

Next Generation Smart Bandage with AI Driven Solutions for Chronic Wound Management

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Abstract

There are serious problems with chronic wounds like bedsores and diabetic ulcers, which are observed and treated with the current wound care methods that mainly use traditional bandages. These bandages only provide basic security and are unable to track wound data like infection and SpO₂ levels. This may lead to delayed detection of problems and prolonged healing times. A smart bandage with several sensors is proposed in this method to overcome the limitations. The developed system's temperature, pH and SpO₂ sensors are mostly used to monitor the wounds. Data from these different sensors is processed by an embedded TinyML-based AI system to assess and provide wound healing stages, detect infections, and notify users regarding infection levels. Important measures, including temperature, pH, and SpO₂ levels, are displayed in a developed application so that patients and doctors can track progress and receive real-time notifications. Using machine learning algorithms, the data will analyze the wound healing phases and also have the ability to perform real-time monitoring and infection detection quickly. This smart sensor represents a significant advance over traditional approaches for better wound care management.

Keywords: Smart Bandage, Sensors, Chronic Wound, Wound Monitoring, Artificial Intelligence, Machine Learning

1. Introduction

Chronic diseases like diabetic ulcers, bedsores and other complex wounds require more advanced systems for continuous monitoring and effective treatment for the patients. In the early days, the complications of these diseases, including severe infection, tissue damage and insufficient healing conditions, could not be detected using traditional wound care techniques, which involved no active treatment and frequent changing of bandages for patients. These kind of methods are particularly difficult for older patients and for those who cannot afford medical services, as they require extra care and monitoring of the wounds. The proposed system introduces a smart bandage with built-in sensor technology and a real-time monitoring process for the wound care. Many existing methods either have unreasonable costs, lack of diagnostic capabilities, or fail to take consider important needs such as tissue swelling, infection identification and individual treatment. Additionally, these systems are not affordably designed, lacking the requirements for poor and elderly people, and they do not feature user-friendly interfaces.

This study develops a unique Smart Bandage for Chronic Wound Management that overcomes these problems by implementing modern sensors, real-time monitoring, and intelligent data processing into a portable, affordable device. The smart bandage includes temperature, moisture, pH and oxygen sensors are all included in the smart bandage to continuously track the severe wound details. The collected data from the sensors is processed by an AI-powered algorithm that offers early identification of complicated diagnosis and healing conditions. Additionally, this system has an IoT remote access connection with a basic online dashboard for tracking important features and automated alerts for unusual symptoms in patients, allowing caretakers or doctors to take immediate action. This smart system allows for advanced real-time diagnostics and of patients, significantly improving upon past methods. The proposed smart bandage method addresses early detection of problems by decreasing dependence on frequent hospital visits. It also improves the patient medical outcomes and quality of life by helping them manage chronic wounds effectively.

2. Literature Review

As the review [1] describes, the AI-generated smart sensors provide real-time skin monitoring, especially for chronic wounds. According to sensing methods such as glucose

level, pH, and temperature, and AI-based analytics like image classification, anomaly detection, and healing predictions, all are categorized in this proposed technology. The article pays attention to the closed-loop capability for smart dressings that provide real-time detection through signal-triggered feedback or on-demand medicine delivery. In this work [2], a bioelectrically made smart bandage model illustrates a new area where bioelectric signals are used for data collection and healing stimulation. This work also shows the healing process based on the electrical indicators mainly used for predictive analysis and AI models. This multipurpose model is a step toward managing self-dressings and combines the therapy and diagnostics process for the patients. The research [3] method investigates the AI algorithms for wound classification, tissue segmentation, and healing prediction, such as deep learning, convolutional neural networks, and machine learning processes. The analysis of different datasets, model performance indicators, and clarification issues are ways to look at this work. According to this review, the image-based AI systems are more reliable today, but they still require real-world validation and standardized datasets to process the wounds. The research [4] explains the possible uses of smart dressings for quick treatment and real-time monitoring. Compared to ineffective bandages, these dressings combine internal electronics with biomaterials to enable multi-modal sensing. An overview of stimuli-responsive materials is one of the primary contributions that produce medicine after AI-mediated signal identification. This study also offers promising treatment by combining AI-based decision-making with smart materials. This review [5] proposed by Dadas focuses on AI-based clinical decision systems for wound care. It examines the implementation of AI models for risk identification and treatment plans for specific patients using Electronic Health Records (EHRs). In this work, four domains for AI applications in patient treatment are categorized: diagnosis, monitoring, wound prediction, and treatment planning.

In the study [6], advanced wound dressings that serve as the physical substrates for AI-enabled systems, such as hydrogels, foams, and electrospun fibers, are reviewed. The work investigates the material-based characteristics that integrate the sensor and release medicine for the patients. This work enhances AI-testing based treatments to overcome the technical difficulties in making these responsive devices biocompatible. This research [7] is the first study that implements the basic foundation for intelligent diagnosis in wound dressings. When AI wasn't established at that time, this work discusses the pH, prediction of infection, and oxygen level biosensors as a path for future integrated AI-based platforms to care for patients.

It is still important to understand how smart bandages have changed from sensor-based intelligent systems. The research [8] reviewed the entire wound material pipeline from the lab to the patients' side. It implements intelligent components, including AI-based devices that examine medical translation, manufacturing, and safety issues. One of the most comprehensive reviews is that it uses different techniques that work together to transform the wound. The importance of AI in real-time wound monitoring is examined in this research [9] by focusing on the accurate management of combining nano sensors and bioinformatics. It examines different case studies that utilize wearable AI platforms, edge computing, and image processing. Data security and ethical safety issues in remote monitoring are the main issues surveyed in this work. An overview of deep learning and sentiment analysis are the techniques used for wound care and skin repair discussed in this research [10]. It offers improved awareness of artificial intelligence (AI) that is used to process non-image-based data for wound treatment by investigating the use of natural language processing (NLP) to evaluate medical notes and patients' queries.

3. System Design

Next Generation Smart Bandage with AI Driven Solutions for Chronic Wound Management is designed with a flexible approach by integrating multimodal sensors. The entire system is designed to execute a particular task and cooperates to provide accurate real-time monitoring and appropriate treatment recommendations. This design simplifies user interaction to perform a particular treatment for chronic wound patients. An overview of the main elements and components that contribute to the system is provided below:

A. Arduino Uno Microcontroller

The Arduino Uno serves as the system's primary processing unit, managing output, control logic, and sensor input. The Arduino platform has been selected because of its ease of use, adaptability, and wide range of library support which are useful in real-time applications like wound monitoring and testing. The AI-based Smart Bandage for Chronic Wound Management system's central processing unit is the Arduino UNO. Based on the ATmega328P microprocessor, the Arduino Uno is a common microcontroller development board made to simplify embedded systems and electronic tasks. It is compatible with a variety of sensors and actuators because it runs at 5V and has 14 digital input/output ports (6 of which can provide PWM outputs, and 6 analog input pins. It has enough space for code and small data storage

with 32 KB of flash memory, 2 KB of SRAM, and 1 KB of EEPROM, which enhances patient outcomes and makes the healthcare system more effective.

B. Temperature Sensor

By measuring the surface temperature of the wound site, temperature sensors [fig 1] can identify early infection symptoms and offer important insights into the healing process. High or varying temperatures in wound care can be a sign of infection, inflammation, or poor blood circulation that can affect the healing process. Doctors can virtually evaluate the state of the wound and modify treatment plans based on accurate, real-time information by integrating a temperature sensor into smart bandages designed to continuously collect and send temperature data. A smart bandage's temperature-sensing technology additionally helps in the early detection of infections and improves the care of chronic wounds by providing information directly to doctors for treatment changes.



Figure 1. Temperature Sensor

C. pH Sensor

A pH sensor [fig 2] built into a smart bandage measures the acidity or alkalinity of the wound conditions and is a key indicator of wound health. The slightly acidic pH of healthy wounds promotes cell activity and inhibits infection, whereas the pH of chronic or infected wounds tends to become more alkaline. A smart bandage's pH sensor continuously monitors the pH levels of the wound and sends real-time data to medical personnel. pH variations may be a sign of issues like infection or delayed recovery.



Figure 2. pH Sensor

D. Arduino IDE

The Arduino IDE is a user-friendly platform that supports C/C++ and comes with libraries to make controlling different hardware components easier. It is used to program the Arduino Uno.

The board is suitable for people of all levels because it is simple to set up the program and connects to a computer via USB. Its ability to efficiently collect, process, and send data in real-time applications has made it an ideal option for projects in robotics, the Internet of Things, and medical monitoring systems.

E. SpO2 Sensor

Sensor-based smart bandages provide an advanced way of wound treatment. These sensors offer real-time information on wound healing by continuously monitoring key variables like temperature, moisture, pH, and oxygen levels. This helps physicians optimize treatment programs, minimize the need for repeated visits, and make quick decisions. Smart bandages improve monitoring and healing quickly. The SpO2 sensor [fig 3] is a useful tool for tracking blood oxygen saturation and particularly helpful in treating chronic wound problems. The amount of oxygen carried by hemoglobin in the blood is indicated, and the sensor monitors peripheral oxygen saturation. Decreased SpO2 values around the wound site could be the result of poor oxygen supply or impaired blood flow, causing a delayed healing process. Physicians can remotely monitor wound conditions and make required medication changes by integrating an SpO2 sensor into a smart bandage, which provides real-time oxygen level data.



Figure 3. SpO2 sensor

F. 16x2 LCD Display

The 16x2 LCD is the key component of user interaction that shows the condition of the system in real time. It allows the user to easily monitor the system by displaying sensor output.

G. UART

UART (Universal Asynchronous Receiver Transmitter) specifications: The LCD contains two rows of 16 characters each, which is enough to display important information without overpowering to the user. This format is very easy for older people to use.

H. Power Supply

An essential part of the smart bandage system is the power supply. It provides the

transmitter with energy to enable a serial connection between the sensors and the microcontroller for effective data transfer. It allows sensor data to be transmitted in real time through Wi-Fi to other devices. Furthermore, UART guarantees minimal power consumption, which is essential for wearable technology, facilitates firmware modifications, sensor calibration, and debugging during development.

I. AI Integrated Microcontroller

A specific kind of microcontroller known as an AI-integrated microcontroller [fig 4] combines hardware and software to execute artificial intelligence (AI) algorithms, such as machine learning (ML) models, in addition to handling standard control tasks. Instead of depending on external computer resources or cloud-based servers, these microcontrollers are designed to handle complicated data locally on the device, or at the edge. This makes it possible to make decisions in real time and respond quickly. It utilizes resources more effectively for applications like embedded systems, wearable technology, and the Internet of Things.

An AI system built into this microcontroller continuously examines sensor data to assess the condition of a wound in real time. The AI provides predictive data by evaluating metrics such as tissue swelling and oxygenation levels, which enables the system to modify treatment recommendations and notify physicians of any issues. By guaranteeing ideal healing conditions and lowering the danger of infections or other complications, the implementation of AI enhances the microcontroller's capacity to deliver active and individualized wound care. In addition to automating data processing, this smart solution helps in decision-making that improves patient outcomes.



Figure 4. AI Integrated Microcontroller ESP8266 NodeMCU Board

J. IoT BOARD ESP8266

The ESP8266 is common Internet of Things (IoT) board that is frequently used to give embedded devices with a Wi-Fi connection. It is widely used in sensor networks, smart home

applications, and other Internet of Things devices because of its affordability, usability, and adaptability. It is the ideal choice for connecting devices to the internet because it has a complete TCP/IP stack and microcontroller functionality. It also supports making smart decisions that improve patient outcomes.

K. Embedded C++

An extension of the C programming language designed specifically for embedded system development is called C++. It is suitable for working with microcontrollers and embedded devices where direct hardware connection is supported for hardware-specific functionality, including managing registers and low-level operations.

L. IoT Cloud

The cloud-based services and infrastructure used to handle and process data produced by Internet of Things (IoT) devices are referred to as IoT Cloud. In addition to enabling remote control and device monitoring options, it offers a platform for securely gathering, storing, analyzing, and visualizing data from connected devices. Devices, sensors, and apps can be easily connected with the IoT cloud to create smart devices that exchange data in real time.

4. Methodology

Using advanced hardware and software, the Smart Bandage System for Chronic Wound Management is designed to deliver real-time monitoring and useful data. Temperature, pH, and SpO2 are measured by flexible sensors, data is processed and sent wirelessly by an MCU. A mobile app warns of infection threats and utilizes AI-powered analytics to identify abnormalities and predict healing developments. By providing individualized care proposals and ongoing monitoring, this approach seeks to improve the treatment of chronic wounds. An overview of the main system architecture and functions is discussed below. Each system component mentioned in fig 5 is important for collecting, processing, and give real-time wound data and treatment recommendations. As the primary microcontroller in a smart bandage, the Arduino Uno receives information from sensors that track wound details like temperature, pH, SpO2, and humidity. To improve wound care, it processes this data and controls interactions with external devices, which enables virtual monitoring and real-time tracking. The DS18B20 sensor is well-suited for temperature monitoring in smart bandages because of its high accuracy

and stability. It offers precise wound temperature measurements, facilitating the early detection of disease and infections. Its long-term biocompatible design provides secure, constant interaction with the wound surface to support efficient real-time health monitoring for the treatment of chronic wounds.

Peripheral oxygen saturation (SpO_2) surrounding the wound site is measured by the MiCSO₂ sensor in the smart bandage. Since adequate oxygen is required for tissue repair, monitoring oxygen levels is vital for assessing wound healing. Low SpO_2 values can indicate delayed healing or poor circulation, allowing for quick action to improve recovery. Real-time data transfer via Wi-Fi is made possible by the smart bandage's UART (Universal Asynchronous Receiver Transmitter), facilitating effective serial connection between the sensors and microcontroller. It guarantees minimal power consumption is also important for wearable technology and helps with firmware upgrades, sensor calibration, and debugging throughout development.

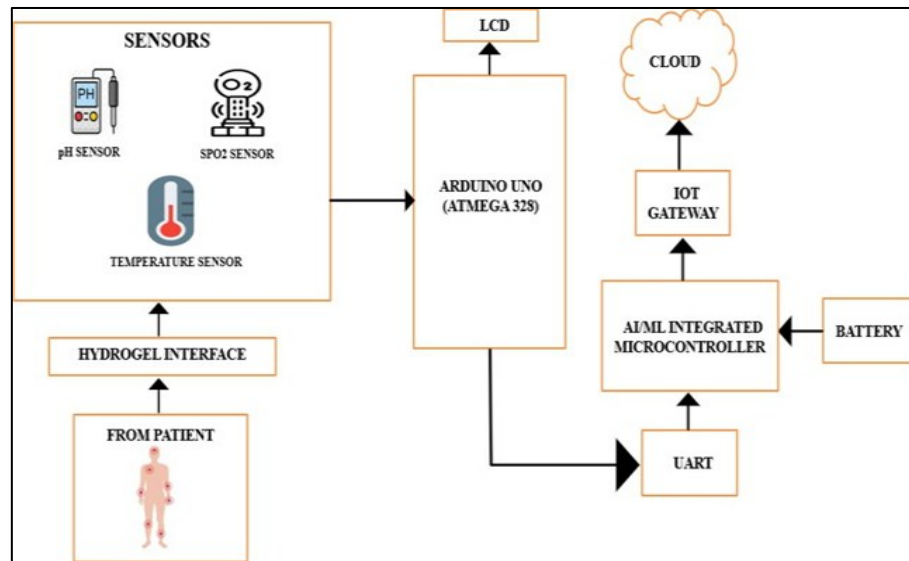


Figure 5. Block Diagram of Proposed System

A. Control Logic Implementation

The temperature, moisture, pH, and SpO_2 sensors provide data to the Arduino. For further investigation of wound conditions, the AI microcontroller uses AI algorithms to process the data. For every parameter, the system compares sensor values to specific requirements. It can identify abnormalities, including low SpO_2 (showing insufficient oxygenation), high temperature (indicating infection), excess moisture (indicating risk of damage), or abnormal pH (indicating infection). The AI microcontroller sends an alert if it detects any abnormalities.

The smart bandage provides real-time feedback by showing the current state of the wound and providing notifications for any unusual situations through a mobile app or any device. Furthermore, data is sent to a cloud-based platform using wireless communication (via Wi-Fi or Bluetooth) so that medical professionals can monitor it remotely. Fig 6 shows the experimental setup.

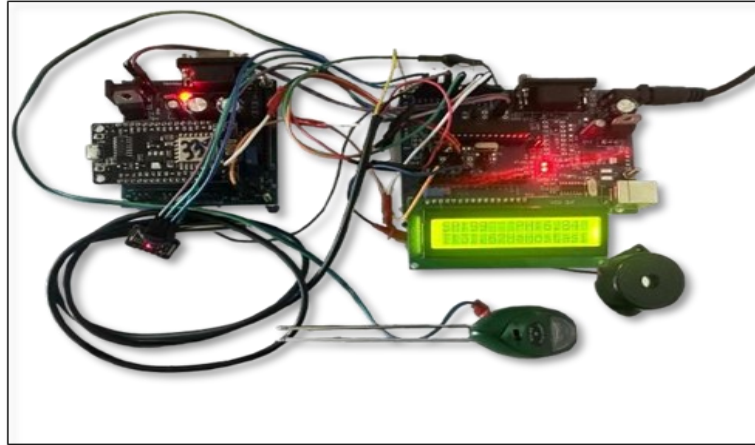


Figure 6. Experimental Setup

5. Discussion

The AI Smart Bandage for Chronic Wound Management combines cutting-edge sensor technology and AI for accurate, continuous treatment, offering a possible solution for the real-time monitoring and management of chronic wounds. This technology aims to completely transform wound care by providing potential cases to identify problems like infection, low oxygenation, or excessive moisture earlier, thereby overcoming critical healing challenges. The accuracy of the system by is discussed in terms of its useful advantage, difficulties encountered, and potential areas for improvement in the below sections below.

A. Accuracy and Precision of Wound Parameter Detection

Accurate real-time wound condition monitoring is one of the smart bandage's main objectives. Temperature, moisture, pH, and SpO₂ sensors are utilized to identify abnormalities that may indicate problems like infections or slow healing. These factors are detected by the system's sensors, which analyze data in real time using the MAX78000 AI microcontroller. The system is trained to identify variations that improve accuracy by using calibrated sensors and AI algorithms. For example, temperature increases may signal an infection, while variations in pH or moisture can indicate other problems affecting wound healing. This high

degree of accuracy enables better treatment planning and quick action especially for patients with severe chronic wounds.

B. Real-Time Monitoring of Wound Stages

The smart bandage's primary goal is its ability to monitor conditions in real time. The microprocessor processes data that the sensors embedded in the bandage continuously collect on a various wound features. AI algorithms analyze this data to find any unusual patterns that may require to handle quickly. Patients with chronic conditions and those unable to frequently contact medical professionals will benefit from this feature. The method prevents additional challenges and encourages the most effective healing by offering immediate feedback, which improves the quality of treatment and enables quick responses.

C. System Cost and Accessibility

One of the biggest challenges in the creation of medical devices is finding a balance between cost and utility. Both patients and physicians can afford the smart bandage because it incorporates dependable but reasonably priced components like communication modules, flexible sensors, and the MAX78000 AI microcontroller. The system can be manufactured at a fair price due to the use of readily available components, which is essential for guaranteeing accessibility in healthcare settings in both urban and rural areas. Additionally, using an open-source software development platform (like the Arduino IDE) lowers development expenses by making customization and future updates easier to achieve. Wireless communication also enables remote monitoring, increasing the system's usefulness without incurring significant additional costs.

D. Safety and Reliability

When unusual measurements, such as high temperature or low SpO₂, are detected, the AI microcontroller analyzes the sensor data and sounds an alarm. This ensures that patients or their relatives are informed as soon as possible by providing alerts via a device or mobile app. The system helps users monitor the healing process and identify issues early by providing constant, real-time data regarding the condition of the wound.

E. Challenges Encountered and Solutions

The optimization of sensor calibration and data processing algorithms was necessary to provide reliable data gathering in a variety of environmental circumstances (such as varying ambient moisture levels). The AI-based systems used to analyze sensor data required training to accurately identify wound problems. This was resolved by improving the accuracy of the machine learning models using a variety of datasets. Because the bandage was wearable, it was essential to optimize power consumption. Energy-efficient sensors and a low-power microprocessor contributed to reducing power usage, and an additional power system ensured continuous monitoring. Simplifying the data visualization on the device was necessary to create a simple user experience for non-expert users, especially elderly patients. Larger text or visual clues for simpler understanding could be added as future enhancements.

F. Potential for Future Improvements

Adding other sensors such as blood pressure or glucose detecting sensors can provide more details of the patient's health and helps to identify problems like diabetic foot ulcers. It may be possible to predict the results of wound healing using historical data by using advanced machine learning models that can allow for preventative measures and preventing problems before they happen. Additional features including specific treatment recommendations, connections with other medical equipment, and improved remote monitoring abilities for medical professionals can be provided by an advanced feature of mobile application. In order to provide an integrated approach for wound care, future works may include advanced functions like AI-driven wound picture analysis or interaction with additional diagnostic instruments.

G. Comparison with Existing Wound Management Systems

Compared with standard wound care techniques, the smart bandage has a number of benefits. Conventional bandages require regular physical supervision and treatment that can be challenging and open to mistakes. On the other hand, the smart bandage offers continuous real-time monitoring, alerting patients and medical professionals of possible problems immediately, most probably lead to improved patient outcomes and a quick response. Additionally, incorporating AI enables automated analysis that is more accurate, decreasing the need for repeated visits to the clinic and particularly treating the wound care.

H. Clinical and Practical Implications

By enabling early detection of diseases, abnormal healing, or other issues, continuous monitoring lowers the risk of serious medical complications and ensures quick management. The technology helps create the most effective situations for wound healing by giving real-time feedback that promotes quicker recovery and improve overall health.

6. Result

Multiple sensors have been integrated into the designed smart bandage to provide real-time monitoring of wound healing. The chosen sensors consist of:

- DS18B20 digital temperature sensor for accurate temperature monitoring.
- MAX30102 SpO₂ sensor for oxygen saturation measurement.
- 3-in-1 pH sensor to monitor wound conditions and detect infection risks.

The values for important physiological parameters related to the various stages of wound healing, including temperature, SpO₂, and pH, are shown in table 1. These limits were determined after a thorough analysis of clinical survey papers and research studies.

Table 1. Physiological Parameters Values for Wound Healing Stages

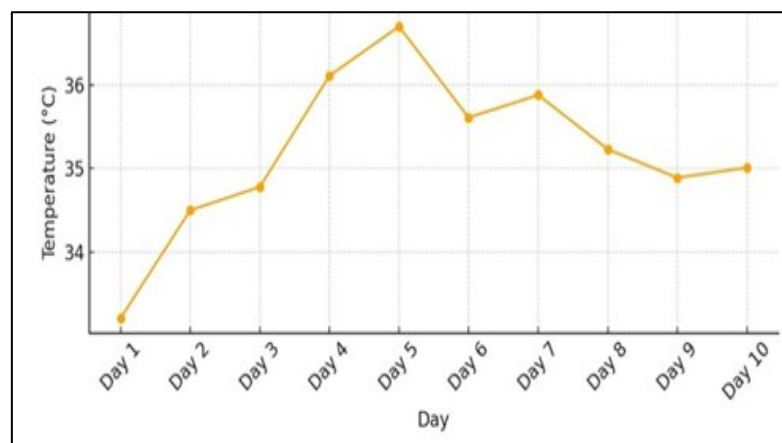
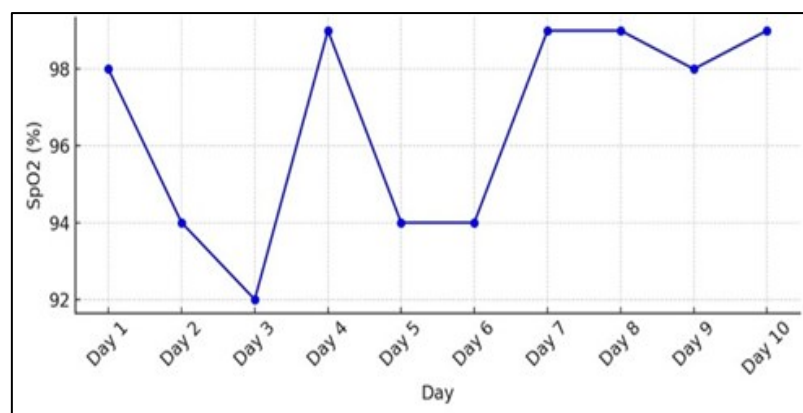
Days	Temperature (°C)	SpO ₂ (%)	pH Level	Healing State
0-1	31.08 – 34.64	90-95	8.02 – 8.66	Hemostasis
1-7	30.88 – 34.44	80-83	7.83 – 8.69	Inflammatory
4-24	31.06 – 34.54	85-95	6.85 – 8.93	Proliferative
21-30	31.06 – 34.54	95-99	6.60 – 8.82	Remodelling

The table 2 represents the data at an initial state of chronic or impaired wound healing that gradually improved over the ten days as indicated by the normalization of temperature, improvement in oxygen saturation, and a favorable shift in pH levels.

Table 2. Real Time Data Collection from the Sensors

Day	Temperature (°C)	SpO2 (%)	pH Level
1	33.21	98	9
2	34.5	94	9
3	34.78	92	8
4	36.11	99	8
5	36.7	94	7
6	35.61	94	8
7	35.88	99	8
8	35.23	99	7
9	34.89	98	7
10	35.01	99	6

Figure 8, 9, 10 illustrates the variations in temperature, SpO2 and pH values over the test trials.

**Figure 8.** Temperature Based Wound Healing Stage**Figure 9.** SpO2 Based Wound Healing Stage

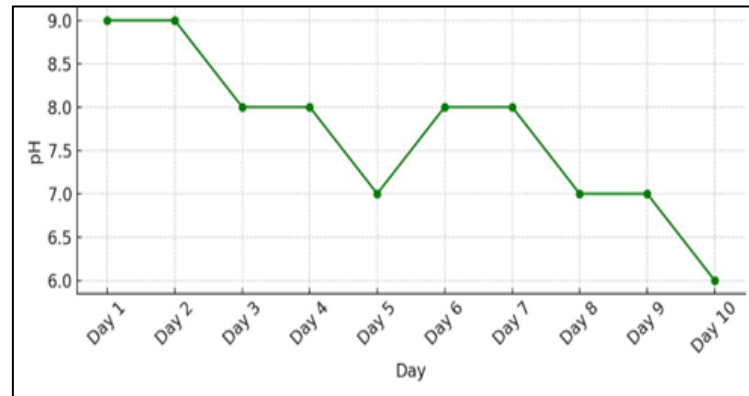


Figure 10. pH Based Wound Healing Stage

An AI model processes the collected sensor data to identify the condition of wound healing. The AI system examines changes in temperature, SpO₂, and pH levels to classify the wound into several healing stages. This predictive analysis increases treatment effectiveness and helps in the early detection of any problems. For sensor embedding, a hydrogel-based polymer matrix mixed with polyvinyl alcohol (PVA) was chosen as the biomaterial. This substance is widely known for its ability to maintain moisture, which makes it appropriate for managing chronic wounds. The hydrogel-PVA combination decreases inflammation and speeds up healing by creating a comfortable breathing environment. The substance is safe for extended skin contact and non-irritating, according to cytotoxicity studies. The results of this study show that it is possible to incorporate several sensors into a biocompatible smart bandage for the purpose of monitoring chronic wounds. AI improves real-time wound diagnosis and offers helpful data about the healing process. The selection of materials ensures both feasibility and patient comfort. Future developments include improving AI algorithms and sensor placement to make more accurate predictions about wound healing.

Challenges

The accuracy of the smart bandage depends on the precision of pH, temperature, and SpO₂ sensors. These sensors might need to be recalibrated over time to manage complicated maintenance. Battery life can be rapidly drained by sensors and wireless communication modules operating continuously. Optimizing power efficiency is still challenging. IoT integration for reliable and secure wireless data transfer in various household and clinical settings is essential. Inaccurate readings could result from changes in wound conditions or

external impacts, triggering unnecessary alarms. Advanced AI-driven filtering is required to enhance security.

7. Conclusion

The Next Generation Smart Bandage with AI Driven Solutions for Chronic Wound Management offers an innovative approach to wound care by combining real-time monitoring, IoT connectivity, and AI-driven analysis into a device that is affordable, easy to use, and effective. The device provides both patients and physicians access to wound healing stages and allows for the early detection of problems like infections or slow healing by continually monitoring the wound measures including temperature, pH, and SpO₂. In addition to increasing diagnosis accuracy, this preventive approach reduces the need for repeated hospital visits by encouraging patients to take care of their own health. The smart bandage was created with patient comfort and continuous tracking in mind and has the potential to revolutionize wound care, particularly for people with long-term illnesses or those living in underprivileged areas. This study offers an effective method for enhancing wound care results by utilizing simple, affordable technology, demonstrating the ability of biomedical engineering to handle complex health issues. More sensors, predictive analytics for individualized care, and more advanced functions like remote monitoring by medical experts are possible future developments. The Smart Bandage has the potential to transform wound care management, improve results for patients, and save long-term healthcare expenses with additional testing and improvements. Finally, this project supports the primary goal of improving healthcare through innovation by integrating accuracy, usability, and continuous improvement to meet essential health requirements. It includes innovative features like remote monitoring by medical specialists.

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