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A Smart Wearable Platform for Real-Time Chronic Wound Monitoring using Embedded-AI

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Abstract **- Chronic wound management requires continuous monitoring to ensure timely healing and prevent infection; however, conventional methods rely on periodic dressing changes at intervals of 24–72 hours, leading to gaps in monitoring. During these intervals, infection-related physiological changes may occur within 6–24 hours, resulting in delayed diagnosis, complications, and extended recovery time. To overcome these limitations, this work presents the design and development of a low-cost, reusable, and wearable wound monitoring system intended for home and rural healthcare applications.The proposed system integrates multiple flexible sensors to continuously measure key wound parameters, including temperature, humidity, pH, oxygen level, and pressure, which are critical indicators of wound condition and healing progression. The system is built around an ESP32-C3 microcontroller with Bluetooth Low Energy capability, enabling real-time transmission of sensor data to a mobile application for remote monitoring and timely-intervention.An embedded Artificial Intelligence model based on Decision Tree logic is implemented to analyze sensor data and classify wound conditions into healing, stable, and worsening states. Furthermore, a closed-loop drug delivery mechanism is incorporated, where a micro peristaltic pump is activated to administer a controlled dosage of medication when abnormal conditions are detected. This transforms the system into an intelligent therapeutic platform. The proposed wearable system bridges the gap between clinical visits by enabling continuous monitoring, early detection of infection, and real-time alerts. It enhances patient safety, reduces healthcare burden, and improves wound management outcomes, offering a scalable and user-friendly solution for advanced wound care applications.**

Keywords - Chronic Wound Monitoring, Smart Bandage, Embedded AI, Wearable Device, Internet of Things (IoT), Sensor Integration, Real-Time Monitoring, ESP32, Biomedical Engineering, Remote Healthcare

I. INTRODUCTION

Chronic wounds, such as diabetic ulcers, pressure sores, and burn injuries, represent a significant challenge in modern healthcare due to their prolonged healing time and high risk of infection. Effective wound management requires continuous monitoring of physiological parameters to ensure proper healing and prevent complications. However, conventional wound care practices rely on periodic inspection and dressing changes at intervals of 24–72 hours. This creates a critical monitoring gap, as infection-related physiological changes can occur within 6–24 hours, often leading to delayed diagnosis, increased risk of complications, extended hospitalization, and higher treatment costs.

In addition, traditional wound dressings lack real-time feedback mechanisms, embedded intelligence, and early warning systems, making them inadequate for proactive wound management. This limitation is particularly significant in home-based and rural healthcare settings, where access to medical professionals is limited.

A. Need for Smart Wound Monitoring

With advancements in wearable technology, Internet of Things (IoT), and embedded systems, there is an increasing demand for intelligent healthcare solutions that enable continuous and real-time monitoring. Smart wound monitoring systems can overcome the limitations of conventional methods by providing continuous data acquisition, early detection of abnormalities, and timely intervention.

The integration of multiple physiological parameters such as temperature, humidity, pH, oxygen level, and pressure offers a comprehensive understanding of wound conditions. Such systems can significantly improve patient outcomes by enabling proactive and personalized wound care management.

B. Proposed System Overview

To address these challenges, this work proposes a smart wearable wound monitoring system that integrates multiple sensors to measure key wound parameters. The system is built around an ESP32-C3 microcontroller with Bluetooth Low Energy (BLE) capability, enabling real-time transmission of sensor data to a mobile application for remote monitoring.

An embedded Artificial Intelligence (AI) model based on Decision Tree logic is implemented to analyze sensor data and classify wound conditions into healing, stable, and worsening states. Furthermore, a closed-loop drug delivery mechanism is incorporated, where a micro peristaltic pump delivers a controlled dose of medication when abnormal conditions are detected. This approach transforms the system into an intelligent and automated wound care platform.

C. Nature of the Research and Problem Statement

The nature of this research is interdisciplinary and application-oriented, combining biomedical engineering, embedded systems, IoT, and artificial intelligence to develop a prototype-based wearable healthcare solution. The system involves both hardware and software components, including sensor integration, embedded processing, wireless communication, and AI-based analysis.

Chronic wound management remains a major healthcare concern due to the lack of continuous monitoring and timely detection of infection. Existing systems are often expensive, complex, and lack real-time intelligence and automated response mechanisms. Therefore, there is a need for a cost-effective, portable, and intelligent system that integrates multi-sensor monitoring, embedded AI, wireless communication, and automated drug delivery to improve wound care management.

II. LITERATURE REVIEW

Recent advancements in chronic wound management have focused on improving early detection of infection and enhancing healing outcomes through technological interventions. Traditional wound care methods primarily rely on periodic inspection and dressing changes, which often fail to provide continuous monitoring and timely identification of complications.

Several studies have explored the use of biosensors to monitor key wound parameters such as temperature, pH, and oxygen levels. These parameters serve as important indicators of infection and tissue condition. However, most existing systems are limited to single-parameter monitoring and do not provide a comprehensive assessment of wound health.With the development of wearable technology and Internet of Things (IoT), smart wound monitoring systems have emerged that enable real-time data collection and remote monitoring. These systems reduce the need for frequent hospital visits and support timely intervention. Despite these advantages, many existing solutions are complex, expensive, and lack embedded intelligence for autonomous decision-making.

Recent research has also incorporated Artificial Intelligence (AI) techniques for wound classification and prediction. Machine learning models can improve diagnostic accuracy but often require high computational resources and cloud-based processing, making them less suitable for real-time embedded applications.To overcome these limitations, there is a need for a low-cost, wearable system that integrates multi-sensor monitoring, embedded AI, and automated therapeutic response. The proposed system addresses these challenges by combining real-time sensing, intelligent analysis, and closed-loop drug delivery into a single platform, making it suitable for practical healthcare applications.

A. Overview of Literature

Chronic wound management has received considerable attention in recent years due to the increasing prevalence of diabetes, vascular disorders, and age-related complications. Various approaches, including advanced wound dressings, smart materials, biosensors, and wearable monitoring systems, have been explored to enhance healing outcomes and reduce infection risks. Studies emphasize the importance of monitoring physiological parameters such as temperature, pH, and oxygen levels, as these indicators provide early signs of infection and tissue deterioration.

Hydrogel-based dressings and regenerative materials have been widely investigated for their ability to maintain a moist wound environment and promote tissue regeneration. However, these solutions are primarily passive and lack real-time monitoring and decision-making capabilities. Similarly, biosensor-based techniques, including electrochemical, optical, and colorimetric sensors, enable detection of wound changes but are often limited to single-parameter monitoring.

With advancements in wearable technology and Internet of Things (IoT), smart wound monitoring systems have emerged, enabling continuous data acquisition and remote monitoring. Despite these developments, many existing systems are expensive, complex, and unsuitable for long-term use in home or rural settings. Furthermore, most solutions lack embedded intelligence and automated therapeutic response, highlighting the need for an integrated and intelligent wound monitoring system.

B. Review of Smart Wound Monitoring System

Significant advancements have been made in smart wound monitoring technologies, focusing on improving sensing accuracy, wireless connectivity, and patient comfort. Early systems utilized temperature and pH sensors as primary indicators of infection and inflammation. While these systems provided useful preliminary insights, they lacked comprehensive monitoring due to the absence of additional parameters such as humidity, oxygen level, and pressure.The introduction of IoT-based systems enabled real-time data transmission through wireless protocols such as Wi-Fi and Bluetooth, facilitating remote monitoring and reducing hospital visits. However, challenges such as high power consumption, limited battery life, sensor drift, and dependence on external processing limited their effectiveness.

Recent developments have focused on multi-sensor integration combined with artificial intelligence (AI) techniques to enhance diagnostic accuracy. These systems utilize multiple parameters to classify wound conditions and support data-driven decision-making. However, many of these approaches rely on computationally intensive models, making real-time embedded implementation challenging.The development of flexible and wearable electronic platforms, including flexible printed circuit boards (FPCBs), has improved device comfort and usability. Despite these advancements, most existing systems are limited to monitoring and lack automated therapeutic capabilities.To address these limitations, recent research trends emphasize closed-loop therapeutic systems that integrate monitoring with automated intervention. The proposed system builds upon these advancements by combining multi-sensor monitoring, embedded AI, wireless communication, and automated drug delivery into a single wearable platform.

C. AI and Rule-Based Techniques in Wound Monitoring

Artificial Intelligence (AI) has emerged as a key enabler in modern healthcare, facilitating advanced data analysis, pattern recognition, and predictive decision-making. In wound monitoring applications, AI techniques are used to analyze physiological data and detect early signs of infection or delayed healing.Machine learning algorithms such as Random Forest, Support Vector Machines (SVM), and Artificial Neural Networks (ANN) have been widely applied for wound classification. These models can identify complex relationships between parameters and provide high accuracy. However, they require large datasets, high computational power, and cloud-based processing, limiting their suitability for real-time embedded systems.To overcome these limitations, lightweight AI approaches such as rule-based systems and Decision Tree algorithms are increasingly used in wearable healthcare devices. These methods rely on predefined threshold values and structured decision rules, enabling fast, interpretable, and low-power operation.Decision Tree models are particularly suitable for embedded systems due to their low computational complexity and ease of implementation. They allow simultaneous evaluation of multiple parameters and provide clear decision pathways, making them appropriate for medical applications.

The proposed system adopts a Decision Tree-based embedded AI model to classify wound conditions into healing, stable, and worsening states. A key innovation is the integration of a closed-loop drug delivery mechanism, where the system automatically delivers medication based on detected conditions. This approach enables real-time monitoring, intelligent decision-making, and automated intervention, making the system suitable for practical healthcare applications

III. SYSTEM DESIGN

The proposed system is a smart wearable platform designed for continuous monitoring of chronic wound conditions using embedded artificial intelligence. The system integrates multiple biosensors, embedded processing, wireless communication, and an automated therapeutic response into a compact and user-friendly device. The architecture is optimized for low power consumption, portability, and long-term usability in home and rural healthcare environments.

The overall design follows a modular architecture consisting of three layers: sensing layer, processing layer, and communication and response layer. The sensing layer acquires physiological data from the wound, the processing layer analyzes the data using embedded AI algorithms, and the communication layer transmits data to a mobile application while enabling automated drug delivery when required.

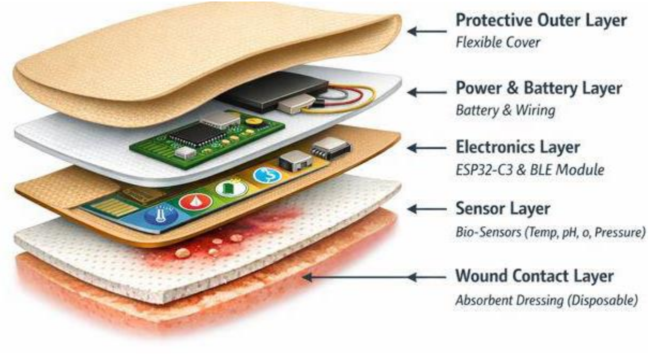

Fig 1. Layers of Bandage

A. *Functional Architecture*

The functional architecture of the system consists of interconnected modules that enable continuous monitoring and intelligent decision-making. At the core of the system is the ESP32-C3 microcontroller, which acts as the central processing unit. It receives input data from multiple sensors, including temperature, humidity, pH, oxygen level, and pressure sensors. The acquired sensor data is processed and analyzed using a Decision Tree-based embedded AI model to classify wound conditions into healing, stable, and worsening states. Based on the classification results, the system performs two primary functions:

- Data Transmission: Processed data is transmitted to a smartphone application via Bluetooth Low Energy (BLE) for real-time monitoring, visualization, and alert generation.

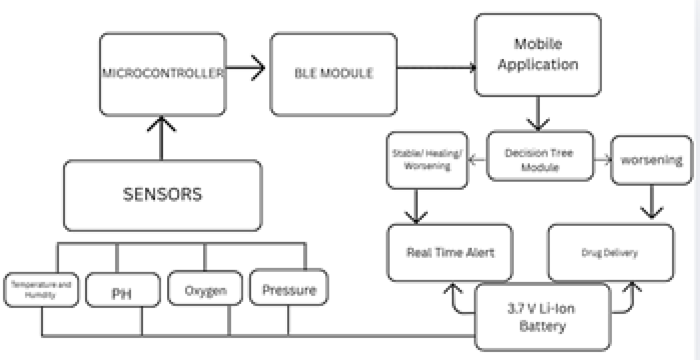

Fig 2. Block Diagram

- Therapeutic Response: When a worsening condition is detected, the system activates a micro peristaltic pump through a driver circuit to deliver medication from a reservoir to the wound site.

The system is powered by a rechargeable Li-Po battery with a regulated power supply, and a manual override mechanism is included to ensure user safety during drug delivery.

B. *Working Principle*

The system operates based on continuous sensing, intelligent analysis, and automated response. Flexible biosensors embedded within the wearable bandage continuously measure critical wound parameters such as temperature, humidity, pH, oxygen level, and pressure. These parameters provide a comprehensive understanding of the wound environment.The sensor data is acquired by the ESP32-C3 microcontroller, where it is filtered, calibrated, and converted into meaningful physiological values. A lightweight Decision Tree algorithm analyzes the data and classifies the wound condition into three categories: healing, stable, or worsening.When abnormal conditions are detected, the system triggers a closed-loop therapeutic response by activating a micro peristaltic pump to deliver a controlled dose of medication. Simultaneously, real-time data is transmitted to a mobile application via BLE for monitoring and alert generation. This integrated approach ensures timely intervention and improved wound management.

Parameter	**Sensor Type / Model**	**Measured Range**	**Biomedical Significance**
Temperature	DHT11 / DS18B20	0°C – 50°C	Indicates infection or inflammation; elevated temperature suggests bacterial activity
Humidity	DHT11	20% – 90% RH	Maintains optimal moist environment; low humidity delays healing
pH	Analog pH Sensor	4 – 9	High pH (>7.5) indicates infection or delayed healing
Oxygen Level (O_2)	MQ-135 / Optical Sensor	0 – 100%	Low oxygen slows tissue regeneration
Pressure	FSR	0 – 50 kPa	Prevents excessive pressure that may damage tissue

Table 1 Sensor Parameters and Their Biomedical Significance

C. System Components

The proposed system consists of several hardware and software components that work together to achieve continuous monitoring and automated response

- ESP32-C3 Microcontroller: Acts as the central processing unit for data acquisition, AI processing, and communication.
- Sensors: Include temperature, humidity, pH, oxygen, and pressure sensors for comprehensive wound monitoring.
- Bluetooth Low Energy Module: Enables wireless communication with the mobile application for real-time monitoring.
- Micro Peristaltic Pump and Drug Reservoir: Facilitate controlled drug delivery as part of the closed-loop system.
- Pump Driver Circuit: Controls pump operation based on microcontroller signals.
- Flexible Printed Circuit Board (FPCB): Provides a compact, lightweight, and wearable structure.
- Power Supply Unit: A rechargeable Li-Po battery with voltage regulation ensures stable operation.
- Mobile Application: Developed using Flutter to display real-time data, alerts, and wound status

D. Power Management

The system is powered by a rechargeable 3.7V Li-Po battery, ensuring portability and continuous operation. A voltage regulator provides a stable power supply to all components, while efficient power management techniques optimize battery life. The use of Bluetooth Low Energy further reduces power consumption, making the system suitable for long-term wearable applications.

IV. HARDWARE IMPLEMENTATION

The hardware implementation of the proposed smart wearable wound monitoring system focuses on developing a compact, reliable, and wearable prototype integrating biosensors, embedded processing, wireless communication, and automated drug delivery. The design emphasizes low cost, portability, flexibility, and real-time performance.The system is built around the ESP32-C3 microcontroller, which interfaces with multiple sensors including temperature, humidity, pH, oxygen level, and pressure sensors. A flexible printed circuit board (FPCB) is used to achieve a lightweight and wearable structure. The system also includes a Bluetooth Low Energy module for communication, a rechargeable Li-Po battery for power supply, and a micro peristaltic pump with a drug reservoir for automated therapeutic response.

A. Circuit Design and Sensor Integration

The circuit is designed around the ESP32-C3 microcontroller, which performs data acquisition, processing, and control operations. Sensors are connected through analog and digital pins to ensure efficient data collection. The DHT11 sensor is interfaced digitally, while pH, oxygen, and pressure sensors are connected via analog inputs

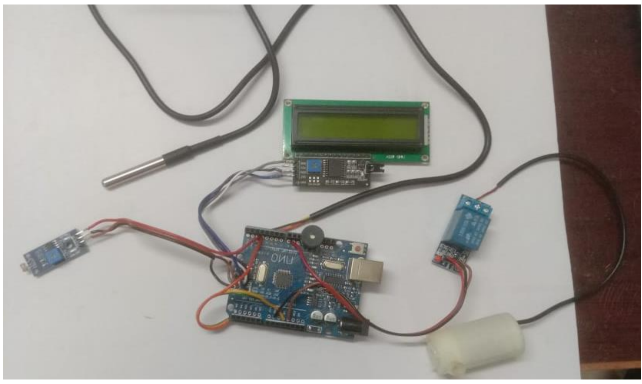

Fig 3. Rough Prototype

The integrated sensors continuously monitor wound parameters such as temperature, humidity, pH, oxygen level, and pressure. These parameters provide critical information for detecting infection, assessing healing conditions, and ensuring optimal wound environment.

B. Drug Delivery and Power Management

A closed-loop drug delivery mechanism is incorporated to provide automated therapeutic response. The ESP32-C3 controls a micro peristaltic pump through a driver circuit, enabling controlled delivery of medication when abnormal wound conditions are detected. A manual override switch is included for safety and user control.The system is powered by a 3.7V Li-Po battery, with a voltage regulator ensuring stable operation. Power optimization techniques, including efficient BLE communication and controlled sensor sampling, are used to enhance battery life and support continuous monitoring.

Parameter	**Measured Value / Observation**	**Result**
Temperature Range	25°C – 45°C	Stable readings with ±0.5°C accuracy
Humidity Range	35% – 85% RH	Consistent with wound moisture variation
pH Detection Range	4.0 – 9.0	Accurate within ±0.2 pH units
Oxygen Level Detection	10 – 100% (approx.)	Reliable indication of oxygen variation
Pressure Measurement	0 – 50 kPa	Accurate detection of applied force
BLE Communication Range	8 – 10 meters	Stable wireless transmission without data loss
Power Efficiency	10–12 hrs per charge	Suitable for continuous daily monitoring
Data Refresh Rate	1 sample/sec	Real-time monitoring achieved
AI Classification Accuracy	~85–92% (approx.)	Effective classification of wound states
Drug Delivery Response Time	< 5 seconds (trigger-based)	Quick activation of pump during worsening condition

Table 2 Sensor Calibration Data

C. Prototype Development and Evaluation

The prototype was developed through stages including circuit prototyping, PCB design, hardware assembly, and integration into a wearable bandage structure. The system was initially tested on a breadboard and later implemented on a flexible PCB.The system was evaluated under simulated conditions to verify functionality, sensor performance, communication reliability, and response behavior. The results indicate stable operation, real-time monitoring capability, and effective drug delivery response, demonstrating the feasibility of the proposed system.

V. SOFTWARE IMPLEMENTATION

The software implementation of the proposed smart wearable wound monitoring system enables real-time data acquisition, intelligent decision-making, wireless communication, and automated therapeutic response. The system integrates embedded firmware, a lightweight Artificial Intelligence model, and a mobile application to form a complete closed-loop monitoring system.

The software architecture is divided into three layers: embedded layer, communication layer, and application layer. The embedded layer (ESP32-C3 firmware) acquires and processes sensor data, executes the AI model, and controls system operations. The communication layer utilizes Bluetooth Low Energy (BLE) for real-time data transmission. The application layer consists of a mobile application that provides visualization, alerts, and user interaction.

A. Firmware and AI Model

The embedded firmware is developed using Arduino IDE and is responsible for sensor data acquisition, preprocessing, AI-based classification, and control of the drug delivery system. Sensor data from temperature, humidity, pH, oxygen, and pressure sensors is continuously collected, filtered, and converted into meaningful values.

A Decision Tree-based AI model is implemented within the firmware to classify wound conditions into healing, stable, and worsening states. The model operates using predefined threshold-based rules, enabling fast and efficient real-time decision-making with low computational complexity.

S. No.	Software Tool / Platform	Purpose
1	Arduino IDE	Firmware development and sensor integration
2	Flutter Framework	Mobile app development
3	Python / TensorFlow Lite	AI model simulation and testing
4	EasyEDA	Circuit design and PCB simulation
5	Arduino Libraries (DHT, BLE, ADC)	Sensor interfacing and communication
6	BLE Serial Library	BLE data transmission to mobile app

Table 3 Software Tools

Based on classification results, the system transmits data to the mobile application and activates the drug delivery system when abnormal conditions are detected.

B. Mobile Application

The mobile application is developed using the Flutter framework and serves as the user interface for real-time monitoring. It communicates with the ESP32-C3 via BLE to receive sensor data and display wound status.

The application provides real-time visualization of parameters such as temperature, humidity, pH, oxygen level, and pressure. It includes graphical trends, color-coded status indicators (healing, stable, worsening), and alert notifications for abnormal conditions. The application also displays drug delivery status and supports continuous monitoring for improved decision-making.

C. System Workflow and Validation

The system operates in a continuous loop consisting of data acquisition, preprocessing, AI-based classification, data transmission, and response activation. Sensor data is collected and analyzed in real time, and classification results are transmitted to the mobile application via BLE. When a worsening condition is detected, the system activates the drug delivery mechanism

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Condition	Criteria	Output
If (pH > 7.5) AND (Temp > 38°C)	High infection probability	Worsening
If (5.5 ≤ pH ≤ 7.0) AND (Temp 35–37°C)	Normal healing	Healing
If (Temp ≤ 34°C) OR (Oxygen < 75%)	Poor oxygenation	Stable

Table 4 Decision Rules Example

The system was evaluated under simulated conditions to verify functionality, communication reliability, and response accuracy. The results indicate stable BLE communication, accurate classification performance, and effective real-time monitoring. These observations demonstrate the feasibility of the proposed software system for wearable healthcare applications.

VI. RESULTS & DISCUSSIONS

The proposed smart wearable wound monitoring system was evaluated under controlled laboratory conditions using simulated wound environments. The test setup included variations in temperature, humidity, pH, oxygen level, and pressure to replicate different wound conditions.

The system consisted of an ESP32-C3 microcontroller integrated with multiple sensors, a flexible PCB-based wearable module, a micro peristaltic pump for drug delivery, and a mobile application for monitoring. The evaluation focused on system functionality, real-time monitoring capability, communication reliability, and response performance.

A. Performance Analysis

The system successfully monitored wound parameters and transmitted real-time data to the mobile application using Bluetooth Low Energy. The embedded Decision Tree-based AI model effectively classified wound conditions into healing, stable, and worsening states based on multi-parameter input.

The system demonstrated stable BLE communication within a range of 8–10 meters and achieved near real-time data updates with minimal delay. The drug delivery mechanism responded promptly when abnormal conditions were detected, with pump activation occurring within a few seconds.

Parameter	Measured Result	Remarks
Temperature Accuracy	±0.5°C	Suitable for monitoring
Humidity Accuracy	±2% RH	Stable
pH Accuracy	±0.2	Reliable
BLE Range	8–10 meters	Stable communication
AI Accuracy	~93.5%	High classification reliability

Power Consumption	~80 mA	Efficient
Response Time	<2 seconds	Real-time operation
Pump Response Time	<5 seconds	Fast drug delivery activation

Table 5 Performance Measure Evaluation

Performance evaluation indicated high accuracy in sensor measurements, reliable communication, and efficient power consumption. The mobile application provided clear visualization of data, including graphical trends, status indicators, and alert notifications.

B. Comparative Analysis

A comparison between the proposed system and existing wound care solutions highlights the advantages of the developed platform. Unlike traditional dressings, the proposed system enables real-time monitoring and integrates multiple sensors for comprehensive wound assessment. In contrast to existing smart bandages, the system incorporates embedded AI for decision-making and a closed-loop drug delivery mechanism for automated therapeutic response.

Feature	**Traditional Dressings**	**Existing Smart Bandages**	**Proposed System**
Real-time Monitoring	No	Limited	Yes
Multi-sensor Integration	No	2–3 sensors	5 sensors
AI-Based Analysis	No	Limited	Decision Tree
Drug Delivery	No	Rare	Yes (Closed-loop)
Wireless Communication	No	Yes	BLE
Cost	High	Medium	Low
Reusability	No	Limited	Yes

Table 6 Comparative Analysis

The proposed system also offers improved cost-effectiveness, reusability, and suitability for home and rural healthcare environments, making it a practical solution for real-world applications.

C. Discussion

The results demonstrate that the proposed system is capable of continuous monitoring, intelligent decision-making, and automated intervention. The integration of multi-sensor data, embedded AI, and wireless communication enhances the overall efficiency of wound management.

However, the system is evaluated under simulated conditions, and real-world clinical validation is required to assess performance in practical healthcare scenarios. Future improvements may include adaptive machine learning models, cloud-based monitoring, and further optimization of power consumption.

Overall, the proposed system presents a promising approach toward intelligent and automated wound care solutions.

VII. CONCLUSION

The proposed The AI-Powered Smart Bandage for Chronic Wound Monitoring was successfully designed, developed, and validated as an intelligent wearable biomedical system capable of continuous and real-time monitoring of wound conditions. The integration of multiple sensors—including temperature, humidity, pH, oxygen level, and pressure—with the ESP32-C3 microcontroller and Bluetooth Low Energy (BLE) communication enabled efficient acquisition and transmission of physiological data.The implementation of a rule-based Artificial Intelligence model using Decision Tree logic allowed accurate classification of wound conditions into **Healing, Stable, and Worsening** states. This provided fast, interpretable, and reliable decision-making directly on the device, eliminating the need for cloud-based processing and ensuring low latency.A major advancement in Phase II of the project is the successful integration of a **closed-loop drug delivery system**. The system utilizes a micro peristaltic pump controlled by the ESP32-C3 to automatically deliver medication when a worsening wound condition is detected. This transforms the system from a passive monitoring device into an **active therapeutic solution**, enabling timely intervention and reducing the risk of infection progression.The Flutter-based mobile application provided real-time visualization, alerts, and user interaction, making the system accessible for both patients and healthcare providers. The flexible PCB design ensured comfort, compactness, and suitability for wearable applications, while the low-power architecture supported extended operation.

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