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INTERNATIONAL SYMPOSIUM ON INNOVATION AND TECHNOLOGY
QUANTUM TECHNOLOGIES: The information revolution that will change the future
International Year of Quantum Science and Technology
SENAI CIMATEC UNIVERSIDADE

Electrochemical biosensors for the transducing of pH as a biomarker, focusing on smart bandage approaches for chronic wounds: a brief review

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Abstract: Chronic wounds represent a major global health burden, often leading to limb amputation and high treatment costs. Real-time monitoring of wound biomarkers, particularly pH, plays a critical role in guiding clinical decisions and improving patient outcomes. This review explores recent advances in electrochemical pH biosensors, focusing on their integration into smart bandage systems. pH fluctuations in the wound microenvironment serve as reliable indicators of infection and healing progression, making pH a key target for biosensing technologies. We discuss the fundamental principles of biosensor operation, with emphasis on electrochemical modalities—such as conductometric, potentiometric, amperometric, voltametric, and impedimetric sensors—and their performance parameters including sensitivity, biocompatibility, and response time. Challenges in sensor miniaturization, long-term stability in exudate-rich environments, and large-scale manufacturing are also addressed. Furthermore, we highlight the potential of printed electronics, conductive polymers, and wireless data transmission as enablers for flexible, cost-effective, and wearable pH sensing platforms. By enabling continuous, non-invasive monitoring of chronic wounds, smart dressings incorporating pH biosensors have the potential to transform wound care through early infection detection and personalized therapeutic delivery.

Keywords: Smart Bandages. Chronic Wounds. Biomarkers. Sensors. pH.

Abbreviations: BLE, Bluetooth Low Energy. C, Carbon. FET, Field-Effect Transistor. IDF, International Diabetes Federation. IrOx, Iridium Oxide. ISFET, Ion-Sensitive Field-Effect Transistor. NFC, Near Field Communication. PANI, Polyaniline. PEDOT:PSS, Poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate). Pt, Platinum. PVB, Polyvinyl Butyral. SBACV, Brazilian Society of Angiology and Vascular Surgery. SUS, Unified Health System (Sistema Único de Saúde). USD, United States Dollar.

1. Introduction

Chronic wounds are skin injuries that remain in the inflammatory state for extended periods of time and show difficulty healing, taking weeks or even months to recover. Their occurrence is often linked to conditions such as diabetes, vascular insufficiency, pressure ulcers, chronic infections, autoimmune diseases, and skin cancer. Under normal circumstances, following a superficial injury, the human body activates several systems to meet the increased metabolic demand for proteins, aiming to cleanse the wound surface and eliminate invasive material, thereby restoring approximately 70% of the skin's normal function. In individuals with diabetes, however, poor blood circulation often occurs, which limits oxygenation and the delivery of proteins necessary for tissue repair [1, 2, 3].

In terms of impact, chronic wounds cause not only physical and psychological suffering but also financial burdens. The statement is since 18% of individuals with diabetes develop chronic wounds and considering data from the International Diabetes Federation (IDF), approximately 537 million people worldwide (10.5% of the global population) are diabetic, demonstrating the financial impact of treating chronic wounds. In the United States, chronic wound care costs around USD 25 billion annually, and other estimates suggest that developed countries spend approximately 2–4% of their annual healthcare budgets on this type of medical treatment. In Brazil, the Oswaldo Cruz Foundation estimates that 5 million Brazilians suffer from chronic wounds. Data from the Unified Health System (SUS) and the Ministry of Health indicate that chronic wound treatments account for 8% of all hospitalization expenses, with costs averaging 60% higher than other treatments. Also in Brazil, according to the Brazilian Society of Angiology and Vascular Surgery (SBACV), historical data from 2012 to 2023 show that 282,000 lower limb amputations related to diabetes were performed within the SUS—an average of 85 amputations per day [4, 5, 6, 7, 8].

Different approaches have been recommended for the treatment of chronic wounds, including the appropriate selection of dressings based on the etiology of the lesion.[9] Conventional dressings serve to protect damaged tissue from environmental factors that could hinder the healing process. However, this approach is passive and does not provide any information about the current status of the wound. As a result, it relies heavily on the expertise of healthcare professionals, whose decisions are based on visual and sensory observations such as wound size, color, odor, and the amount of exudate. Additionally, frequent dressing changes are common, which can interfere with healing by exposing the wound to microorganisms and causing damage to newly formed tissue. In this context, smart dressings have emerged as a solution, capable of providing real-time physicochemical data from the wound site.

These devices help minimize complications related to dressing changes and can detect infections by analyzing biological indicators commonly referred to as biomarkers. Among the biochemical parameters associated with the wound microenvironment, pH has emerged as a critical biomarker, providing valuable information about infection status and healing progression. Healthy skin exhibits an acidic pH (4.0–6.0), which supports fibroblast activity, angiogenesis, and bacterial control. However, when the skin is injured, the exposed tissues tend to show elevated pH values, especially in infected or poorly healing wounds, where levels may reach up to 10.0. These changes can disrupt cellular signaling and exacerbate inflammation [5].

Therefore, monitoring pH in real time offers an effective strategy to assess the wound condition and support timely therapeutic interventions. In this context, electrochemical biosensors integrated into smart bandages offer a promising solution for continuous, non-invasive pH monitoring in chronic wound care. Thus, this study aims to provide a brief review of electrochemical biosensors for pH monitoring in chronic wounds, focusing on their integration into smart bandage systems, recent technological advances, transduction mechanisms, and clinical challenges. For this purpose all references was searching on Clarivate Web of Science databases, using “*electrochemical*”, “*pH sensors*” and “*chronic wounds*” as key words.

TABLE 1. BIOMARKERS IN CHRONIC WOUNDS

Biomarker Type	**Biomarker**	**Indicator**	**Transduction (input – output)**	**Ref**
Physical	Size	Healing or deterioration	Mechanical to Biolectrical	[5]
	Colour	Healing or deterioration	Optical to Optical	[6]
	Temperature	Infection, Inflammation and Oxygenation	Thermodynamic to Electrochemical or Optical	[6]
	Moisture	Healing or infection	Fluidics to Electrochemical	[6]
	Mechanical Forces	Healing	Mechanical to Bioelectrical	[5]
Chemical	pH	Infection	Chemical to Electrochemical or Optical	[6]
	Oxygenation	Hypoxia and Agiogenesis	Biochemical to Electrochemical	[6]
	Biological Charge	Infection	Biological to Electrochemical	[6]
	Enzimes	Abnormalities such as infection	Biochemical to Electrochemical	[6][10]

2. Biomarkers and Transduction in Smart Dressings

The monitoring of chronic wounds increasingly relies on biosensors capable of transducing physical, chemical, and biological parameters into measurable signals. Among the key biomarkers used for wound assessment are temperature, moisture, oxygenation, enzymatic activity, and particularly pH, which stands out for its diagnostic relevance in detecting infection and tracking healing stages [5, 6, 1110].

3. pH and Biosensors Fundamental Concepts

Biological sensors, commonly referred to as biosensors, are defined as devices that transduce biological/biochemical parameters into various physical/chemical signals. Examples of biosensors include magnetic, thermal, piezoelectric, and optical types. With usage directly related to the need for qualitative assessment of infections in chronic wounds, pH biosensors are basically divided into two main classes: colorimetric and electrochemical [11, 14].

Colorimetric pH biosensors are devices that perform transduction based on the optical sensitivity of light (color/brightness) to identify the presence of hydrogen ions in biological materials. This type of transducer is characterized by high sensitivity, selectivity, and rapid detection. They are divided into two groups according to the detection mechanism. The first type is a detection technique that includes markers attached to the receptor, which help produce colored or fluorescent flash signals after sensor binding. The second type is defined as a marker-free process, which includes direct interaction between the analyte and the receptor. Colorimetric biosensors are divided into five different types based on their optical output: fluorimetric, luminometric, colorimetric, optical fiber, and plasmonic resonance. They are designed to be robust, easy-to-use dressings and can be employed without integrated electronic instrumentation. The advantages of these biosensors are low-cost manufacturing, visual estimation, and no need for probes (e.g., smartphone). The disadvantages include possible biocompatibility issues of the dye, need for probes (e.g., optoelectronic probe), and the requirement for algorithm development [10, 11, 15].

Electrochemical biosensors are defined as devices that perform the transduction of electrochemical parameters from biological systems into electrical parameters such as voltage, current, and impedance. They are extensively employed due to their high selectivity, sensitivity, and detection capability. The advantages of these biosensors are lower cost, simplified operation, low-waste manufacturing, potential for large-scale production, and high versatility. The disadvantages include long detection time, difficulty in miniaturizing potentiostats, need for external power sources, possible electrode fouling in contact with wound fluid, and low repeatability, stability, and adaptability to more complex clinical samples [10, 11, 15].

The basic structure of a biosensor consists of five main components (**Figure 1**): the analyte, which is the biological material containing the target parameters (such as viruses or bacteria); the receptor, composed of specific biological molecules—such as enzymes, antibodies, or nucleic acids—responsible for selectively interacting with the analyte; and the transducer, typically electrodes, which convert this interaction into an electrical signal proportional to the analyte concentration. Electrodes are classified into three types: working (where the reaction occurs), reference (with a known and stable potential), and counter (which completes the circuit and stabilizes the voltage). The generated signal is processed by an electronic system, including amplifiers and processors, and displayed on a readout device, such as a computer or smartphone, which translates the signal into interpretable graphical data.

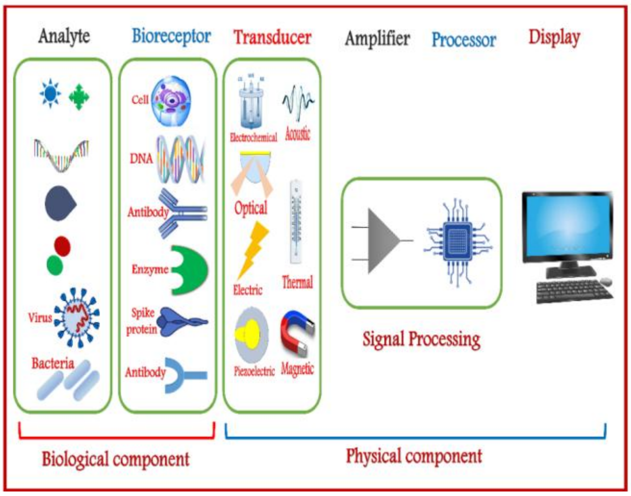

Figure 1. Biosensor structure. Source: Noori and Abdulameer [10].

3.1. Conductometric

This work by measuring a variation in electrical conductivity resulting from redox reactions between receptors and analytes, occurring between the working and reference electrodes. When an interaction occurs between receptors and analytes, such as the action of enzymes, changes in ion numbers may occur, altering the sensor's conductivity [10].

The conductivity of the conductometric electrochemical sensor results in the dissociation of the dissolved substance, an electrolyte, into ions, and their migration through an electric field. When a potential difference is applied to the electrode, there is an electric field within the electrolyte, making so that the movement of the ions is influenced by the orderly and opposite movement of the ions (those with negative charge move toward the anodes, while those with positive charge move toward the cathodes). Thus, the electric current in the electrolyte occurs, caused by the movement of ions toward the electrodes, where the ions are neutralized and isolated as atoms or neutral molecules [19].

Conductometric transducers present a series of advantages compared to other electrochemical sensors. These advantages are lack of sensibility to light, not requiring reference electrodes, can be miniaturized, and thin-film manufacturing technology is applicable to this type of sensor. One disadvantage is the wave frequency, which can affect the performance of the biosensor. At low frequencies, the biosensor presents a capacitive response, measuring capacitive properties of the interface between the electrode and the solution, instead of detecting pH changes [10, 16, 20].

3.2 Potentiometric

Operate by measuring the resulting electric potential on the surface of a working electrode with accumulated charges, when the current is equal to zero. When biological molecules interact with the analyte, there is either consumption or production of charged species that accumulate selectively on the electrode surface [10].

Potentiometric transducers can be ion-selective electrodes, which are electrochemical sensors and may be made of thin films or selective membranes, acting as the recognition element for the desired material in the sensor. ISFETs (Ion-Sensitive Field-Effect Transistors) are examples of electrodes using FET transistors, which are used to determine ion concentrations and consist of an ion-selective membrane applied directly to the insulated gate of the FET [10, 16].

Conductive polymers could selectively detect ions, however, the choice of polymer is very important, as it defines the sensor's application, sensitivity, and selectivity. One polymer used for pH measurements is polyaniline (PANI), due to its high conductivity, ease of synthesis, and stability. Andrade et al. developed a potentiometric sensor placed on a band-aid, using PANI as the working electrode and polyvinyl butyral (PVB) as the reference electrode (Figure 1). The results showed the efficiency of a potentiometric sensor with a Nernstian response of -58 mV/pH in the pH range of 4.35 to 8.00, with a response time of less than 20 seconds. The authors also reported that after 1000 bending cycles, the band-aid showed the same Nernstian response as before [17].

3.3. Amperometric

Operate by measuring a variation in electric current resulting from oxidation and reduction reactions when the voltage at the working electrode is constant relative to the reference electrode. Typically, a working electrode made of Pt, Au, or C is used, or a set of electrodes relative to a reference electrode, which also serves as an auxiliary electrode. The currents for this type of sensor need to be in the order of 10^{-6} to 10^{-9} A [10, 16].

3.4. Voltammetric

These operate by applying an electric current through oxidation and reduction reactions when the voltage applied to the working electrode is not fixed [10].

3.5. Impedimetric

These operate by measuring the electrical impedance of oxidation and reduction reactions between the working electrode and the solution when voltages are applied over a range of different frequencies [10].

4. Specific Applications for Smart Bandages

The development of pH biosensors applied to smart dressings requires the observance of essential technical criteria to ensure functionality, biological safety, analytical precision, and clinical applicability. The main requirements include flexibility and conformability to the skin surface, biocompatibility, stability under wound microenvironment conditions, high sensitivity and selectivity within the physiological pH range, fast response time, and feasibility for large-scale production.

The use of conductive polymers with a well-established biomedical history is an important advantage, as it reduces the risk of rejection or inflammation in adjacent tissues [6, 22, 23].

Maintaining functional stability under adverse conditions is a critical requirement. Sensors with carbon electrodes have shown reproducibility within physiological pH ranges, but the time limitation of 125 minutes is still insufficient for long-term clinical applications. The durability of sensors with PANI and PEDOT:PSS for up to 7 days is a relevant advantage. However, these materials are susceptible to oxidation and chemical degradation in the presence of complex exudates [6, 21, 23].

Electrochemical sensors with low Nernstian response offer high precision in the clinical interest range, which is essential for monitoring inflammatory or infectious processes. Systems with PEDOT:PSS/IrOx ensure high response current but are subject to electrochemical instability in high-humidity environments. Obtaining responses within seconds is a clear advantage for immediate clinical interventions. Colorimetric and electrochemical sensors with reading times under 1 minute are effective for continuous monitoring [6, 21, 23].

The production of sensors with a thickness below 620 µm and unit cost under US$ 1 represents an efficient solution for technological democratization and large-scale application. Methods such as screen printing and spray coating are suitable for industrial environments and allow high reproducibility. However, miniaturized sensors may suffer losses in electrochemical performance, especially if there is no proper control of the uniformity of the active materials. Direct printing on disposable substrates, such as treated paper and medical cotton, is advantageous due to its simplicity and accessibility, but these materials are more vulnerable to moisture and mechanical degradation, which may compromise sensor durability. The economic viability is clear, but the challenge lies in balancing cost, stability, and analytical fidelity [6,12,21,22,23,24].

In summary, pH biosensors used in smart bandages combine optical and electrochemical strategies with flexible and biocompatible materials, ensuring precise, responsive, and accessible readings of the chronic wound microenvironment. The choice between technologies — encapsulated dyes versus electronic reading — will depend on clinical need, cost, robustness, and integration requirements with mobile or therapeutic platforms.

The integration of pH biosensors with smart dressing platforms is essential to enable continuous, safe, and effective monitoring of the wound microenvironment. This integration involves four main dimensions: wireless communication, energy management, data processing, and user interface. The transmission of data collected through wireless connectivity can be performed by sensors and is enabled by technologies such as Bluetooth Low Energy (BLE) and Near Field Communication (NFC), which offer low energy consumption and compatibility with mobile devices. An example was systems with Bluetooth sensors for simultaneous monitoring of pH and oxygen demonstrated in functional dressings [6].

4. Conclusion

Chronic wounds pose a significant burden to healthcare systems worldwide. Real-time monitoring of biomarkers, particularly pH, is crucial for reducing costs, enhancing patient comfort, and improving clinical outcomes. This review highlights recent advances in pH biosensing using flexible substrates and their integration into smart bandages. Despite ongoing challenges—such as monitoring large wound areas and developing biocompatible, low-cost materials—emerging technologies like artificial intelligence and smart drug delivery hold great promise for transforming wound care.

Acknowledgement

The authors would like to thank SENAI CIMATEC for financial supporting of this work.

References

[1] Frykberg, R. G., & Banks, J. (2015). Challenges in the Treatment of Chronic Wounds. Advances in Wound Care, 4(9), 560–582. DOI: 10.1089/wound.2015.0635.

[2] G. Han, R. Ceilley. "Chronic Wound Healing: A Review of Current Management and Treatments". Adv Ther (2017) 34:599–610.

[3] Armstrong, D. G., et al. (2017). Diabetic Foot Ulcers and Their Recurrence. New England Journal of Medicine, 376(24), 2367–2375. DOI: 10.1056/NEJMra1615439

[4] Jamal Hossain, Al - Mamun, Rabiul Islam. Diabetes mellitus, the fastest growing global public health concern: Early detection should be focused. Health Sci Rep. 2024 Mar 22;7(3):e2004. doi: 10.1002/hsr2.2004.

[5] M. Jose et al. Convergence of biocompatible printed electronics and sensing in wound dressings: a leap forward in sustainable health monitoring. npj Flexible Electronics | (2025) 9:46. https://doi.org/10.1038/s41528-025-00421-8

[6] H. Derakhshandeh et al. Smart Bandages: The Future of Wound Care. Trends in Biotechnology, December 2018, Vol. 36, No. 12. https://doi.org/10.1016/j.tibtech.2018.07.007

[7] Ministério da Saúde. POLÍTICA NACIONAL DE REDUÇÃO DA MORBIMORTALIDADE POR ACIDENTES E VIOLÊNCIAS. Available in: bvs.saude.gov.br/bvs/saudelegis/gm/2017/MatrizesConsolidacao/comum/37526.html

[8] SBAVC. Brasil bate recorde de amputações de pés e pernas em decorrência do diabetes. Available in: Brasil bate recorde de amputações de pés e pernas em decorrência do diabetes – SBACV.

[9] SHI, Chenyu et al. Selection of Appropriate Wound Dressing for Various Wounds. Front. Bioeng. Biotechnol. Sec. Biomaterials, v. 8, 2020. DOI: https://doi.org/10.3389/fbioe.2020.00182

[10] H. N. Noori and A. F. Abdulameer. "A Review of Biosensors; Definition, Classification, Properties, and Applications." Iraqi Journal of Science 64. 2023. pp. 5665-5690. DOI: 10.24996/ijs.2023.64.11.18

[11] H. Derakhshandeh, S. S. Kashaf, F. Aghabaglou and I. O. Ghanavati, A. Tamayo. "Smart Bandages: The Future of Wound Care." Trends in Biotechnology 36. 2018. pp 1259-1274. https://doi.org/10.1016/j.tibtech.2018.07.007

[12] K. Youssef, A. Ullah, P. Rezai, A. Hasan and A. Amirfazli. "Recent advances in biosensors for real time monitoring of pH, temperature, and oxygen in chronic wounds." Materials Today Bio 22. 2023. Pp.1-18. https://doi.org/10.1016/j.mtbio.2023.100764

[13] B. Adhikari and S. Majumdar. "Polymers in sensor applications." Progress in Polymer Science 29. 2004. pp. 699-767. https://doi.org/10.1016/j.progpolymsci.2004.03.002

[14] P. Mehrotra. "Biosensors and their applications – A review." Journal of Oral Biology and Craniofacial Research 6. 2016. pp. 153-159. http://dx.doi.org/10.1016/j.jobcr.2015.12.002

[15] A. Pusta, M. Tertis, C. Cristea and S. Mirel. "Review Wearable Sensors for the Detection of Biomarkers for Wound Infection." Biosensors. 2022. 12. pp. 1-20. https://doi.org/10.3390/bios12010001.

[16] D. R. The´venot, K. Toth, R. A. Durst and G. S. Wilson. "Mini-Review ElectroChemical Biosensors: Recommended Definitions and Classification." Analytical Letters. 34(5). 2001. pp. 635–659.

[17] M. T. Ghoneim, A. Nguyen, N. Dereje, J. Huang, G. C. Moore, P. J. Murzynowski, and C. Dagdeviren. "Recent Progress in Electrochemical pH-Sensing Materials and Configurations for Biomedical Applications." Chemical Reviews 119. 2019. Pp. 5248-5297. DOI: 10.1021/acs.chemrev.8b00655

[18] O. V. Soldatkina, O. O. Soldatkin, T. P. Velychko, V. O. Prilipko, M. A. Kuibida and S. V.

Dzyadevych. “Conductometric biosensor for arginine determination in pharmaceutics.” Bioelectrochemistry 124. 2018. pp 40-46. https://doi.org/10.1016/j.bioelechem.2018.07.002

[19] N. Jaffrezic-Renault and S. V. Dzyadevych. “Review Conductometric Microbiosensors for Environmental Monitoring.” Sensors 8. 2008. pp. 2569-2588.

[20] M. Salman and M. Aslam. “Three-Dimensional Conductometric Network Based on Reduced Graphene Oxide for Soil pH Sensors.” ACS Applied Nano Materials 6. 2023. Pp. 17376-17386. https://doi.org/10.1021/acsanm.3c02033

[21] LU, Zhiwei et al. Ionic liquid/poly-L-cysteine composite deposited on flexible and hierarchical porous laser-engraved graphene electrode for high-performance electrochemical analysis of lead ion. Electrochimica Acta, v. 295, p. 514–523, 2019. DOI: https://doi.org/10.1016/j.electacta.2018.10.176.

[22] MOTA, Fátima A.R. et al. Biomarkers in the diagnosis of wounds infection: An analytical perspective. TrAC - Trends in Analytical Chemistry, v. 143, p. 116405, 2021. DOI: https://doi.org/10.1016/j.trac.2021.116405.

[23] SZUNERITS, Sabine et al. Biosensors integrated within wearable devices for monitoring chronic wound status. APL Bioengineering, v. 9, p. 010901, 2025. DOI: https://doi.org/10.1063/5.0220516.

[24] YANG, Chengduan et al. The trends in wound management: sensing, therapeutic treatment, and "theranostics". Journal of Science: Advanced Materials and Devices, v. 8, p. 100619, 2023. DOI: https://doi.org/10.1016/j.jsamd.2023.100619.

[25] QUIN, Mei et al. Advances in flexible and wearable pH sensors for wound healing monitoring, 2019 J. Semicond. 40 111607. DOI: https://doi.org/10.1088/1674-4926/40/11/111607.