (North Tehran Branch), Islamic Azad University, Tehran, Iran*
Tel: +98 13 33368540
E-mail: ms.naderi@iau-tnb.ac.ir

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1. Introduction

The skin, as the largest organ in the human body by surface area, plays a crucial role in protecting internal tissues from various external threats, including mechanical damage, microbial infections, ultraviolet radiation, and extreme temperatures. Given its protective function, the skin is particularly susceptible to injuries, which can have a significant impact on individual health and the healthcare system as a whole [1,2]. Skin wounds are a common and serious public health concern, often leading to complications that affect patients' quality of life. These injuries can cause pain, loss of function, reduced mobility, and mental health issues like depression, anxiety, and social isolation [3,4].

1.1 *Understanding Wound Healing Stages*

Cutaneous wound healing is a dynamic and meticulously regulated process that begins immediately after an injury and can extend for years. The acute healing process traditionally unfolds in four overlapping phases: haemostasis, inflammation, proliferation, and remodeling [3].

1.1.1 *Haemostasis*

Haemostasis marks the first phase of healing, kicking in right after an injury to stem the bleeding. Blood vessels constrict to reduce blood loss, and clotting factors form an act as a protective barrier against bacterial threats [1,3]. This clot also forms a temporary matrix, supporting the migration of cells later on. It acts as a reservoir for growth factors essential for healing [5]. The final role is to prevent blood loss, create a scaffold for immune cells, and guard against infection [6].

1.1.2 *Inflammation*

During the inflammatory phase, the innate immune system responds to clear pathogens from the wound. Once injured, skin cells, such as keratinocytes and macrophages, detect danger signals or pathogen-specific molecules [7].

These molecules are detected by pattern recognition receptors, such as toll-like receptors (TLRs). This detection triggers the inflammatory response, drawing immune cells, such as neutrophils, to the wound site [8]. Moreover, the imbalance between proinflammatory and anti-inflammatory factors plays a crucial role in maintaining the persistent inflammation seen in chronic wound healing [9].

1.1.3 *Proliferation*

The proliferative phase includes Neoangiogenesis, Formation of granulation tissue and extracellular matrix (ECM), and Re-epithelialization [9].

Neoangiogenesis: A critical process in the wound healing cascade that is essential for optimal recovery [9].

Formation of granulation tissue and extracellular matrix (ECM): During the proliferative phase, nutrients and oxygen become critical due to heightened metabolic activity. Likewise, macrophages play a pivotal role in their interaction with fibroblasts, similar to the process in neoangiogenesis [9].

Re-epithelialization: Re-epithelialization involves covering the wound surface with a new layer of epithelium. This process relies on the differentiation, proliferation, and migration of epidermal keratinocytes [9].

1.1.4 *Remodeling*

This phase involves various proteinases that contribute to the coordinated process of wound healing. Their activity is regulated by time-dependent and spatial modifications in expression patterns [9].

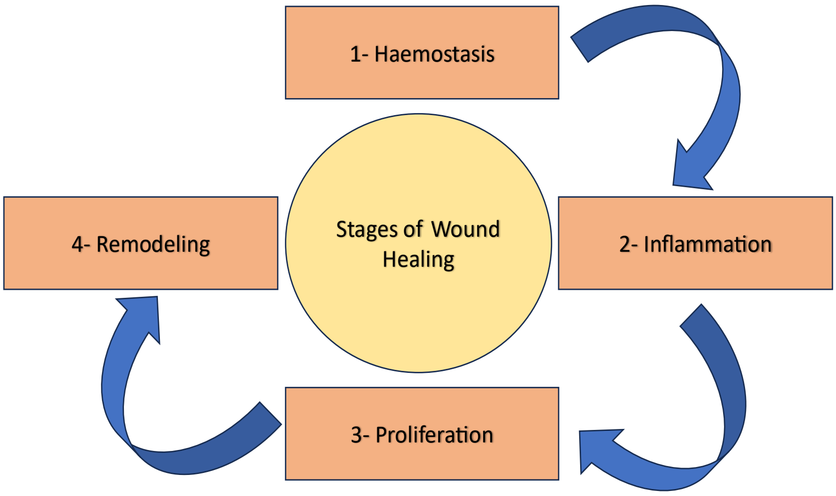

Figure 1. illustrates the four distinct stages of wound healing, providing a clear visual representation of the complex processes involved. By clearly outlining these stages, the figure offers a thorough yet approachable explanation of the body's intricate process of responding to and healing from injury.

1.2 Innovations and Challenges in Wound Healing Treatments

Challenges: For many years, traditional dressings such as cotton wool, lint, and gauze have been widely used to keep wounds clean and prevent bacterial infections. However, these dressings tend to adhere to the wound and do not create an optimal moist environment. Modern dressings, designed with improved biocompatibility, degradability, pain relief, and moisture retention, have been developed to not only cover wounds but also facilitate the healing process. These advanced dressings include hydrocolloid, alginate, hydrogel, foam, and film dressings, which are commonly used in clinical practice [10,11].

Advancements: Researchers have identified key wound-related biomarkers and their corresponding detection thresholds, which are essential for diagnosing poorly healed wounds caused by bacterial infection and inflammation. Recent advances in biomarker detection techniques and sensors have been introduced to aid in understanding modern wound management. These state-of-the-art, innovative wound dressings combine controllable drug delivery, wound monitoring, and on-demand treatment, offering significant progress and promising prospects. Nonetheless, many challenges must be addressed before these innovative wound dressings can be widely adopted in clinical settings [12].

Current wound dressings, such as films, sponges, and hydrogels, continue to play a vital role in clinical wound management. However, these treatments struggle to provide real-time assessment of the wound condition while meeting the dynamic needs of chronic wounds under passive treatment. Prioritizing timely infection detection and appropriate treatment based on wound status is crucial in developing next-generation wound dressings [13].

Advances in material science, particularly in nanotechnology and biosensing, along with extensive research into the healing process, have led to the creation of new functional dressing materials. These innovative dressings can accelerate wound healing and monitor various biological parameters at different stages of healing [14].

1.3 Materials & Methods

To provide a thorough examination of the role of innovative dressings and wearable technologies in wound healing, this review employed a systematic and structured approach to gather, analyze, and synthesize relevant information. The research focused on recent advancements in material science, nanotechnology, and biosensing that have contributed to the development of innovative dressing materials.

These materials are designed not only to expedite the healing process but also to facilitate real-time monitoring of key biological parameters. A comprehensive literature search was conducted using established academic databases, including Google Scholar, PubMed, and Elsevier. The search was limited to peer-reviewed articles published in recent years, ensuring the inclusion of the most up-to-date and relevant studies. Keywords such as "smart dressings," "wound healing," "wearable technology," and "biosensing in wound care" were carefully selected and used in combination to refine the search results. Each retrieved study underwent a critical appraisal process to assess its relevance, methodology, and contribution to the topic. Priority was given to articles that detailed experimental results, technological innovations, or comprehensive reviews in the field of study. By synthesizing the findings from these sources, this review aims to identify trends, highlight key breakthroughs, and discuss the practical implications of these technologies in modern wound care.

2. Wound Classification

2.1 Acute Wounds

Wounds resulting from trauma or surgical procedures generally heal within 30 days, following an orderly process that restores both anatomical structure and function. Acute wounds, in particular, heal in a timely and systematic manner, typically within 5 to 30 days, and are often the result of trauma or surgery. For example, a surgical procedure to remove a skin tumor may leave a non-contaminated wound that cannot heal by primary intention due to tissue loss. Traumatic wounds can involve soft tissue or be associated with bone fractures.

The AO Foundation classification system (originally derived from the German term “Arbeitsgemeinschaft für Osteosynthesefragen”) is commonly used to evaluate such injuries, considering the extent of damage to the skin, muscle, tendon, and neurovascular structures, which in turn influences the prognosis of the injured limb [15].

2.2 Chronic Wounds

Chronic wounds are those that fail to progress through the normal stages of healing in a timely manner, often due to factors such as infection, tissue hypoxia, or excessive inflammation. These wounds are more common in older populations and can include diabetic, pressure, arterial, and venous ulcers [15].

The healing process in chronic wounds is often incomplete and disrupted, with prolonged stages of haemostasis, inflammation, proliferation, or remodelling. Factors like infection, tissue hypoxia, necrosis, excess exudate, and high levels of inflammatory cytokines can contribute to this prolonged state. A persistent inflammatory environment can perpetuate a non-healing state, leading to poor functional and anatomical outcomes and frequent relapses. Chronic wounds can result from various causes, including neuropathic, pressure, arterial and venous insufficiency, burns, and vasculitis [15].

2.3 Complicated Wounds

Complicated wounds, marked by infection and tissue defects, present significant challenges due to the persistent risk of infection and the intricate nature of tissue damage. Infection remains a constant threat, influenced by factors such as the virulence and quantity of microorganisms, local blood supply, and the patient's immune response. Common signs of infection include redness, heat, pain, swelling, and limited function. These wounds can arise from trauma, post-infection scenarios, or extensive tissue resection, such as in tumor management. The severity of infection is contingent on the wound type, surgical technique, and location [15].

3. The Evolution of Wound Dressings

A variety of wound dressings and technologies have been developed to aid the body in closing wounds and repairing damaged tissues. Significant advancements in wound healing technology have often resulted from the independent efforts of scientists and doctors. However, collaboration between medical and scientific fields is essential for translating laboratory discoveries into effective bedside treatments. Examining the history of wound dressings highlights that deeper interdisciplinary collaboration can expedite the development of new wound-healing technologies [16].

3.1 A Historical Overview of Wound Dressings

Since ancient times, wound care methods and materials have evolved significantly. Around 2500 BC, the Mesopotamians documented treatments on clay tablets and cleaned wounds with milk or water before applying dressings made of resin and honey. From 460 to 370 BC, Hippocrates in ancient Greece used wine or vinegar to clean wounds. The Romans made significant contributions by introducing the four cardinal signs of inflammation: rubor (redness), tumor (swelling), calor (heat), and dolor (pain). The advent of antibiotics marked a substantial advancement in antiseptic techniques for infection control. By the twentieth century, modern wound dressings had been developed, and today, over 5000 wound care products are available [17,18].

3.2 Progression in Wound Dressings

Wound dressings now come in a wide range of forms and materials, such as foams, hydrogels, films, and nanofibers/composites, among others [17].

3.2.1 Foams

Foam dressings are absorbent wound coverings that come in the form of sheets or filler chips. Their capacity to absorb exudate depends on their composition and vapor transmission rate. These dressings offer protection against trauma and provide thermal insulation. Reticulated (open-celled) foam, commonly used in negative pressure wound therapy (NPWT), helps remove drainage and debride wounds. However, due to rapid tissue ingrowth, reticulated foam is not suitable for intact skin or epithelialization. Hydrophilic foam dressings, which absorb fluid without the need for vacuum assistance, can promote epithelial migration when compressed against the wound surface. It is important to avoid highly absorbent foams in low-exudate wounds, as they can cause drying [16].

3.2.2 Hydrogels

Hydrogel dressings are insoluble polymers with high water content (up to 96%), available in various forms and compositions, and are being explored for drug delivery. These dressings maintain a moist wound environment and can help reduce inflammation. However, their low absorptive capacity may lead to exudate accumulation, necessitating the use of a secondary dressing. Additionally, their small pore sizes can impede cell migration [16].

Cryogels, a subtype of hydrogels formed at sub-zero temperatures, possess a macroporous structure that addresses the limitations of standard hydrogels. Due to their compressibility and injectability, cryogels are suitable for hemostatic applications and have applications in tissue engineering, cosmetics, cell transplantation, and immunotherapy [16].

3.2.3 Semipermeable Films

Semipermeable films are transparent dressings that allow gas exchange but are impermeable to liquids and bacteria. Their transparency enables wound visualization without the need for removal. These films permit limited oxygen penetration, which can inhibit the growth of anaerobic bacteria, but they do not support tissue growth. While waterproof, they trap fluids, aiding in autolytic debridement, but they can also cause exudate buildup and maceration. The "mean vapor transmission rate" (MVTR), which is influenced by the material and thickness, determines the rate at which water vapor escapes. Low MVTR can result in exudate accumulation, making it an essential factor in film selection [16].

3.2.4 Nanofibers/Composites

Electro-spun nanofibers are an innovative material characterized by fibers in the nanometer range, produced through various techniques such as template synthesis, phase separation, drawing, self-assembly, and electrospinning. Among these methods, electrospinning stands out for its ease of production, simplicity, and scalability. These characteristics enhance cell recognition, mimic extracellular matrix (ECM) structures, and improve protein binding, resulting in superior biocompatibility [17]. Due to their high surface-area-to-volume ratio, excellent porous structure, and flexibility, electro-spun nanofibers are widely used in medical applications, including as scaffolds for regenerative medicine, drug delivery systems, and wound dressings [19,20]. Various polymers have been developed into nanofibrous forms to serve as artificial ECM [21]. Common natural polymers used in electrospun nanofibrous scaffolds include chitosan [22], collagen [23], gelatin [24], and silk. Among synthetic polymers, polylactic acid [25], poly-lactic-co-glycolic acid [26], polyglycolic acid, polycaprolactone [24], and poly-caprolactone/lactide copolymer are the most frequently utilized.

4. The Complexities of Traditional Wound Care

Timely and effective management of chronic wounds is crucial for accelerating healing and alleviating patients' pain. Traditional wound care approaches primarily rely on dressings designed to absorb excessive wound exudate, maintain adequate moisture, and provide a protective barrier against external threats [27,28]. Some of these dressings also include anti-inflammatory drugs, antibiotics, antibacterial compounds, or angiogenic factors, which are gradually released into the wound [29]. While traditional methods have proven effective, they come with notable limitations. One major drawback is the inability to monitor the wound bed status and healing rate in real time, potentially leading to secondary injuries during dressing changes [27]. Typically, clinicians assess wounds through visual inspection, wound sampling, or bacterial cultures, often employing a combination of these methods. These procedures can be invasive, time-consuming, and only provide a snapshot of the wound microbiome at the time of initial sampling. As a result, these methods may lead to misdiagnosis since the wound microbiome could have changed by the time treatment is administered [27].

4.1 Limitations of Traditional Wound Dressings in Chronic and Acute Wounds

Acute and chronic wound infections have emerged as a significant global healthcare burden, leading to high morbidity and mortality rates. Despite extensive research into the underlying mechanisms of infections and the widespread use of standard wound management practices, diagnosing and treating wound infections remain challenging due to factors such as biofilm formation, delayed healing, and drug resistance [30].

Acute wounds, which typically heal predictably, display signs of infection like redness, swelling, warmth, and pus. On the other hand, chronic wounds, such as diabetic ulcers, experience slow healing due to various factors, including aging, diabetes stage, treatment compliance, peripheral neuropathy, a weakened immune system, and blood flow issues. Despite advancements in wound management, scientists and clinicians are continuously seeking new methods to prevent and control infections in both acute and chronic wounds.Acute wounds are generally treated with antibiotics administered intravenously or orally. In contrast, chronic wound infections are often treated with antimicrobial creams, ointments, or gels designed to target deep infections [31].

5. Results

5.1 Overview of Smart Wound Dressings

Researchers have developed a range of wearable devices to monitor human health indicators such as body temperature, heart rate, blood pressure, blood oxygen levels, and sweat markers. These advancements have paved the way for the creation of smart wound dressings, which incorporate sensors to detect physicochemical signals crucial to the wound healing process. These innovative dressings address the limitations of traditional wound care methods by providing real-time monitoring and point-of-care diagnosis. The data collected is transmitted wirelessly, creating a closed-loop system that enables on-demand treatment and ultimately enhances healing outcomes [13].

5.2 The Mechanics of Smart Wound Dressings

Numerous experiments have demonstrated the effectiveness of wound dressings in wound care and treatment, consistently highlighting their positive results. Modern dressings have become a priority in research and development [32,33]. These advanced dressings create a moist environment that is essential for wound healing, pain reduction, and antibacterial effects. Furthermore, modern wound dressings are often infused with bioactive components such as antibiotics, growth factors, herbal extracts, essential oils, antioxidants, anti-inflammatory agents, and vitamins to enhance therapeutic outcomes and address the limitations of traditional dressings. These bioactive components also serve as crucial elements in drug delivery systems [34].

Smart wound dressings have immense potential, but their performance in terms of accuracy, sensitivity, long-term stability, and environmental tolerance needs significant improvement. The complex nature of wound healing, coupled with the moist and protein-rich environment, can compromise the accuracy and sensitivity of wearable sensors. Furthermore, these sensors face substantial challenges when operating under extreme conditions, such as high or sub-zero temperatures. Early-stage changes in biomarker levels indicating wound infection tend to be subtle and are often susceptible to external noise [12].

5.3 Wearable Technology

The shortcomings of conventional wound management have spurred the creation of smart wound dressings. These innovative dressings provide clinicians with a deeper insight into the wound's condition throughout the healing process, enabling swift and precise treatment decisions to promote tissue repair. Researchers have integrated wearable sensors that track wound biomarkers, wireless transmission technology, and sophisticated drug delivery systems into a single, comprehensive dressing. This facilitates remote, real-time monitoring, early diagnosis, and timely, on-demand drug administration [12]. To achieve early detection of wound conditions, various physicochemical markers—including temperature, pH, humidity, inflammatory factors, toxins, and bacterial enzymes—are being investigated [13].

5.4 *Innovative Wearable Solutions for Monitoring Skin Wounds*

5.4.1 *pH*

There are several methods to determine the pH value of wound beds, ranging from optical to electrochemical techniques. In optical methods, pH sensors typically use chemical species that alter their optical properties in response to pH changes. Electrochemical pH sensors are primarily potentiometric and voltammetric. However, potentiometric measurement is preferred for pH wound monitoring due to its high reliability and wide sensing range. Potentiometric sensors work by measuring the potential generated across two electrodes: the working electrode and the reference electrode [27].

5.4.2 *Temperature*

The temperature of the wound environment can be determined using various sensors, such as infrared sensors and resistance temperature sensors. Portable temperature sensing devices based on infrared sensors are frequently used to provide thermal imaging for monitoring clinical tissue structures during wound healing [35].

5.4.3 *Glucose*

The basic concept of a glucose sensor (biosensor) hinges on the fact that immobilized glucose oxidase (GOx) catalyzes the oxidation of glucose by molecular oxygen, producing gluconic acid and hydrogen peroxide. This reaction is common to nearly all glucose sensors based on GOx enzyme sensing. Most studies on glucose sensing for wound healing rely on fluorescent glucose sensing. A fluorescence glucose sensor molecule includes a glucose receptor, a donor fluorophore, and an acceptor of fluorescent energy or electrons. When glucose binds to the receptor, the sensor molecule undergoes a structural change that separates the fluorescence donor and acceptor, reducing electron transfer to the donor. This binding decreases fluorescence resonance energy transfer, resulting in increased fluorescence [27].

5.4.4 *Uric acid*

Most uric acid-sensing techniques for wound healing rely on various types of electrochemical measurements. A smart bandage was developed by screen printing an amperometric biosensor directly onto a wound dressing to determine uric acid levels [36]. This bandage, equipped with a biosensor, was connected to a custom-designed potentiostat that enabled wireless data transfer of uric acid status to a computer or smartphone using radio frequency identification (RFID) or near-field communication (NFC) [27].

5.4.5 *Oxygen*

Most wearable electronic devices developed for oxygen sensing in wounds rely on electrochemical sensors, oximetry, fluorescence, and similar technologies. A flexible thread-based electrochemical sensor was created to monitor oxygen levels. This sensor is minimally invasive and highly flexible, making it suitable for tissue integration [37].

5.4.6 *Moisture*

Most research on moisture sensing for wound monitoring purposes has focused on impedance and capacitive measurements. A textile sensor based on the conductive polymer poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) was developed to monitor the moisture level of wounds by detecting impedance variations. These variations span several orders of magnitude between dry and wet states [38].

5.4.7 *Proteins*

Immunoaffinity techniques, such as the use of aptamers and antibodies, are currently employed to target proteins and are immobilized on electrochemical biosensors as probes [27]. Key factors associated with wound healing are presented in Table 1, alongside the sensors designed to measure them and detailed insights into their operational mechanisms. The table provides a clear and comprehensive overview of how innovative sensor technologies are applied to monitor essential wound parameters, including pH, temperature, moisture, oxygen levels, and specific biomolecules, advancing our understanding of wound care.

6. Discussion

The body's ability to heal skin wounds is a fascinating display of its unique cellular functions [41]. In recent advancements, smart wound dressings have emerged, offering the capability to monitor wound-related biomarkers in real-time, provide early diagnosis, and deliver on-demand treatments for conditions such as bacterial infections and inflammation. These dressings incorporate wearable sensors, advanced drug delivery systems, and wireless communication technology, presenting a significant improvement in wound management [12].

Table 1. Sensor Technologies for Monitoring Key Wound Healing Parameters

Factors	Measurement Sensors	Sensor Functionality	Reference
pH	Potentiometric/ voltammetric	Potentiometric measurement stands out as a preferred method for pH monitoring in wound care, offering remarkable reliability and an extensive sensing range.	[27]
Temperature	Infrared sensors/ resistance temperature sensors	Portable temperature sensing devices utilizing infrared sensors are commonly employed to deliver thermal imaging, enabling the monitoring of clinical tissue structures throughout the wound healing process.	[35]
Glucose	Fluorescence glucose sensor	When glucose binds to its receptor, the sensor molecule undergoes a structural rearrangement that increases the separation between the fluorescence donor and acceptor, thereby decreasing electron transfer to the donor.	[39]
Uric Acid	Amperometric biosensor	A smart bandage was created by integrating an amperometric biosensor onto a wound dressing through screen printing, enabling the detection of uric acid levels.	[36]
Oxygen	Electrochemical sensors/ oximetry/ fluorescence/ similar technologies	A flexible, thread-based electrochemical sensor was developed to measure oxygen levels. Its high flexibility and minimally invasive design make it well-suited for seamless integration with tissue.	[37]
Moisture	Textile sensor	A textile-based sensor utilizing the conductive polymer PEDOT: PSS was designed to monitor wound moisture levels by measuring changes in impedance.	[38]
Proteins	Electrochemical biosensors	Immunoaffinity techniques, including aptamers and antibodies, are widely used to target specific proteins and are immobilized on electrochemical biosensors, serving as effective probes.	[40]

Clinicians require smart wound dressing systems that can offer real-time updates on wound status and enable remote-controlled treatments. With wireless transmission technologies like Bluetooth, near-field communication, and radio frequency identification, sensors within these dressings can collect biomarker data and transmit it to mobile devices such as smartphones, allowing patients to monitor their wounds from home [12]. The development and design of wearable intelligent sensors hold substantial promise for public health monitoring and healthcare applications. Although this field is still in its nascent stages, foundational research in the interdisciplinary area of wearable sensing is well-established. Intelligent wearable sensors provide unprecedented data and convenience, aiding in the effective management of patient wounds. These advanced dressing sensors offer real-time information about wound characteristics to both doctors and patients [42].

Innovations in new material platforms for modern dressings have led to significant product advancements, as demonstrated by positive test results. The current trend in developing ideal dressings focuses on combining materials with exceptional benefits crucial for the wound healing process [10,43].

7. Conclusion

The primary goal of all wound care is to achieve complete and timely wound closure, though this is not always achievable. Chronic wounds, in particular, present significant challenges for effective treatment. Most clinical guidelines continue to evolve due to ongoing advancements in wound pathology, healing processes, and therapeutic agents. Wound management is inherently complex, with the success of treatment dependent on various factors, including accurate diagnosis, patient comorbidities, anatomical location, physiological status, and wound size. Hence, it is generally recommended that dressing selection be tailored to the specific needs of the wound and patient, guided by the expertise of physicians specializing in wound treatment.

This personalized approach ensures that patients receive the most appropriate treatment tailored to their unique situation, thereby maximizing efficacy and minimizing unnecessary risks during the healing process.

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Authors’ contributions

S H: Conceptualization of the review, primary drafting of the manuscript, and coordination of revisions. M P: Contributed to the design and structure of the review, critical revision of content, and interpretation of data from literature sources. Y Gh: Assisted with literature search, data collection, and initial drafting of sections related to biomaterials and their applications. MS N: Provided input on the technical aspects of wound dressings, assisted in analyzing data, and contributed to manuscript editing. MS N and SM T: Involved in drafting and revising the manuscript, with a focus on the biomedical engineering aspects, and provided critical feedback on the review’s final version. All authors discussed the results and contributed to the final manuscript. All authors have read and approved the final version of the manuscript for publication.

Conflict of interest

No potential conflict of interest was reported by the authors.

Ethical declarations

Not applicable.

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