UNIVERSITY of
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COLLEGE OF SCIENCE
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Regional Centre of Excellence in Biomedical Engineering and e-Health (CEBE)

Design and Development of a GSM-Based Smart Bandage System for Chronic Wound Monitoring and Management

By:

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A Dissertation Submitted to the Regional Centre of Excellence in Biomedical Engineering and e-Health (CEBE), University of Rwanda as partial fulfilment of the requirements for the Master's Degree in Biomedical Engineering.

Supervised by:

Dr. NGENZI Alexander

and

Prof. Ketul C. Popat

DECLARATION

I, **HAKIZIMANA Aimable**, declare that this dissertation entitled “**Design and Development of a GSM-Based Smart Bandage System for Chronic Wound Monitoring and Management**” is my original work based on research and prototype and has not been submitted for any other degree or professional qualification.

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Date: **August 7, 2024**

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CERTIFICATE

This is to certify that the project entitled “**Design and Development of a GSM-Based Smart Bandage System for Chronic Wound Monitoring and Management**” is a record of original work done by HAKIZIMANA Aimable (Reference number: 215028844), a MSc. Degree student in Biomedical Engineering.

This work has been submitted under the guidance of **Dr. NGENZI Alexander** and **Prof. Ketul C. Popat**

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ABSTRACT

Chronic wounds are a significant cause of morbidity and mortality worldwide, necessitating advanced care solutions. This study presents the development of a GSM-based smart bandage system designed for chronic wound monitoring and management. By integrating various sensors, microcontrollers, GSM communication, and cloud technology, the system enables real-time data collection and transmission of critical wound parameters such as temperature and humidity levels. The system includes a mobile application, a monitoring platform, and a management platform, offering a comprehensive approach to wound care. The prototype was rigorously assessed for sensor accuracy, data transmission, and battery life. Results indicated that the system effectively maintained wound temperature within the optimal range of 34.82°C to 36.52°C and moisture levels mostly within 60%-90%. Additionally, a survey revealed that 70% of healthcare professionals are aware of smart bandages with integrated sensors, underscoring a high level of awareness and potential acceptance in the field. Overall, this GSM-based smart bandage system demonstrates significant potential to enhance chronic wound care through continuous monitoring and real-time data insights, paving the way for proactive management strategies. Future research should focus on extensive clinical trials and the exploration of biocompatible materials for sensors to validate and further improve the system's effectiveness in enhancing healing times and minimizing skin irritation.

Keywords: **Smart Bandage, Wound Management, GSM Technology, Data Transmission, Sensors**

LIST OF ACRONYMS

GSM: Global System for Mobile Communications

WLAN: Wireless Local Area Network

RFID: Radio Frequency Identification

GPRS: General Packet Radio Service

MCU: Microcontroller unit

SIM: Subscriber Identity Module

IT: Information Technology

pH: Potential of Hydrogen

LDO: low dropout

LM32: linear monolithic temperature Sensor

ECM: extracellular matrix

POC: point of care

3D: Three Dimensions

PDA: personal digital assistant

UART: universal asynchronous receiver / transmitter

VBAT input: battery voltage,

MUX: Multiplexer

CMOS: complementary metal-oxide semiconductor

TRNG: True Random Number Generator

DAC: digital to analogue converter

Li-Po: Lithium Polymer

PCB: Printed Circuit Board

JTAG: Joint Test Action Group

FR-4: flame retardant

CEBE; Center of Excellence in Biomedical Engineering

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CHAPTER 1. GENERAL INTRODUCTION

1.1 Introduction

Chronic wounds are a significant health problem with devastating consequences for patients' physical, social, and mental health, increasing healthcare systems' costs. Their prolonged healing times, economic burden, diminished quality of life, increased infection risk, and impact on patients' mobility and functionality make them a major concern for healthcare professionals [1]. Although, the application of traditional wound dressings contributes to an effective wound healing outcome, yet the complexity of the healing process remains a major health challenge [2].

The management of chronic wounds has emerged as a major health care challenge during the 21st century consuming significant portions of health care budgets. Chronic wounds such as diabetic foot ulcers, leg ulcers, and sores have a significant negative impact on the quality of life of affected individuals [3]. The innovative devices, incorporating innovative materials and technologies into traditional bandages, offer improved wound care [4] of chronic wounds such as diabetic foot ulcers, leg ulcers, and sores. Healthcare sector worldwide is blooming and the rise of information technology in healthcare in the last few years is evident [5]. Different telemedicine solutions and remote monitoring devices are being developed and used. These solutions not only help the patients by giving them the freedom to move anywhere but also cut off significant amount of hospital medical expenses [6].Wearable sensors that are accurate in measuring the concentration of significant markers in the wound environment have been developed. Although there is a significant difference between the innovative platforms created by researchers and the wound care solutions utilized in clinical practice, it is anticipated that the next generation of multifunctional "smart" dressings will bring about a paradigm shift in wound care [7].

The creation of smart materials that can react to changes in the wound environment, such as the elevation of inflammatory markers, alterations in temperature, ionic concentration, or ambient, has advanced significantly [8]. Numerous dressings have been developed that are recommended for types of chronic wounds based on the characteristics of the wound, such as whether it is clean or infected, dry, or oozing, superficial, or deep [4]. Even with advancements in wound healing technology, there is a need for devices that can intervene in dysfunctional healing processes to efficiently cure chronic wounds, fight infection, and offer diagnostic information [9].

The focus of the project is to develop a smart bandage system for remote monitoring and managing wounds. With the fast development and nowadays available powerful mobile and GSM technology, it is possible to develop such a smart bandage system. However, to make it simple and easy to use for any age group and to fulfill the real-world telemedicine regulations and rules mission, this smart bandage system will be needed to develop with detailed research in the medical and IT field. There are several ongoing research and development projects performing in the world to develop the next generation of e-health or smart health systems.

This novel smart bandage system will not only influence the medical field, but it can also be used very effectively at various places as mentioned in the next section. In the coming chapter 1, more details about the proposed system and the main objectives of this project will be discussed. By referring all the past and ongoing research activities, it can be easily predicted that, in future, the smart bandages the dressing with the electronics features will be the wide use product not only for the wound’s treatment in the hospitals but also for the emergency or aware providing purposes by connecting the patients to the remote medical centers. And therefore, this researched principles and components will be used for realization of a microcontroller-based prototype of the smart bandage in this project. In the project a smart bandage system based on GSM is proposed to be developed that offers a new and more precise method of doing how the wounds are currently being looked after. What we are doing is taking the first big step towards moving the care of the patients out from the hospital directly to their own homes.

By using this technology, people can actively engage and involve with their care management. Also, the valuable resource in the primary and secondary health care that is currently consumed by the chronic and acute wounds will be decrease and this project will prove that how the use of this technology can be a potential benefit to the chronic and acute wounds sufferers. The patient will be helped with a real freedom of movement while receiving the most proper care which will then decrease the burden of healthcare costs. This is a sustainable project not just a complete. Developing the novel smart bandage system and developing the home proof of concept unit will be helped to the digital healthcare field. This project will offer a good possibility to step further in renewable medical research and it will be a good initiative towards the computer or electronic filed health care filed out-reaches. And most importantly, because of the enormous number of chronic and acute patients can benefit from this research. Therefore, it will be a good initiative towards realization and practical development in the innovative healthcare field.

1.2 Background

The proliferation of smart wearable devices has led to the emergence of a new field called smart textiles or smart fabrics [10]. The potential applications of smart textiles span diverse areas such as health, fitness, medical, automotive, aerospace, and defence, including wearable systems for vital signs monitoring, smart clothing for posture detection, novel and non-invasive sensing techniques for continuous monitoring of physiological activities, and wearable systems for tracking the physical and psychological status of athletes and patients [11]. Currently deployed technologies for the continuous monitoring and management of wounds consist of smart bandage systems and wound care devices which are equipped with bio-chemical sensors and used for the detection of inflammation and infection, and enzyme levels [12]. Other advanced systems include negative wound therapy devices [13], ultrasound therapy systems, electromagnetic therapy systems, and oxygen therapy systems [14]. However, the abilities of these systems in providing continuous management and care, especially when the specific types of microbial infections are not known and the clinician-type of care is remote and not available, are very limited and there are no mechanisms for the collection and analysis of data during the treatment process which can support the clinician in achieving a comprehensive, objective, and accurate prognosis of the healing status. This work is proposing the development of a smart bandage system for wounds management, which will provide continuous monitoring and sensing solution compared to the currently used systems and enable the collection of clinically useful data. The proposed system is based on inserting cellular telephone technologies and miniature and low power GSM sensors inside a bandage. The on-board GSM sensors constantly provide GEO-location information, measure the temperature, and monitor the value of moisture of the area around a wound of a patient. Such data are transmitted on a regular basis to a central server, which is then employed to combine information of the location where the measurement has been executed and map it to the clinically built GEO-informatics database to initiate advanced location-based clinical analysis. The main motivation behind such research work is to use the latest advancements in smart technologies and address the significant unmet clinical needs in this area. On the other side, the wound management field may benefit from the integration of smart technologies for providing objective and accurate prognoses of the healing status, compared to the currently used manual methods and non-continuous automated systems. In this work, a multi-discipline approach that involves computer-aided design, novel electronics and low power software, computer programming for system-level simulations, and rapid prototyping was identified during the development of the GSM sensors and the management platform, as well as the actual realization design and testing of the novel smart bandage system.

1.3 Problem statement

A significant global health issue that impacts millions of individuals are chronic wounds [15]. There were 15.03 wounds per 1000 people in the population overall. Acute and chronic wound prevalence was 4.48 and 10.55 per 1000 people, respectively [16]. A broader and more significant class of disorders includes those causing chronic wounds [16]. Chronic wounds present a significant global health challenge, affecting 1-2% of the population in developed countries [17]. In the United States alone, around 6.5 million people suffer from chronic wounds, with an annual management cost estimated between $28.1 billion and $96.8 billion [18]. Similarly, the United Kingdom reports a prevalence of approximately 2.2 million chronic wound cases yearly, costing the NHS about £5.3 billion annually [19]. About 21% of the elderly in India reportedly have at least one chronic disease. Seventeen percent elderly in rural areas and 29% in urban areas suffer from a chronic disease. Hypertension and diabetes account for about 68% of all chronic diseases [20]. These wounds severely impact patients' quality of life, causing considerable pain, discomfort, and social isolation [21]. About 70% of individuals with chronic wounds experience moderate to severe pain, and many suffer from anxiety and depression. Furthermore, diabetic foot ulcers, a common type of chronic wound, are a leading cause of non-traumatic lower limb amputations globally [22]. The complications and mortality rates associated with chronic wounds are alarming. For instance, the five-year mortality rate for patients with diabetic foot ulcers is estimated to be between 30-40% [23].

The process of wound healing and its durations has been problematic in most places [24]. Health practitioners find it challenging to manage wounds and give consistent feedback to the patients. Currently, in wound management, the attention given to patients falls short of the ideal providing requirements [25]. This is because patients must physically present themselves to their doctors or nurses for a checkup. Specialized doctors and health practitioners are not evenly distributed and usually are congested with a large volume of patients. This leaves the patients with only one option, to manage their own wounds and visit the doctors intermittently. This kind of approach in wound management is less effective and hinders the fast recovery of patients. There is a need to bring medical services and attention to the patients in an efficient and reliable manner. Traditional wound dressings are passive devices that provide limited information about the wound healing process [26]. This can make it difficult for clinicians to identify potential problems early and intervene promptly. As a result, wound complications are common and can lead to prolonged healing times, increased costs of care, and reduced quality of life for patients [27]. There is a need to bring medical services and attention to the patients in an efficient and reliable manner. Smart bandages have the potential to address this problem by providing real-time monitoring of wound parameters such as temperature, and moisture levels. This data can be used to identify potential problems early and intervene promptly, which can lead to improved wound healing outcomes and reduced costs of care.

With the prominent rise of GSM technology, it is possible to develop a smart bandage system that can check the state of a wound and wirelessly send the recorded data to a healthcare provider. The real-time nature of GSM ensures that medical professionals will have access to the latest wound status, regardless of their location, and therefore they can give prompt advice to the patient. As such, sensors are increasingly being integrated with wound monitoring systems and in recent years, several studies have been done in this area. However, most of these works either focus on the hardware components of the smart bandage system or the software algorithm used to analyse the data. The systems that are currently available in the market do not work with GSM technology, but they use WLAN, RFID or Bluetooth to allow data transmission. These systems are generally bulky because they are standalone systems that consist of both the monitoring device and the display unit. Also, the mobility of the patient is limited as the patient must stay within the communication range of the monitoring device, which in turn hinders the adoption of these systems. Another drawback is that the patient must always carry the display unit with them if any mobile monitoring is to be realized. These issues can be addressed by deploying GSM-based smart bandage system that was proposed in this project, which uses the GPRS communication protocol for sending data to the healthcare provider. The project of designing Design of a GSM-Based Smart Bandage System for Chronic Wound Monitoring and Management is a key step towards addressing these challenges.

1.3 Research Questions

1. Does the use of a smart bandage system with real-time monitoring and personalized interventions lead to faster healing times compared to standard wound care for chronic wounds?
2. Does the use of a smart bandage system with remote patient management features improve patient adherence to treatment plans and satisfaction with care compared to traditional wound care management?
3. Patients treated with the smart bandage system will experience statistically significant reductions in healing time compared to the control group receiving standard care.

1.4 Objectives

1.4.1 General Objective

The general objective of the project "Design and Development of a GSM-Based Smart Bandage System for Chronic Wound Monitoring and Management" is to create an advanced wound care solution that leverages modern technologies to enhance the monitoring and management of chronic wounds. This solution aims to integrate various sensors, a microcontroller, and a GSM module into a smart bandage system, complemented by a mobile application, to provide real-time data collection and transmission of wound parameters such as temperature and moisture levels. The goal is to enable early detection of complications, improve patient outcomes, and reduce the need for frequent healthcare facility visits.

1.4.2 Specific Objectives

The specific objectives of the project Design and Development of a GSM-Based Smart Bandage System for Chronic Wound Monitoring and Management are as follows:

1. Comprehensive Review of Existing Wound Management and Smart Bandage Technologies

2. Develop a system for smart bandage, which includes a variety of sensors, Microcontroller, and a GSM module.

3. Design and implement a mobile application (Android) for monitoring and early detection of maladies.

4. Use GSM and sensors to collect data on wound parameters such as temperature, and moisture levels and transmit the data collected from the sensors to a remote device for analysis.

1.5 Study Scope

This study will focus on the design, development, and evaluation of a smart bandage system using GSM technology for chronic wound management. The scope includes:

1. Reviewing existing technologies and methods used in wound management and smart bandage systems.

2. Designing and developing a prototype smart bandage system with integrated sensors and GSM module.

3. Implementing data transmission and remote monitoring capabilities using the GSM network.

Certain aspects are excluded from the project's scope.

1. Large-scale clinical investigations comparing the performance of the smart bandage in enhancing healing times to standard treatments are unlikely to fit within the scope of the project.
2. The creation of a comprehensive wound treatment platform and connection with existing hospital systems are not included.

1.6 Significance of the Study

The development of a smart bandage system for chronic wound management has several potential benefits:

1. **Improved patient outcomes**: By providing real-time monitoring and personalized interventions, the smart bandage system can help accelerate wound healing and reduce the risk of complications.

2. **Enhanced patient adherence**: The remote monitoring capabilities of the smart bandage system can improve patient adherence to treatment plans by providing timely feedback and support from healthcare providers.

3. **Reduced healthcare costs**: By enabling remote monitoring and reducing the need for frequent hospital visits, the smart bandage system can help lower healthcare costs associated with chronic wound management.

4. **Increased access to care**: The GSM-based smart bandage system can provide access to wound care for patients in remote or underserved areas where healthcare resources are limited.

5. **Contribution to medical research**: The data collected from the smart bandage system can contribute to medical research on wound healing and inform the development of new treatments and interventions.

In conclusion, this project holds significant value for revolutionizing chronic wound management. The smart bandage system with its real-time monitoring and remote data transmission capabilities has the potential to improve patient care, reduce healing times, and benefit both patients and healthcare systems.

1.7 Organization

This dissertation is organized into six chapters:

Chapter 1: General Introduction: Provides an overview of the study, including the background, problem statement, research questions, objectives, scope, significance, and definitions of key terms.

Chapter 2: Literature Review: Reviews existing literature on chronic wound management, smart bandage systems, and GSM technology.

Chapter 3: Methodology: Describes the research design, methods, and procedures used to develop and evaluate the smart bandage system.

Chapter 4: Design and implementation: Details the design and development of the smart bandage system, including the integration of sensors, GSM module, and data transmission mechanisms.

Chapter 5: Results and Discussion: Presents the findings from the study, including the design and development of the smart bandage system.

Chapter 6: Conclusion and Recommendations: Summarizes the key findings, discusses their implications, and provides recommendations for future research and practice.

1.8 Summary

Chapter 1 introduces the concept of chronic wounds and their significant impact on individuals and healthcare systems. It highlights the limitations of traditional wound care and introduces the idea of smart bandages as a potential solution. The chapter then outlines the specific research questions and objectives of the project, aiming to develop a novel smart bandage system with GSM sensors. Finally, it summarizes the potential benefits and significance of research for improving wound healing outcomes, reducing costs, and advancing the field.

CHAPTER 2. LITERATURE REVIEW

2.1 Literature Review

The skin, the body’s biggest organ, is crucial in defending against pathogens and toxins in the environment, as well as in preventing dehydration and temperature stress. The wound is an integrity of the skin tissue that may occur due to physical damage from daily activities, illness, long-term exposure to excessive load, and traumatic events and burns [28]. Skin qualities can change and become more vulnerable to physical effects because of underlying disorders like diabetes and ischemia [29]. A wound is considered chronic when it cannot heal entirely and naturally (this includes injuries and diabetic foot ulcers), has disordered healing processes, and does not heal after 30 days [30]. Chronic wounds exhibit slow or ineffective wound healing, protracted, uncontrolled inflammation, and compromised extracellular matrix (ECM) [31] the current therapies of wound that are used, such as skin grafts, skin substitutions, negative wound therapy, and others, can be helpful, they typically necessitate procedures or surgical intervention Necrosis, sepsis, and even mortality can result from microbial infection at the site of the wound, which can significantly slow down the healing process. Patients with chronic non healing wounds are increasingly given both topical and systemic antibiotics, however, this increased use, abuse, and improper administration of antibiotics frequently results in bacterial drug resistance, significantly raising morbidity and mortality rates [31]. Covering wounds with suitable dressings facilitates the healing process and is frequent practice in wound management plans [3]. However, standard dressings do not provide insights into the status of the wound underneath [32]. Parameters such as moisture, temperature, and inside the dressings are indicative of the healing rate, infection, and wound healing phase [33]. But owing to the lack of information available from within the dressings, these are often changed to inspect the wound, disturbing the normal healing process of wounds in addition to causing pain to the patient [34]

Despite considerable progress being made in the creation of new bandage materials, only a few of them can offer doctors diagnostic information about the wound’s biomolecular composition at the point of care (POC) [35]. Currently, much of the treatment is done by observation, and the accompanying healthcare provider’s critical judgment and experience are crucial [28].

Smart bandages, also known as interactive dressings, are wound care products that have been developed recently to provide an effective means of monitoring and treating many distinct types of chronic wounds [36]. These bandages are equipped with several types of electronic sensors and drug delivery systems that can be remotely accessed by the clinicians as a way of improving patient care [37]. Bandage is a well-established industry, whereas wearable electronics is an emerging industry [38].

Smart bandages based on multimodal wearable devices could enable real-time physiological monitoring and active intervention to promote healing of chronic wounds [39]. However, there has been limited development in incorporation of both sensors and stimulators for the current smart bandage technologies [40]. Toward the adoption of artificial intelligence-enabled wearable sensors interconnected with intelligent medical objects, this contactless multi-intelligent wearable technology provides a solution for healthcare to monitor hard-to-heal wounds and create optimal efficiencies for clinical professionals by minimizing the risk of disease infection [41].

Recent advances in materials and fabrication technologies have led to the fabrication of dressings that provide proper conditions for effective wound healing. The 3D-printed wound dressings, biomolecule-loaded dressings, as well as smart and flexible bandages are among the recent alternatives that have been developed to accelerate wound healing [42].

A -indicating colorimetric tough hydrogel patch is shown in [43] for potential application as a substrate in intelligent wound dressings purpose to create an innovative hydrogel patch that can recognize alterations, a typical sign of wound infection or healing advancement. The goal of the work is to create a robust hydrogel patch by combining polymers and -responsive indicators. In reaction to changes, the patch changes color, giving a clear indicator of the state of the wound, explains how this -indicating hydrogel patch may be used as a smart wound dressing substrate that would enable real-time monitoring of wound healing and infection identification [44].

Sensors embedded in the dressing would provide clinicians and nurses with valuable information that would aid in wound care decision making, improve patient comfort, and reduce the frequency of dressing changes [45]. The potential benefits of this enabling technology would be seen in terms of a reduction in hospitalization time and health care cost. Modern sensing technology along with wireless radio frequency communication technology is poised to make significant advances in wound management [45].

Smart bandages that incorporate sensors for longitudinal monitoring of metabolites,, temperature, oxygen, and bacteria in wound exudate offer unique potential for accurate, at-home wound assessment [46]. Such advanced sensors can provide previously unavailable real-time insights into wound physiology. While such wearable embodiments are a major advancement in the field of wound care, they usually rely on bulky, complex wireless electronics that preclude their use in constricted body parts (foot, sacrum) most prone to chronic wounds [47]. Further, much of the work in this field focuses on demonstrating the viability of sensors for monitoring wound composition, with little emphasis on interpreting these results for predicting the future course of healing, such as wound closure rate [48]. Demonstrating such capabilities will enable clinicians to recommend wound-specific treatments for rapid closure [47].

Recent demonstrations of wearable sensors enable real-time wound assessment, but they rely on bulky electronics, making them difficult to interface with wounds Herein, a miniaturized, wireless, battery-free wound monitor that measures lactate in real-time and seamlessly integrates with bandages for conformal attachment to the wound bed is introduced [47]. Many kinds of sensors have been developed for use in wound care. For instance, a variety of electrochemical sensors that can continually monitor the wound environment have been developed. Potentiometric measurement is typically used by electrochemical sensors, while conducting polymer sensors [49]. Numerous wound dressings with built-in sensors have been developed using potentiometric readings. Stretchable and flexible substrates can be used to construct these sensors. In a noteworthy study, ecoflex substrate was sprayed with conductive inks and polymers to construct a low-cost flexible sensor. Another kind of sensor that can be utilized to create bandages is colorimetric sensors. These sensors can be used without integrated electronics and are reliable and simple to use [50]. These sensors' readouts are often relied on image processing, but if the color shift is noticeable enough, a naked-eye view may be used to determine the state of a wound or estimate the value [51]. Nonetheless, shielding the skin from the dye that is leached is a major issue when using luminescence devices. Flexible colorimetric and electrochemical temperature sensors are similarly commonly utilized in biological applications as sensors. The most popular kind of flexible temperature sensors are microfabricated metallic resistive sensors [52]. For tracking the skin temperature of cutaneous wounds, one example dressing was created using microfabricated arrays of temperature sensors [53]. The electrical lines could create a conformal contact with the skin as they were stretchable and made on a flexible substrate. The platform was integrated and had the ability to display a map of the wound area's temperature distribution [53]. Flexible and stretchable strain sensors are in great demand for many applications like wearables and home health, [54][55]. These sensors have also been made using material conductive inks to lower the cost of manufacture. The alteration of conductive inks' electrical resistance because of mechanical strain is a significant issue that can compromise temperature sensors' accuracy [56]. Thus, tracking tissue oxygenation yields useful information about the healing of wounds. To monitor the wound bed in real time, one study created a flexible, wireless smart bandage with a customized oxygen sensor using readily available electrical components [56], [57].

In a noteworthy study, the amount of moisture at the time of bandage change was monitored using electrochemical sensors placed underneath dressings [58]. More than 40% of dressing changes happened before the ideal period, according to the results, which suggested that the present clinical practices need to be improved.

Table 2.1 Summarized the some recently Literature review

No	Author	Title	Methodology	Achievement	Gaps
1.	Md. I. Hossain *et al.(* Jan. 2024*)*	Smart bandage: A device for wound monitoring and targeted treatment	1. Smart bandages are utilized to monitor biomarkers such as temperature, pH, and infection status. 2. Flexible oxygen sensors are employed to monitor tissue oxygenation in real-time. 3. Nanomaterials with high surface area are used to enhance drug delivery and targeting.	1. Developed bandages incorporating drug release systems, pH sensors, and antibiotic delivery capabilities. 2. Created an NFC antenna bandage that adapts to the skin, detects biomarkers, and communicates wirelessly. 3. Designed smart bandages that monitor wounds, deliver drugs, and enhance the healing process.	1. Wearable devices are not suitable for clinical settings. 2. There are limited sensing capacities in current wound-sensing devices. 3. Advancements are needed to improve the clinical applicability of wearable wound-sensing technology.
2.	A. Shahul, A. S. George, and A. S. Hovan George(2023)	E-Bandage: Electronic Wound Monitoring and Healing Solutions for Improved Patient Care	1. Monitoring wound temperature using thermistors, thermocouples, and infrared sensors. 2. Post-surgical monitoring is conducted using E-	1. Developed advanced sensors for enhanced wound monitoring. 2. Provided hands-on training for healthcare providers on the use of new	1. Limited integration of E-bandages with telemedicine platforms. 2. Challenges in enabling remote monitoring and virtual

			bandages for tracking incision healing.	wound monitoring technologies. 3. Engineered flexible electronic substrates for the integration of E-Bandage systems.	consultations for personalized care plans. 3. Difficulties in reducing patient visits and ensuring adherence to treatment plans.
3.	A. Levin, S. Gong, and W. Cheng,(Apr. 2023)	Wearable Smart Bandage-Based Bio-Sensors	1. Review of bandage-based smart sensors for wearables. 2. Discussion on technical characteristics, future applications, and manufacturing processes of the sensors. 3. Emphasis on end-user acceptance, system approvals, and disposal advantages. 4. Machine learning algorithms are employed to interpret sensor data for wound healing progress. 5. Conductive materials and hydrogels are utilized for sensing and therapy.	1. Demonstrated that bandages can serve as a foundation for enhancing wearable healthcare monitoring systems. 2. Showcased smart bandages that provide user acceptance and approval benefits for wearable technology. 3. Bridged the gap between medical-grade systems with the development of wearable biosensors.	1. Bandages as the base for wearables bridge validation and acceptance. 2. Bandages offer comfort, reliability, and adherence for wearable biosensors. 3. Enhancing user acceptance and approval for wearable biosensors remains challenging.

4.	Y. Jiang *et al*(May 2023*)*	Wireless, closed-loop, smart bandage with integrated sensors and stimulators for advanced wound care and accelerated healing	1. Flexible printed circuit boards for smart bandages were fabricated with passive components, a thermistor, a sensor transponder, a crystal oscillator, and operational amplifiers. 2. These boards were assembled with tin-lead solder paste and coated with a silver/silver chloride paste to prevent corrosion. 3. Conducting adhesive hydrogels with different PEDOT 4. concentrations were synthesized and tested for their electrochemical and mechanical properties. 5. Animal testing involved various wound models to assess biocompatibility, cell migration, and wound healing effectiveness.	1. Developed flexible printed circuit boards with essential components for smart bandages. 2. Achieved effective corrosion protection through coating and precise assembly with solder paste. 3. Optimized electrochemical and mechanical properties of conductive adhesive hydrogels. 4. Demonstrated successful biocompatibility, cell migration, and wound healing in animal tests.	1. Limited development in integrating sensors and stimulators in smart bandages. 2. There is a need for portable, autonomous, inexpensive devices for improved wound care. 3. Current smart bandage systems require further advancements to enhance integration and cost-efficiency.
5.	N. Tang *et al (Apr. 2021)*	Wearable Sensors and	1. Developed a conductive thread-	1. Developed wearable sensors for wound	1. Challenges include sensing

		Systems for Wound Healing-Related pH and Temperature Detection,	based pH sensor with a microfluidic splitter for enhanced detection accuracy. 2. Explored electrochemical methods for transducing wound biomarkers into measurable signals like potential, current, or impedance. 3. Investigated wearable, flexible temperature sensors for continuous real-time monitoring of wound status.	monitoring that measure pH and temperature. 2. Created smart bandages that integrate pH sensors for enhanced wound monitoring.	performance, infection identification, large-area detection, and monitoring reliability. 2. Wearable sensors need improvements in 3D detection. 3. Long-term monitoring capabilities of wearable sensors require further enhancement.
6.	N. T. Garland et al (Nov. 2023)	A Miniaturized, Battery-Free, Wireless Wound Monitor That Predicts Wound Closure Rate Early	1. Utilized a miniaturized, wireless, battery-free design for the wound monitor, incorporating lactate measurement capabilities. 2. Implemented a UV protective membrane to ensure sensor stability and enhance biocompatibility. 3. Performed an in vitro biocompatibility test using a mouse	1. Achieved an 83% accuracy rate in predicting wound closure. 2. Developed a miniaturized, wireless, battery-free wound monitor.	1. Design multi-analyte wound monitors for improved prediction accuracy. 2. Explore additional wound parameters, such as cytokines, to enhance prediction models. 3. Poor mass transport across

			fibroblast cell line to assess sensor safety. 4. Employed self-powered sensing technology integrated with wireless electronics and mathematical models for improved functionality. 5. Fabricated a wireless electronic module to support the operational needs of the sensor.		UV protective films.
7.	Q. Pang *et al* (Mar. 2020)	Flexible integrated sensing platform for monitoring wound temperature and predicting infection	1. Fabricated a Flexible Integrated Sensing Platform (FISP) incorporating Flexible Sensor Chip (FSC) and Conductive Polymer Composite Base (CPCB) components. 2. Monitored wound temperature using a flexible sensor chip integrated with a smartphone application. 3. Developed a Flexible Integrated Sensing Platform (FISP) for	1. Developed a flexible integrated sensing platform for comprehensive wound monitoring. 2. Demonstrated the ability to detect temperature changes in infected wounds using the sensing platform. 3. Identified different bacterial infections based on localized temperature changes.	1. Include local pH, uric acid, lactic acid, and glucose as indicators. 2. Enhance precision medicine, telemedicine, and AI diagnosis with the Flexible Integrated Sensing Platform (FISP). 3. Address the need for additional indicators and technologies to improve

			wound monitoring and infection prediction. 4. Applied statistical analysis with SPSS 19.0 software for interpreting data.		diagnostic accuracy and integration.
8.	A. Pusta, M. Tertiș, C. Cristea, and S. Mirel (Dec. 2021)	Wearable Sensors for the Detection of Biomarkers for Wound Infection,	1. Utilized electrochemical, colorimetric, and fluorometric sensors for detection. 2. Integrated wearable sensors into wound dressings for biomarker detection. 3. Embedded a pH-sensitive dye in a hydrogel wound dressing for pH detection. 4. Enabled wireless data transfer through RFID or NFC for sensor operation.	1. Developed wearable sensors for monitoring wound infection biomarkers. 2. Integrated nanomaterials to enhance the sensitivity of the sensors. 3. Focused on creating fully autonomous sensors with wireless data transfer capabilities.	1. Combine diagnostic and treatment strategies in 'smart dressing' for efficiency. 2. Address miniaturization challenges related to potentiostats, optic probes, and batteries. 3. Lack of information on long-term toxicity of nanomaterials used. 4. Need for fully autonomous sensors with wireless data transfer.

9.	Y. Zhang et al (Jul. 2021)	Flexible integrated sensing platform for monitoring wound temperature and predicting infection,	1. Fabricated a Flexible Integrated Sensing Platform (FISP) using Flexible Sensor Chip (FSC) and Conductive Polymer Composite Base (CPCB) components. 2. Monitored wound temperature with Bluetooth Low Energy (BLE) technology for data transmission. 3. Conducted statistical analysis with SPSS software to develop wound infection prediction models.	1. Developed a flexible integrated sensing platform (FISP) for advanced wound monitoring. 2. Proposed a novel method for visual and dynamic monitoring of wounds. 3. Fabricated the FISP incorporating a flexible sensor chip and circuit board. 4. Structured the FISP for real-time wound monitoring via a smartphone application.	1. Clinical value of healing factors is less than expected. 2. Inadequate medical resources for large-scale events. 3. Enhance precision medicine, telemedicine, and AI diagnosis with FISP technology.

10	K. Youssef, A. Ullah, P. Rezai, A. Hasan, and A. Amirfazli (Oct. 2023)	Recent advances in biosensors for real time monitoring of pH, temperature, and oxygen in chronic wounds	1. Utilized biosensors for real-time monitoring of pH, temperature, and oxygen levels. 2. Developed sensors specifically for monitoring wound biomarkers. 3. Applied electrochemical detection techniques for oxygen biosensing.	1. Developed biosensors for monitoring wound infections using colorimetric and electrochemical methods. 2. Created a highly stretchable wearable pH sensor designed for point-of-care applications. 3. Designed a transparent, flexible pH sensor with wireless monitoring capability. 4. Engineered a low-cost, omniphobic, paper-based smart bandage for continuous pH monitoring. 5. Created a dual-function wireless wound dressing for simultaneous pH and temperature monitoring.	1. Utilize microneedle arrays for efficient wound fluid collection. 2. Implement advanced image processing for enhanced accuracy in colorimetric sensors. 3. Combine multiple sensors for comprehensive wound infection status analysis.

2.2 Summary

Chronic wounds pose a significant challenge due to their slow healing and the need for constant monitoring. Traditional dressings, while helpful, lack the ability to continuously track wound progress. This literature review explores smart bandages as a promising solution for improved chronic wound management.

Smart bandages integrate sensors to monitor various wound parameters like, temperature, moisture. This real-time data can revolutionize wound care by enabling better-informed decisions, potentially leading to reduced hospital stays, lower healthcare costs, and improved patient comfort through less frequent dressing changes. Early detection of complications like infection is another potential benefit.

However, existing smart bandage technology faces limitations. Some designs are bulky and complex, making them unsuitable for specific body parts. Additionally, research often focuses on developing sensors without emphasizing data interpretation for predicting wound healing progress. Colorimetric sensors, while easy to use, might raise skin irritation concerns due to the dyes used.

The review also highlights advancements in miniaturized, wireless, and battery-free wound monitors for improved user comfort and integration. Different sensor types exist, offering functionalities like continuous monitoring, temperature distribution tracking, and oxygen level measurement, all crucial for wound healing. Research on moisture sensors can further optimize the healing environment and reduce unnecessary dressing changes.

Overall, the literature review emphasizes the tremendous potential of smart bandages to revolutionize chronic wound care. However, addressing current limitations and focusing on data interpretation for better treatment decisions are crucial steps towards wider adoption in clinical practice.

CHAPTER 3. RESEARCH METHODOLOGY

3.1 Introduction

This chapter outlines the methodology used to achieve the objectives of designing and developing a GSM-Based Smart Bandage System for Chronic Wound Monitoring and Management. It includes the data collection methods, research design methods, tools used, and concludes with the system model.

3.2 Data Collection Methods

The data for this research was collected using two primary methods: a prototype smart bandage system equipped with sensors and a questionnaire administered to healthcare professionals.

3.2.1 Questionnaire Data Collection

Sample: We worked on a sample of 20 healthcare professionals in Rwanda who are involved in wound care, including physicians (e.g., dermatologists, surgeons), nurses (e.g., wound care nurses), and physician assistants.

Survey Content: The questionnaire focused on the current level of awareness and adoption of smart bandages among healthcare professionals, perceived benefits and challenges associated with using smart bandages, preferences for functionalities and features in smart bandages, and the potential impact of smart bandages on wound care practices and patient outcomes.

Google Forms: The questionnaire was administered via Google Forms, and the data collected was analyzed using Google Forms' built-in tools. The insights gained from this analysis were used to inform the design and development of the GSM-Based Smart Bandage System.

3.2.2 Prototype Data Collection

Sensor Integration: The SHT31 sensor was integrated into the bandage to continuously monitor temperature and humidity levels at the wound site.

Real-time Data Transmission: Data was transmitted in real-time to the Blynk Cloud Platform via the SIM800L GSM module.

Data Logging: The Blynk Cloud Platform logged the data, making it accessible for analysis through its dashboard and data export functionalities.

3.3 Research Design Methods

The research design involved a systematic approach to developing the smart bandage system through the following steps:

3.3.1 System Design Process

The system design for chronic wound monitoring begins with establishing initial design specifications based on clinical needs, patient comfort, and usability. Clinically, the system must accurately monitor wound parameters such as size, temperature, and moisture levels. The devices should be non-invasive, lightweight, and comfortable for patients, ensuring ease of use for both patients and healthcare providers with intuitive interfaces and minimal maintenance.

Next, a detailed plan of the system architecture is developed. This involves selecting appropriate sensors, such as optical and temperature sensors, and microcontrollers with sufficient processing power for real-time data acquisition and processing. Reliable communication modules like Bluetooth or Wi-Fi are chosen for seamless data transmission, and suitable power sources are identified to ensure continuous operation.

The data flow is then defined to integrate hardware and software components seamlessly. This includes capturing accurate sensor data, processing it with algorithms to extract meaningful information, securely transmitting the data to the mobile application, and displaying it in a user-friendly format for real-time monitoring and decision-making by healthcare providers.

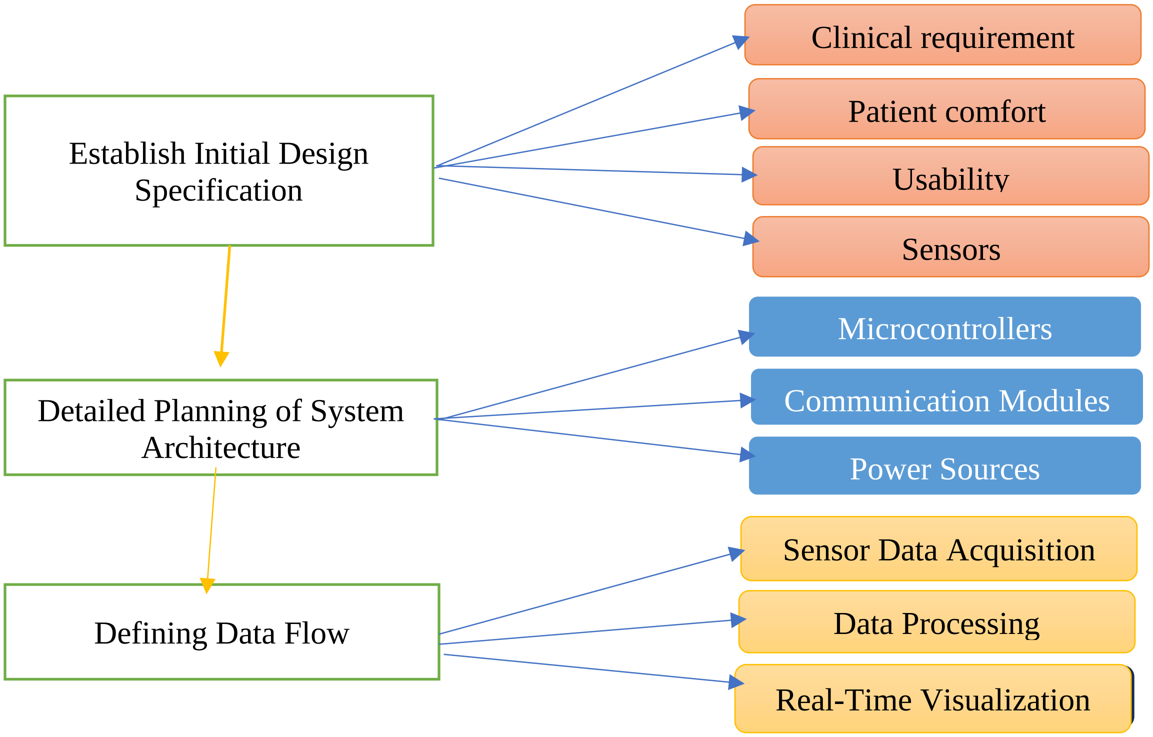

Figure 3.1 System Design Process

Overall, the system design aims to create an integrated solution combining robust hardware and intuitive software, providing reliable, real-time insights into wound healing progress.

3.3.2 Prototype Development Process

Table 3.1 Steps to Prototype smart bandage system

N⁰	Steps	Function
1.	Assembling the hardware components	Arduino Nano microcontroller, SIM800L GSM module, SHT31 temperature and humidity sensor, LM2596 voltage regulator, and a rechargeable battery
2.	Developing the Firmware	using the Arduino IDE to handle sensor data acquisition, processing, and communication with the GSM module.
3.	Integrating the GSM Module	enable wireless data transmission to the Blynk cloud platform
4.	Creating the Mobile Application Interface	Blynk mobile app for real-time data visualization and alerts.

3.3.3 Pilot Testing

Conducting pilot tests to thoroughly assess the accuracy and reliability of both the sensor data and GSM communication systems. These tests are designed to ensure that the data collected by the sensors is precise and that the GSM communication is robust and dependable. Additionally, evaluating the prototype’s performance under real-world conditions to determine whether it adheres to the established design specifications and operates effectively in practical scenarios. This involves testing the prototype in various environments and situations to validate its functionality and performance against the intended design goals.

3.3.4 Iterative Refinement

Refining the system based on the outcomes of pilot tests, with a focus on enhancing overall performance and reliability. This involves addressing any issues identified during testing, such as fine-tuning sensor calibration, optimizing power management, and improving data transmission reliability. The process includes iterative cycles of testing and adjustments to systematically address and resolve any deficiencies. Each iteration aims to progressively enhance the prototype until it consistently meets the established performance and reliability standards..

3.4 Tools Used and Definitions

3.4.1 The hardware used

3.4.1.1 Arduino Nano

Arduino nano is an intelligent development board designed for building faster prototypes with the smallest dimension, provides enough interfaces for your breadboard-friendly applications. At the heart of the board is an ATmega328 microcontroller clocked at a frequency of 16 MHz the board offers twenty digital input/output pins, eight analog pins, and a mini-USB port[59].

Table 3.2 Arduino Nano: Description, Functions, and Specifications

Description	A compact microcontroller board designed for easy integration into small projects.
Functions	Central processing unit that handles data acquisition, processing, and communication with other components.
Specifications	Based on the ATmega328P, it features 20 digital I/O pins, 8 analog inputs, and operates at 16MHz.

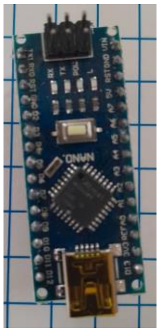

Figure 3.2: Arduino nano hardware

3.4.1.2 SIM800L Module

The SIM800L is a GSM module that gives any microcontroller GSM functionality, meaning it can connect to the mobile network to receive calls and send and receive text messages, and connect to the internet using GPRS, TCP, or IP. Another advantage is that the board makes use of existing mobile frequencies, which means it can be used anywhere in the world[60].

Table 3.3: SIM800L GSM Module: Description, Functions, and Specifications

Description	A versatile GSM/GPRS module that facilitates mobile communication.
Functions	Enables the transmission of data to the Blynk Cloud Platform and can send/receive SMS.
Specifications	Supports quad-band GSM (850/900/1800/1900MHz), operates at 3.7V – 4.2V, and interfaces via UART.

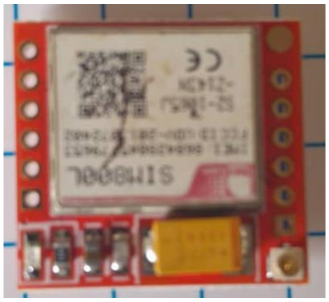

Figure 3.3: SIM800l module hardware

3.4.1.3 SHT31 Sensor

Table 3.4 SHT31 Sensor Specifications and Functions

Description	A highly accurate digital sensor for measuring temperature and humidity.
Functions	Provides critical data on the wound environment, aiding in effective wound management.
Specifications	Measures temperature from -40°C to 125°C with ±0.2°C accuracy and humidity from 0% to 100% with ±2% accuracy.

The SHT31 outperforms the competition because of its superior durability, increased operating range, remarkable precision, and intuitive digital interface. This results to accurate and dependable data collection for this smart bandage's efficient wound healing monitoring.

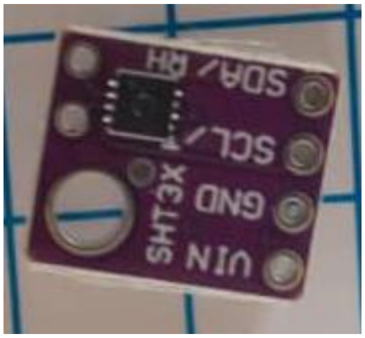

Figure 3.4:SHT31 Digital Temperature and Humidity sensor

3.4.1.4 Power Supply

To ensure continuous and reliable operation of the smart bandage device, a suitable power supply solution was required. A rechargeable lithium-polymer battery (9V, 1000mAh) was selected as the power source due to its high energy density, lightweight, and compact size.

The battery was integrated into the hardware design, along with a charging circuit and protection mechanisms. The charging circuit allows the battery to be recharged using a standard USB port.

3.4.1.5 USB cable

A Universal Serial Bus (USB) is a common interface that enables communication between devices and a host controller such as a personal computer (PC) or smartphone. It connects peripheral devices such as digital cameras, mice, keyboards, printers, scanners, media devices, external hard drives, and flash drives. It is used to connect any board with personal computer (pc) like Arduino nano.

Figure 3.5 USB cable

3.2.1.6 Jump wires

Jump wires are cables that are used to connect two locations in a circuit together. They are usually used in conjunction with breadboards and other prototyping equipment to facilitate the easy modification of circuits as needed.

Figure 3.6 Jump wires

3.4.2 The software used

3.4.2.1 Blynk Cloud Platform

In the smart bandage system, the Blynk cloud platform acts as the intermediary between the Arduino Nano, which collects sensor data, and the Blynk mobile app, which visualizes this data. The Blynk cloud serves as the central hub, receiving temperature and humidity readings from the Arduino Nano via the SIM800L module. It stores this data, facilitating trend analysis over time, and implements security measures to ensure the privacy and integrity of sensitive patient information. Real-time data delivery from the Blynk cloud to the mobile app allows immediate visualization, aiding in timely monitoring of the wound's condition. Utilizing Blynk cloud simplifies data management by providing a centralized platform for data reception, storage, and routing, while ensuring real-time delivery and scalability to support future growth. The cloud's focus on security also ensures the confidentiality of patient data.

Table 3.5 Blynk Cloud Platform: Overview, Functions, and Features

Description	An IoT platform designed for managing and visualizing real-time data.
Functions	Stores data from the smart bandage system and displays it through the Blynk mobile app, providing real-time monitoring and alerts.
Features	Secure data storage, customizable dashboards, and real-time data updates.

3.4.2.2 Arduino IDE

The firmware for the smart bandage device, developed using the Arduino Integrated Development Environment (IDE) and the Arduino programming language, is crucial for sensor data acquisition, processing, and communication with the GSM module. It interfaces with temperature and humidity sensors, handles initialization and periodic readings, and employs algorithms to filter out noise for accurate monitoring. Using AT commands, it communicates processed data to the SIM800L GSM module, which then transmits this information via GPRS or SMS to the mobile application. To extend battery life, the firmware incorporates power management strategies, including low-power modes and efficient sleep/wake cycles. Additionally, robust error handling and debugging ensure reliable operation. The firmware was rigorously tested and refined to guarantee optimal performance and efficiency of the smart bandage system.

Table 3.6 Arduino IDE for Firmware Development: Description, Functions, and Features

Description	A software platform used for programming and uploading code to Arduino boards.
Functions	Facilitates firmware development for the Arduino Nano, including coding, debugging, and uploading.
Features	User-friendly interface, extensive library support, and compatibility with C/C++.

3.4.2.3 Android application

In the smart bandage system, the mobile application acts as a window into the wound's healing process, with the Blynk Mobile App serving as the user interface and data visualization component. The app centralizes the visualization and interaction with data collected by the smart bandage. It offers real-time data visualization, enabling users to monitor temperature and humidity readings from the SHT31 sensor embedded in the bandage, providing immediate insights into the wound environment. Blynk's widgets, such as gauges, graphs, and charts, present this data clearly and user-friendly.

Additionally, the app can store historical data on temperature and humidity, allowing users to track trends over time and identify potential issues in wound healing. This historical data analysis is valuable for healthcare professionals in making informed treatment decisions. The app can also generate alerts and notifications if readings fall outside predefined normal ranges, crucial for timely intervention and preventing complications.

Blynk's platform simplifies app development by providing a visual interface for designing user-friendly interfaces without extensive coding experience. This ensures that both patients and healthcare professionals can easily navigate the app. Blynk's pre-built features allow developers to focus on core functionalities, ensuring the app is accessible and compatible with various mobile operating systems, making it seamless on a wide range of smartphones and tablets used by patients and healthcare providers.

3.4.2.4 Google Forms

Table 3.7 Google Forms: Description, Functions, and Features

Description	An online survey tool for creating and distributing questionnaires.
Functions	Collects data from healthcare professionals on their perceptions and needs regarding smart bandages.
Features	Customizable forms, real-time response collection, and integrated data analysis tools.

These tools and components are integral to the design, development, and functionality of the GSM-based smart bandage system, ensuring it meets the requirements for effective chronic wound monitoring and management.

3.5 Proposed System Model

The proposed system diagram for the GSM-based smart bandage system illustrates the various components and their interactions. The key components include the Arduino Nano, SIM800L GSM module, SHT31 temperature and humidity sensor, LM2596 voltage regulator, and a rechargeable battery. The software ecosystem comprises the Arduino Integrated Development Environment (IDE), Blynk mobile app, and Blynk cloud platform.

Table 3.8 System Diagram and Data Flow for the GSM-Based Smart Bandage System

Data Acquisition	The SHT31 sensor continuously measures temperature and humidity levels at the wound site and transmits the data to the Arduino Nano.
Data Processing	The Arduino Nano processes the data and detects any anomalies indicating infection or other complications
Data Transmission	The processed data is sent to the Blynk cloud platform via the SIM800L GSM module.
Data Visualization	The Blynk cloud platform stores the data and makes it available for real-time visualization on the Blynk mobile app. The app generates alerts for abnormal readings, enabling prompt intervention

The system architecture is depicted in Figure 3.6. below

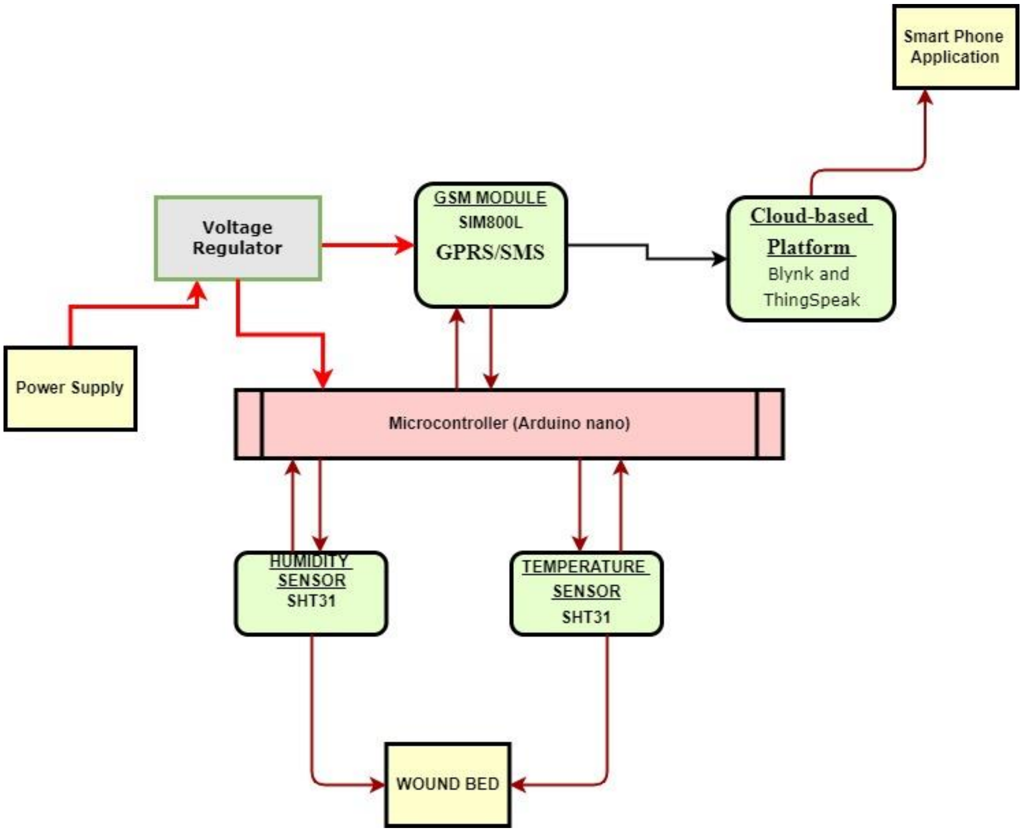

Figure 3.6 The system architecture of smart bandage system!

The GSM-based smart bandage system leverages the integration of advanced sensors, microcontrollers, GSM communication, and cloud technology to offer a comprehensive solution for chronic wound monitoring. By enabling real-time data acquisition, processing, transmission, and visualization, the system improves patient care and facilitates timely interventions by healthcare providers.

3.6 Summary

This chapter has outlined the research methodology for developing the GSM-based smart bandage system, including data collection methods, research design, tools used, and the system architecture.

CHAPTER 4. SYSTEM DESIGN AND IMPLEMENTATION

In this chapter, we will discuss the detailed system design and implementation of the GSM-based smart bandage system for chronic wound monitoring and management. The system is designed to continuously monitor the wound environment and transmit data to a remote server for real-time monitoring by healthcare providers. illustrated with flow charts for clarity.

4.1 System Requirements

4.1.1 Functional Requirements

1. **Real-time Monitoring**: The system should provide real-time monitoring of the wound environment.
2. **Data Transmission**: The system should transmit data to a remote server using GSM technology.
3. **User Interface**: The system should have a user-friendly interface accessible via a mobile application.
4. **Alert System**: The system should be capable of sending alerts in case of abnormal conditions.

The functional requirements define the essential functions the system must perform to achieve its objectives. Flow chart below illustrate functional requirements of smart bandage system.

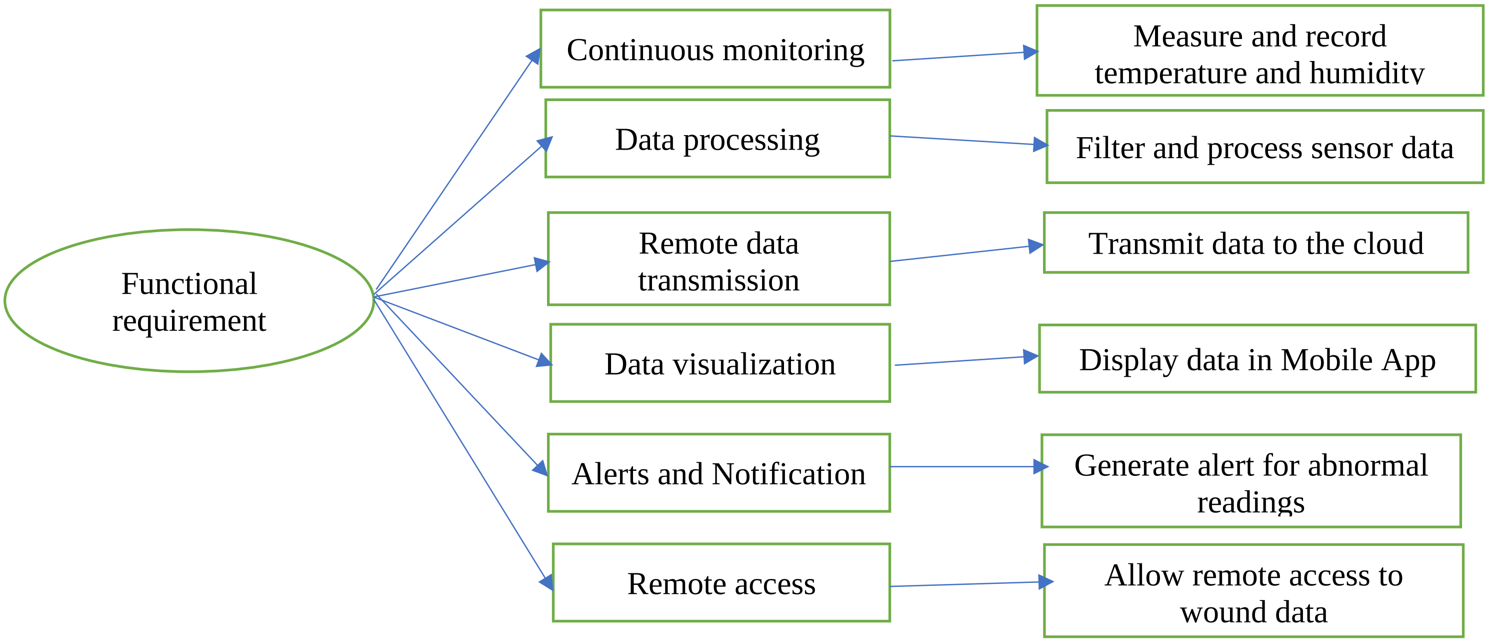

Figure 4.1 The functional requirements of smart bandage system

4.1.2 Non-Functional Requirements

The non-functional requirements ensure the system's performance, reliability security, and usability.

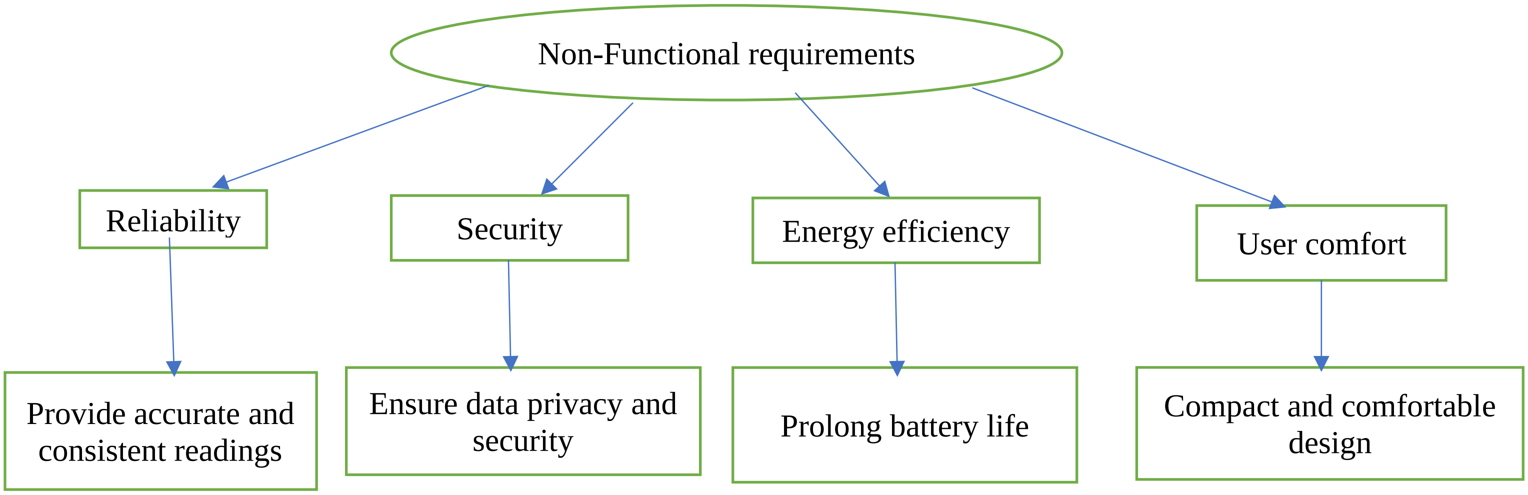

Figure 4.2 Non-Functional Requirements

1. Reliability: The system should be reliable and provide accurate data.
2. Battery Life: The system should have a long battery life to avoid frequent recharges.
3. Scalability: The system should be scalable to accommodate additional sensors or features in the future.
4. Usability: The system should be easy to use for both patients and healthcare providers.

4.2 System Components

The system components describe the overall components, including hardware and software components.

4.2.1 Hardware Components

In this figure 4.3, describe all the hardware components used in prototyping smart bandage system and their corresponding functions.

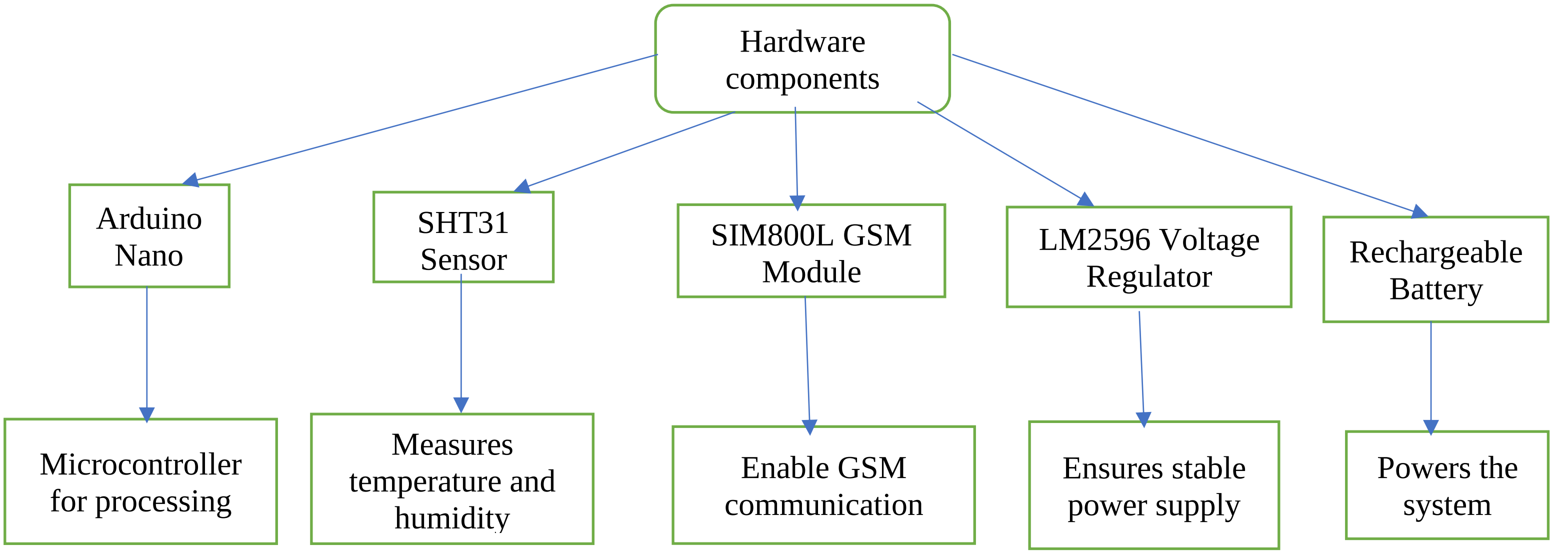

Figure 4.3: Summary of hardware components used in prototyping smart bandage

4.2.2 Software Components

The software components used in designing this system, and how the components interact:

1. **Arduino IDE:** This is used for programming the Arduino Nano.
2. **Blynk Cloud Platform**: The data collected by the Arduino is sent to this platform for storage and visualization.
3. **Blynk Mobile App**: This app interacts with the Blynk Cloud Platform, providing a user-friendly interface for real-time monitoring and alerts.

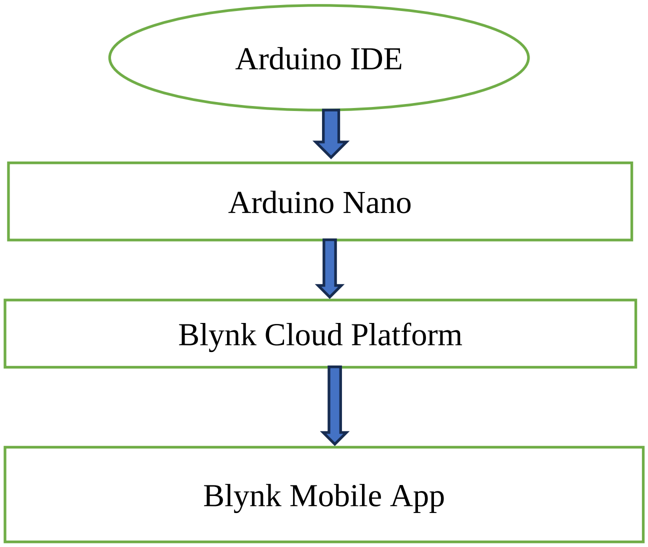

Figure 4.4: Summary of software components used in this system

Figure 4.4 shows the flow from programming the Arduino Nano with the Arduino IDE, to data storage and visualization on the Blynk Cloud Platform, and finally to real-time monitoring and alerts on the Blynk Mobile App.

4.3 System architecture

The system architecture consists of three main layers: the sensing layer, the communication layer, and the application layer.

1. **Sensing Layer**: Comprises the SHT31 sensor which collects data on temperature and humidity from the wound environment.
2. **Communication Layer**: Includes the Arduino Nano and SIM800L module. The Arduino processes the sensor data and uses the SIM800L to send it to the Blynk Cloud Platform.
3. **Application Layer**: Consists of the Blynk Cloud Platform and the Blynk Mobile App, which store, analyze, and display the data to the user.

To represent the system architecture with its three main layers, we use a layered diagram that shows how each component fits into the sensing, communication, and application layers.

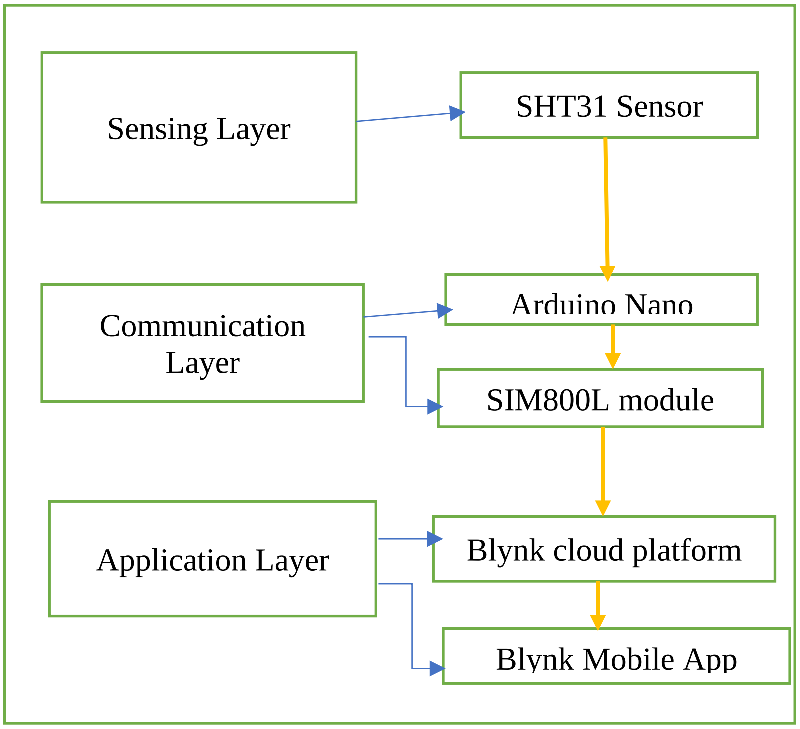

Figure 4.5: Diagram that illustrates how the components are organized within the three layers of the system architecture

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4.4 Circuit Design

The circuit design involves connecting the SHT31 sensor to the Arduino Nano, which processes the data and uses the SIM800L module for data transmission. The LM2596 voltage regulator ensures that the Arduino and SIM800L receive a stable voltage from the battery.

1. **SHT31 Sensor Connection**: The SHT31 sensor is connected to the Arduino Nano via I2C protocol.
2. **SIM800L Module Connection**: The SIM800L module is connected to the Arduino Nano via serial communication (TX and RX pins).
3. **LM2596 Voltage Regulator Connection**: The voltage regulator is connected to the battery and provides a stable 5V output to the Arduino Nano and SIM800L module.

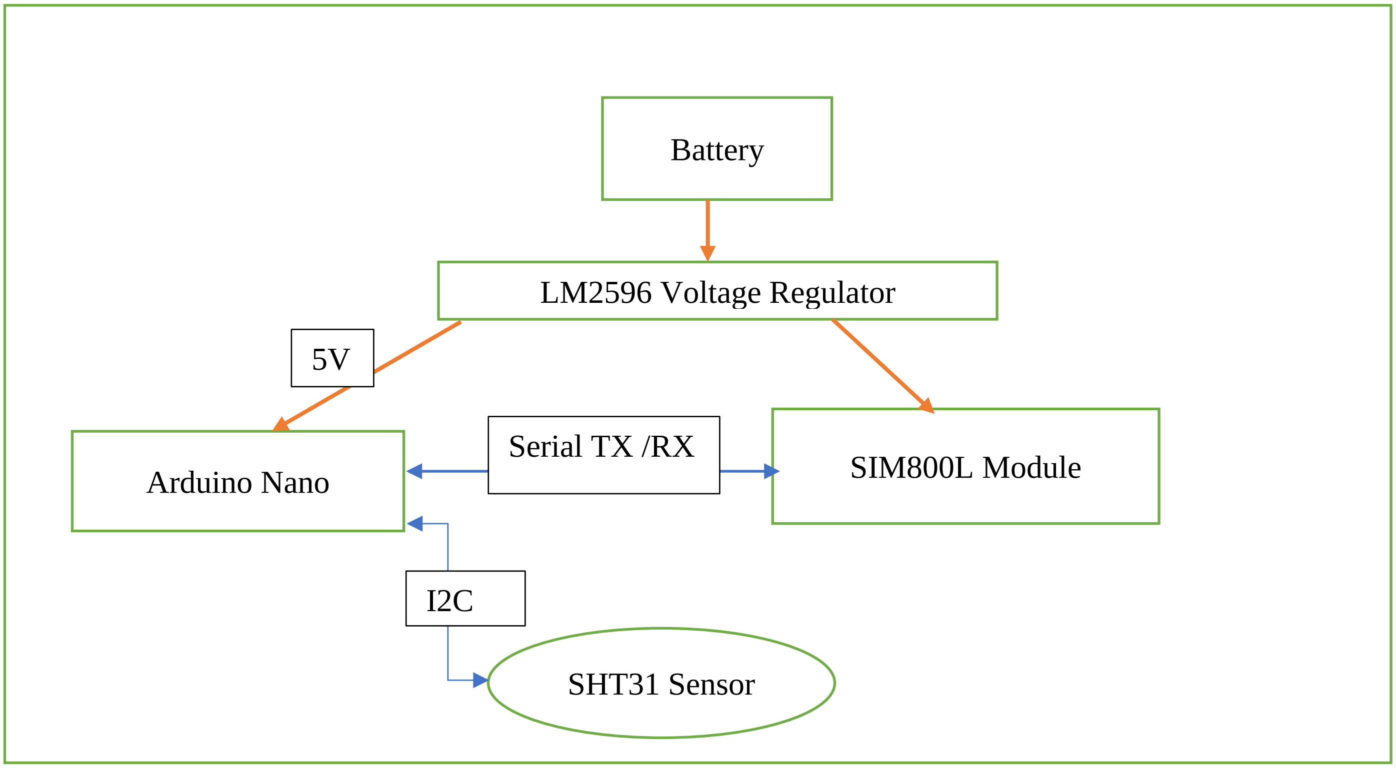


Figure 4.6: The diagram shows the Circuit design of a smart bandage system

4.5 Software Design

The software design involves programming the Arduino Nano to read data from the SHT31 sensor and transmit it to the Blynk Cloud Platform using the SIM800L module. The Blynk Mobile App is configured to receive and display the data.

1. **Arduino Nano Programming**: The Arduino is programmed using the Arduino IDE to read data from the SHT31 sensor at regular intervals and send it to the Blynk Cloud Platform using the SIM800L module.
2. **Blynk Cloud Configuration**: The Blynk Cloud Platform is configured to receive data from the Arduino Nano and store it in a database.

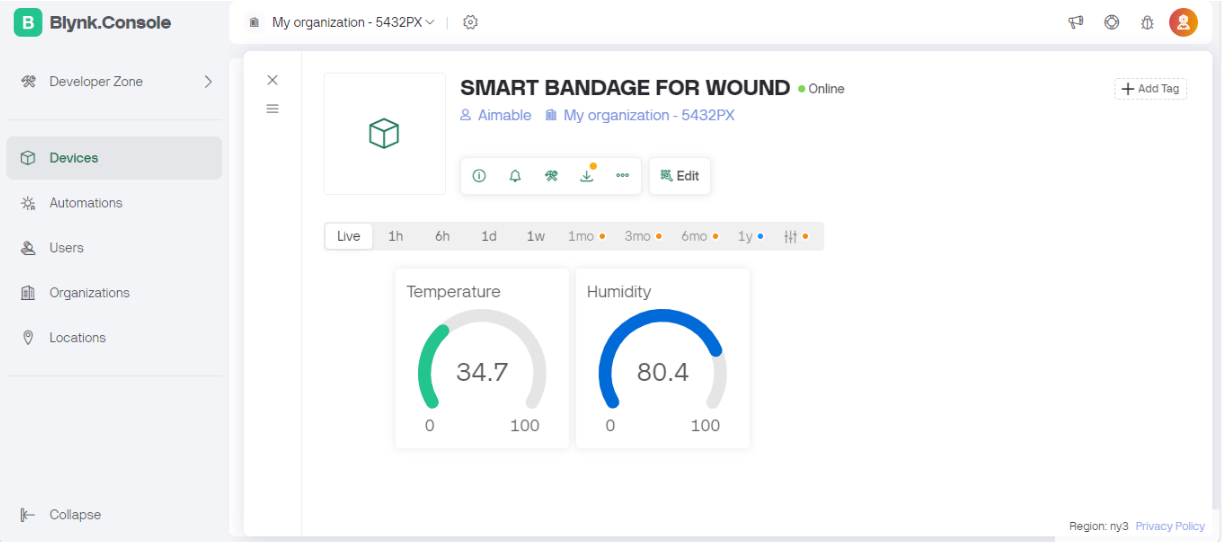


Figure 4.7: Blynk cloud Web Dashboard

3. **Blynk Mobile App Configuration**: The Blynk Mobile App is configured to display the data in real-time and send alerts in case of abnormal conditions.

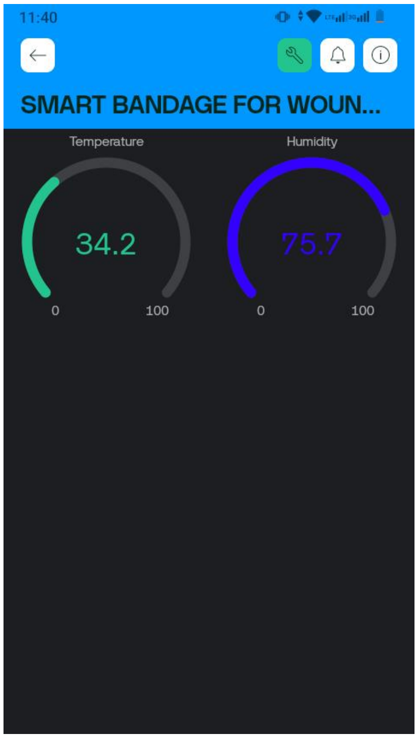


Figure 4.8: Smart bandage mobile app

4.6 System Integration

System integration combines the hardware and software components into a functional prototype.

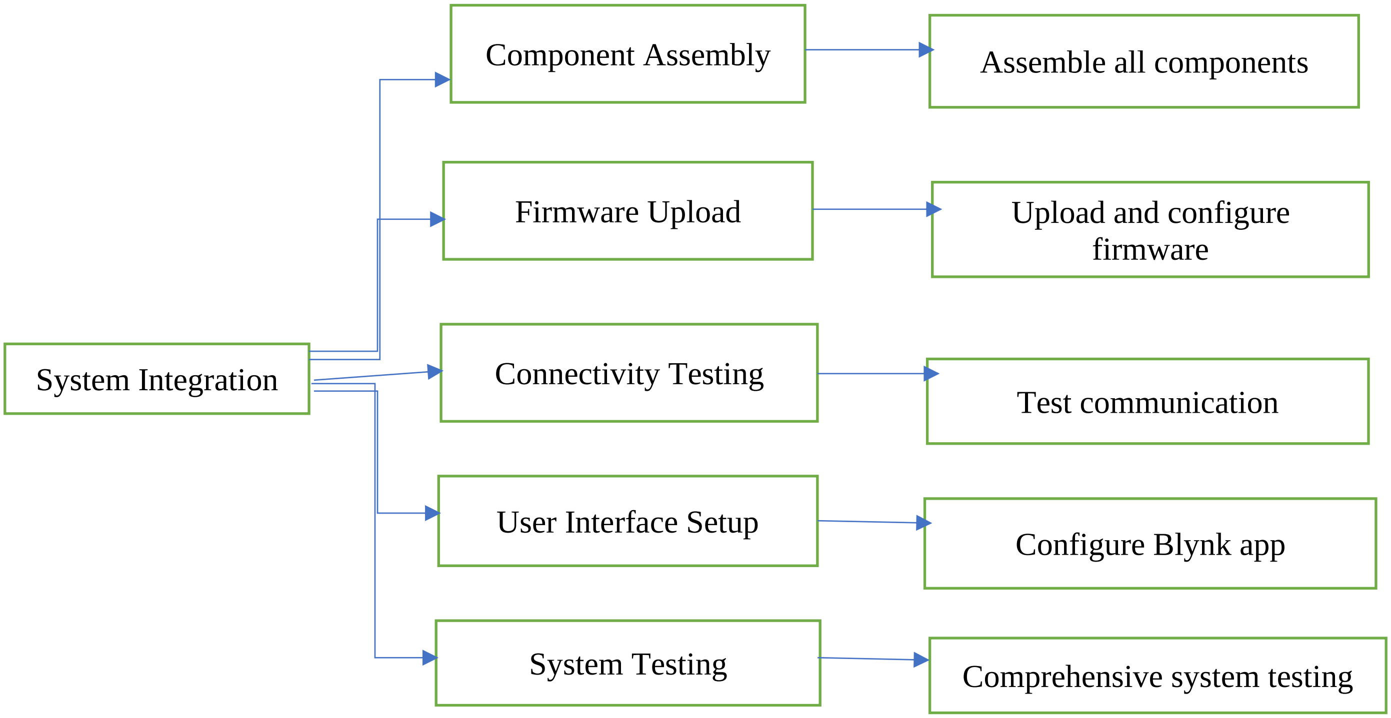


Figure 4.9: The summarized steps for system integration

4.8 Smart bandage system flow chart

4.8.1 Continuous Closed-Loop Monitoring Process for Smart Bandage Wound Care

In the continuous closed-loop monitoring process for smart bandage wound care, the system begins with the measurement phase, where temperature and humidity sensors embedded within the smart bandage capture data from the wound site. This data, critical for understanding the wound environment, is then processed by the Arduino Nano microcontroller. The microcontroller filters and processes the raw sensor data to ensure accuracy and reliability.

Once processed, the data is transmitted to the Blynk Cloud via the SIM800L GSM module. This cloud platform acts as a central repository, storing the data securely and facilitating further analysis. The cloud platform then forwards the data to the Blynk mobile app, which provides real-time visualization and alerts. Through the mobile app, users can monitor the wound's condition continuously. If the data indicates any abnormalities, such as elevated temperature or humidity levels that could signal an infection or other issues, the system generates alerts. These alerts prompt immediate intervention, ensuring timely and appropriate wound care. This continuous feedback loop enhances the ability to monitor and manage wound healing effectively, potentially improving patient outcomes. The system flow chat summarizing the above description is presented in Figure 4.10.

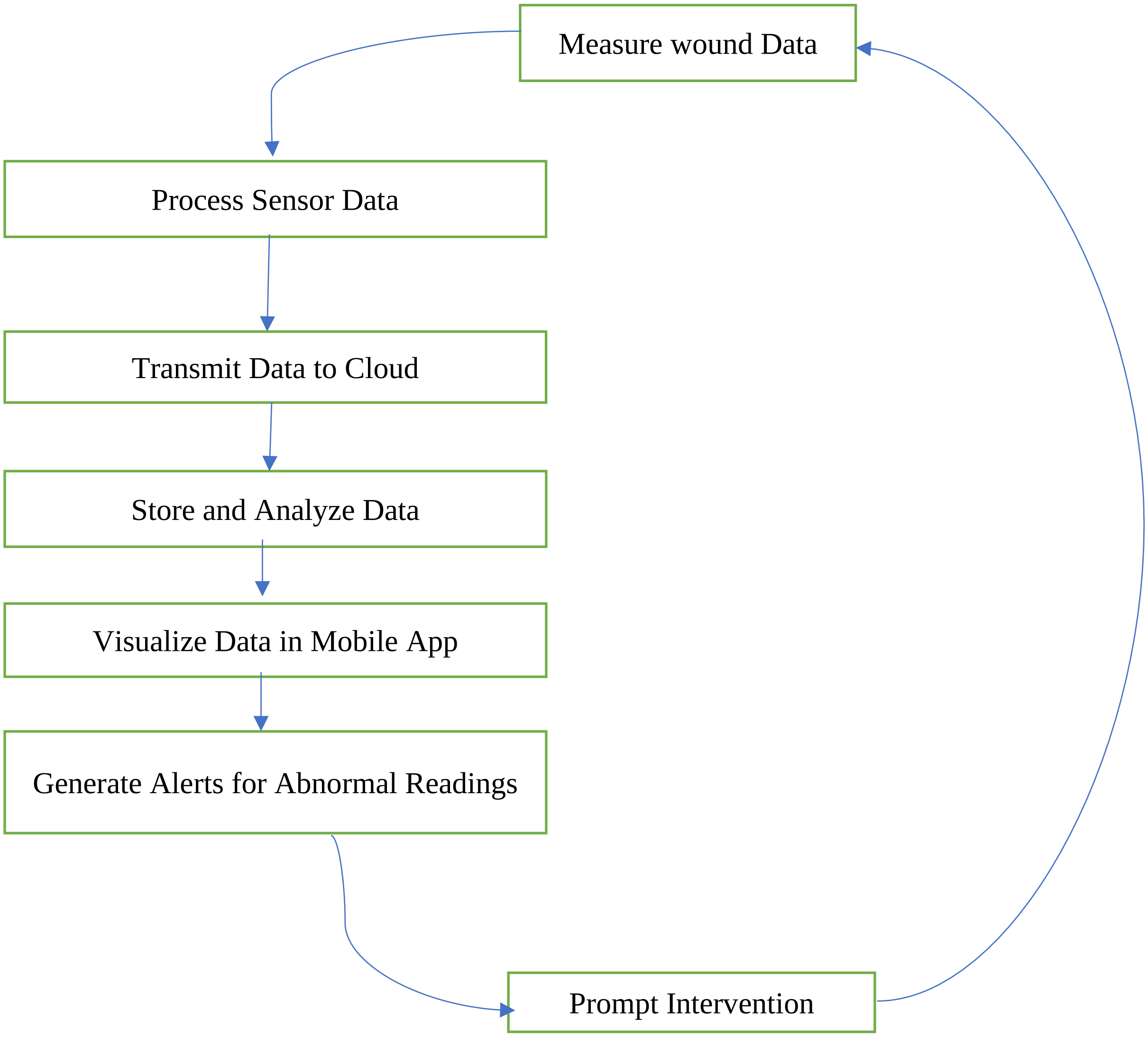


Figure 4.10: The continuous closed-loop monitoring process for smart bandage wound care

In summary, this system design for the smart bandage enables continuous, real-time monitoring of wound conditions through an integrated process involving data measurement, processing, transmission, storage, visualization, and intervention. This closed-loop system ensures that any potential issues are promptly identified and addressed, thereby enhancing the effectiveness of wound care management.

4.8.2 Checking for Abnormalities in the Smart Bandage System

The smart bandage system is designed to monitor wound conditions continuously and identify potential abnormalities that may indicate issues such as infection, poor healing conditions, or other complications. The process involves several key steps:

The smart bandage system integrates the SHT31 sensor to continuously monitor temperature and humidity levels at the wound site, providing essential insights into the wound environment. Upon data collection, the

Arduino Nano undertakes rigorous processing, focusing on noise filtration and algorithmic application to ensure the data's accuracy and reliability. This processed data is then compared against established normal ranges, informed by medical standards for optimal wound healing conditions. In real-time, the Arduino Nano analyzes the data, promptly identifying any deviations from these norms as potential abnormalities. Based on this analysis, the system makes decisions regarding the presence of abnormalities, triggering an alert generation if necessary. Alerts are transmitted via the SIM800L GSM module to the Blynk Cloud platform, which subsequently notifies users through the Blynk mobile app. This alert mechanism empowers healthcare providers and patients to swiftly address issues by adjusting treatment strategies or seeking medical attention, thereby enhancing overall wound care management.

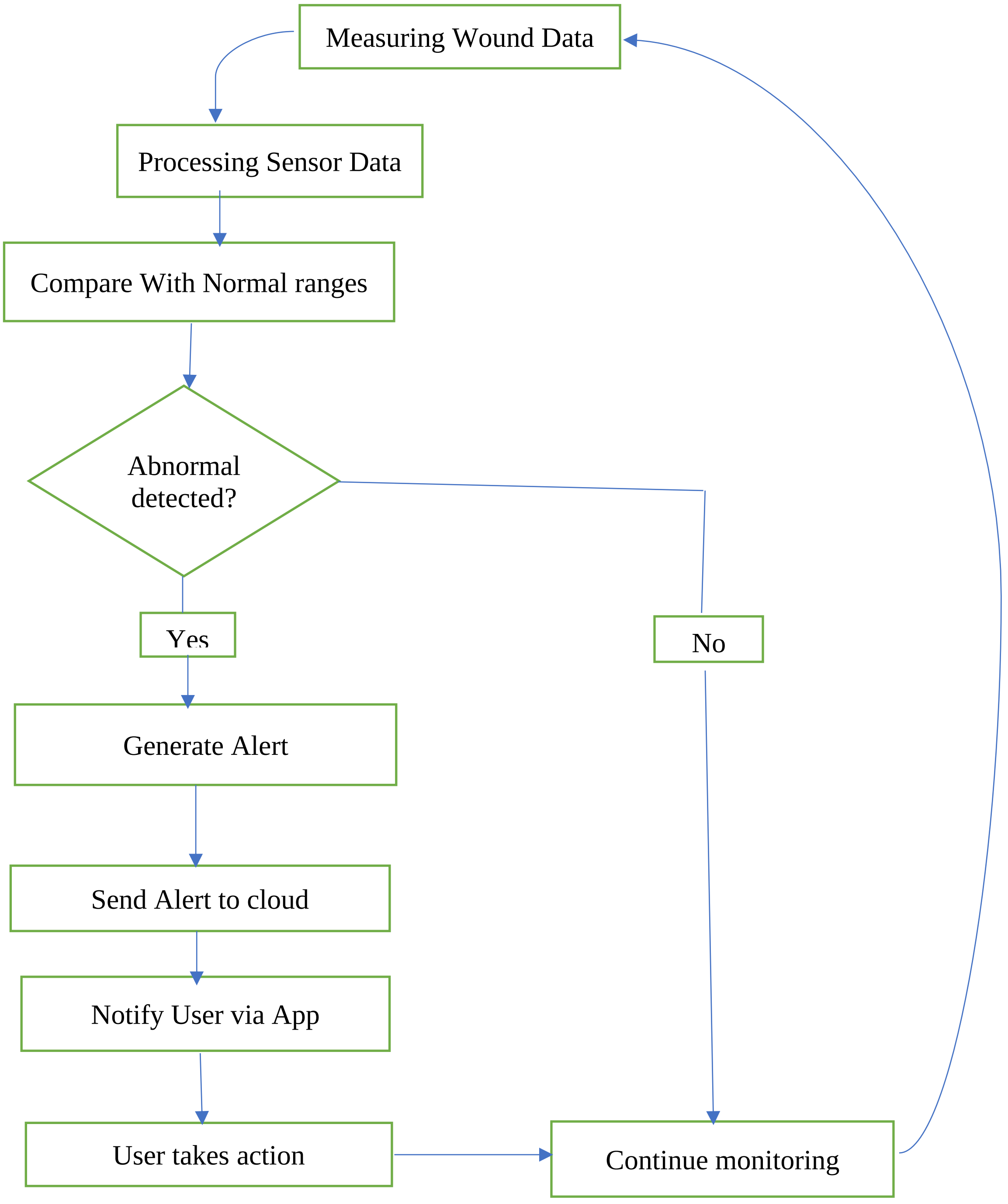
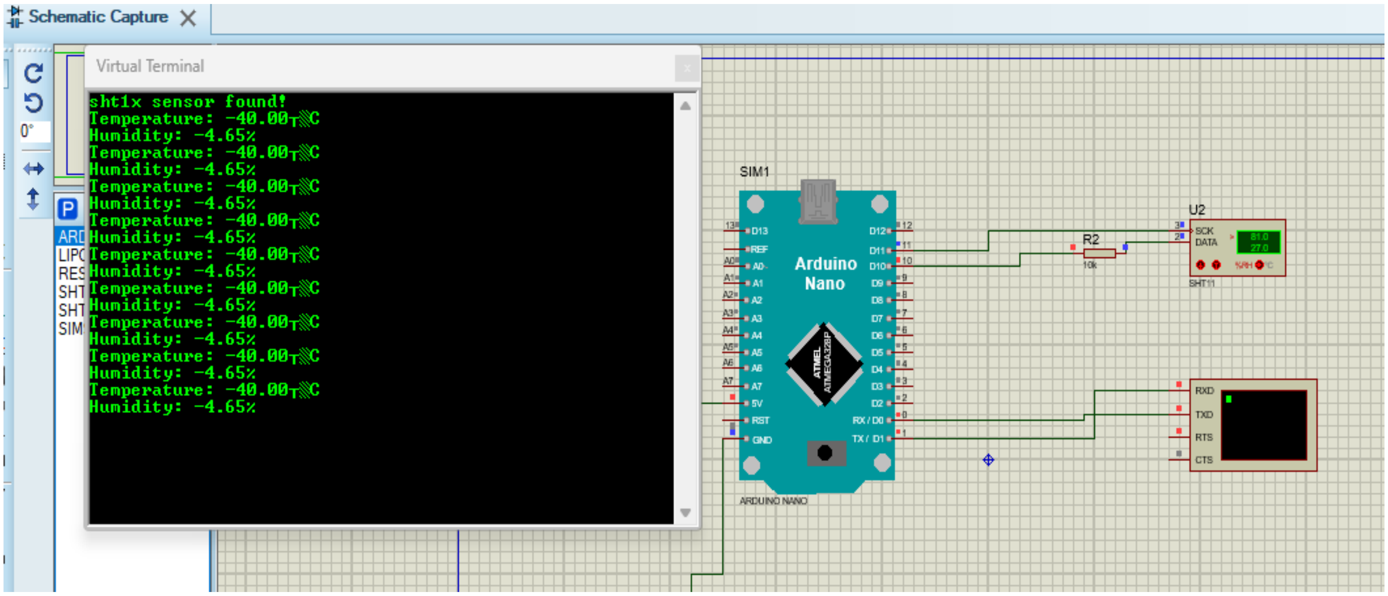


Figure 4.11: Checking for Abnormalities in the Smart Bandage System

4.9 Simulation Model

The simulation model used is proteus 8 professional for anticipating the results of the system. This proteus helps us to get sensor data about Temperature and Humidity status on Serial monitor



```
sht1x sensor found!
Temperature: -40.00┬░C
Humidity: -4.65%
Temperature: -40.00┬░C
Humidity: -4.65%
Temperature: -40.00┬░C
Humidity: -4.65%
Temperature: -40.00┬░C
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Temperature: -40.00┬░C
Humidity: -4.65%
Temperature: -40.00┬░C
Humidity: -4.65%
```

Figure 4.12: Proteus simulation to display Temperature and Humidity

The Proteus simulation confirms promising functionality for the core components of the smart bandage system. The Arduino Nano successfully communicated with the SHT31 sensor via I2C protocol, as evident by the virtual terminal displaying simulated temperature and humidity readings. This demonstrates the ability to acquire sensor data.

4.9 Prototype Development

The prototype of the GSM-based smart bandage system was developed using the components and design described in Chapter 3. The system was assembled and programmed to monitor the wound environment and transmit data to the Blynk Cloud Platform.

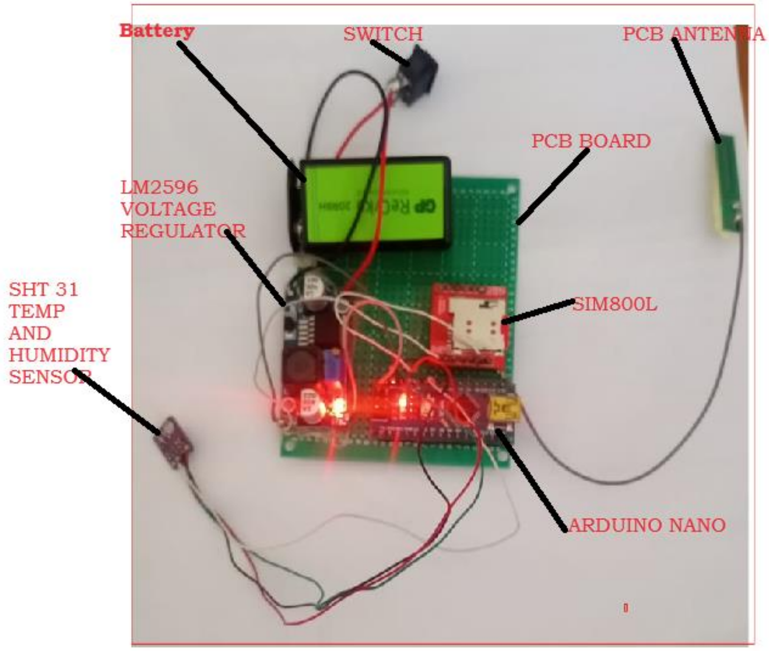


Figure 4.13: The complete hardware setup for the GSM-Based Smart Bandage System

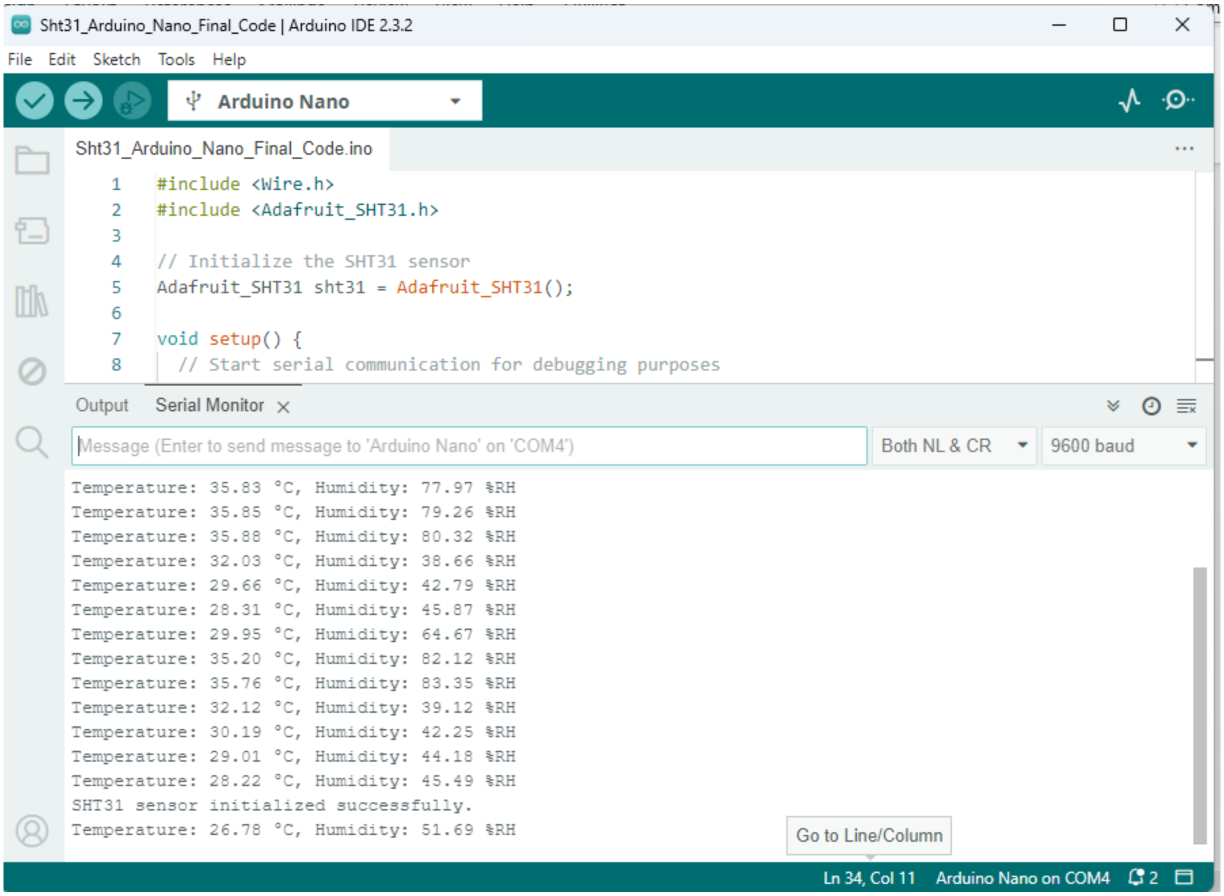
This prototype smart bandage represents a wearable solution for monitoring wound healing. Figure 4.13 shows the complete hardware setup for the GSM-Based Smart Bandage System. Key components include the battery, which powers the system, and a switch for managing power consumption. The LM2596 voltage regulator ensures a stable 5V supply to the Arduino Nano and SIM800L module. The SHT31 temperature and humidity sensor collects data from the wound environment, which the Arduino Nano processes. The SIM800L module transmits this data to the Blynk Cloud Platform, with the PCB antenna enhancing signal strength. All components are securely mounted on a PCB board, supporting accurate data collection, processing, and wireless transmission for effective wound monitoring.

This combination of components paves the way for real-time wound monitoring and data analysis, potentially leading to improved wound care practices.

4.10 Testing and Validation

The system was tested under different conditions to validate its performance. The tests included:

Sensor Test: The SHT31 sensor was tested by using a serial monitor



```
#include <Wire.h>
#include <Adafruit_SHT31.h>

// Initialize the SHT31 sensor
Adafruit_SHT31 sht31 = Adafruit_SHT31();

void setup() {
  // Start serial communication for debugging purposes
```

```
Temperature: 35.83 °C, Humidity: 77.97 %RH
Temperature: 35.85 °C, Humidity: 79.26 %RH
Temperature: 35.88 °C, Humidity: 80.32 %RH
Temperature: 32.03 °C, Humidity: 38.66 %RH
Temperature: 29.66 °C, Humidity: 42.79 %RH
Temperature: 28.31 °C, Humidity: 45.87 %RH
Temperature: 29.95 °C, Humidity: 64.67 %RH
Temperature: 35.20 °C, Humidity: 82.12 %RH
Temperature: 35.76 °C, Humidity: 83.35 %RH
Temperature: 32.12 °C, Humidity: 39.12 %RH
Temperature: 30.19 °C, Humidity: 42.25 %RH
Temperature: 29.01 °C, Humidity: 44.18 %RH
Temperature: 28.22 °C, Humidity: 45.49 %RH
SHT31 sensor initialized successfully.
Temperature: 26.78 °C, Humidity: 51.69 %RH
```

Figure 4.14: The Serial Monitor output from the Arduino IDE

The Serial Monitor output from the Arduino IDE, as shown in the provided figure 35, displays temperature and humidity readings from the SHT31 sensor. The temperature values range from approximately 26.78°C to 35.85°C, consistent with the typical wound environment and human body temperatures. This confirms the sensor's accuracy and responsiveness to changes in temperature.

The humidity readings range from approximately 38.66% RH to 83.35% RH, covering a broad spectrum of relative humidity levels crucial for effective wound management. These readings ensure that the wound environment maintains an optimal balance, preventing issues related to excessive dryness or moisture. The SHT31 sensor's reliable performance in monitoring humidity is essential for the system's overall effectiveness. Additionally, the successful initialization of the SHT31 sensor is confirmed by the message "SHT31 sensor initialized successfully" in the Serial Monitor. This indicates proper integration and functionality of the sensor with the Arduino Nano. The system's capability to continuously monitor temperature and humidity in real-time is validated, ensuring immediate feedback for wound management. The results demonstrate that the smart bandage system is reliable and effective for chronic wound monitoring and management.

Data Transmission Test: The reliability of data transmission via the SIM800L module was tested by monitoring the success rate of data uploads to the Blynk Cloud Platform.

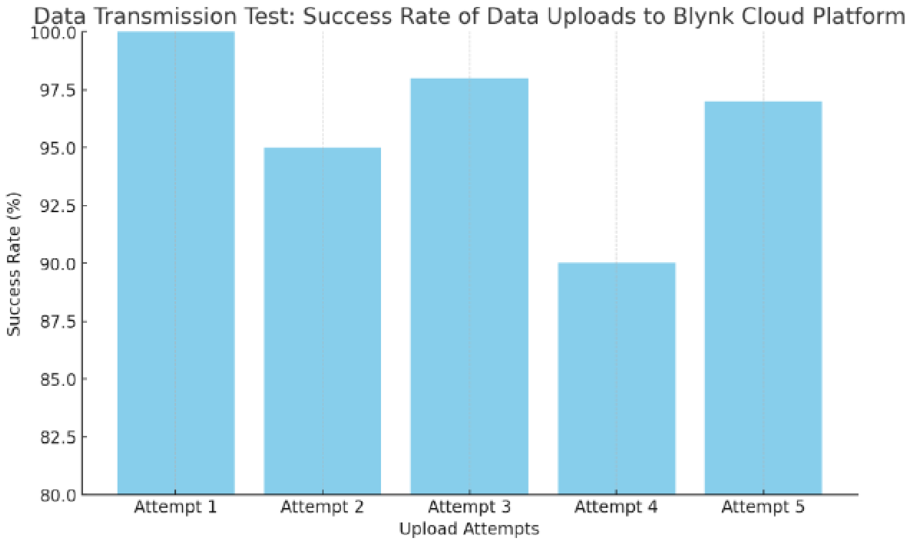


Figure 4.15: A bar chart shows the success rate of data uploads to the Blynk Cloud Platform.

Battery Life Test: The battery life was tested by measuring the duration for which the system could operate continuously on a single charge.

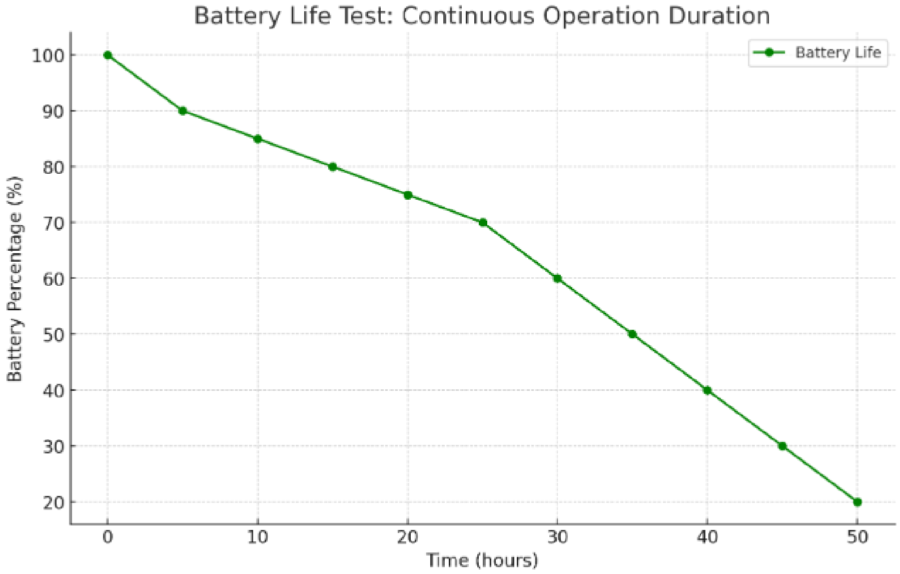


Figure 4.16: A line chart that illustrate the battery life over time

A line chart illustrates the battery life over time, showing how long the system can operate continuously on a single charge.

4.11 Summary

This chapter has detailed the system design and implementation of the GSM-Based Smart Bandage System for Chronic Wound Monitoring and Management. The system requirements, architecture, hardware and software design considerations, integration processes, and a flow chart were thoroughly discussed. The next chapter will present the results analysis and discussion of the smart bandage system.

CHAPTER 5. THE RESULTS ANALYSIS AND DISCUSSION

5.1 Introduction

This chapter presents a comprehensive analysis of the data collected through questionnaires distributed to administered to healthcare professionals in Rwanda and the performance data from the GSM-based smart bandage system The data provide insights into the current wound care practices, awareness and adoption of smart bandages, perceived benefits and challenges, and the impact of smart bandages on wound care practices and patient outcomes.

5.2 Questionnaire Data Analysis

The data were collected from 20 healthcare professionals in Rwanda, including physicians, nurses, and physician assistants. The Google Forms platform was used to design and distribute the questionnaires, and responses were automatically compiled for analysis.

5.2.1 Current Wound Care Practices

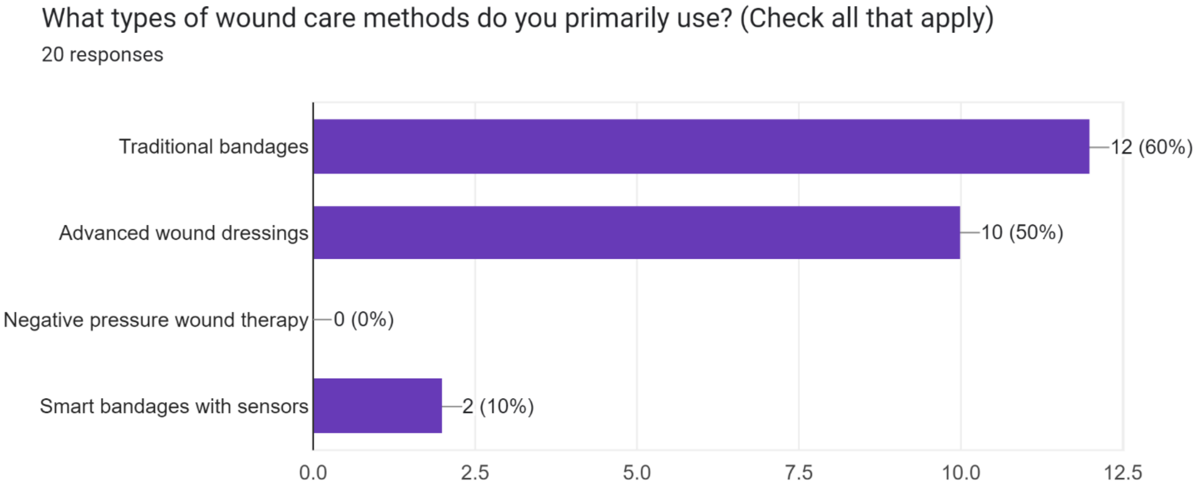


Figure 5.1 Current wound care practices

The findings show that most healthcare professionals (60%) primarily use traditional bandages, followed closely by advanced wound dressings (50%). This indicates that while traditional methods remain dominant, there is a significant use of more advanced dressings. However, the usage of NPWT and smart bandages is notably low, with only 10% of respondents using smart bandages. This suggests a need for increased awareness and availability of advanced wound care options.

5.2.2 Challenges with Traditional Methods

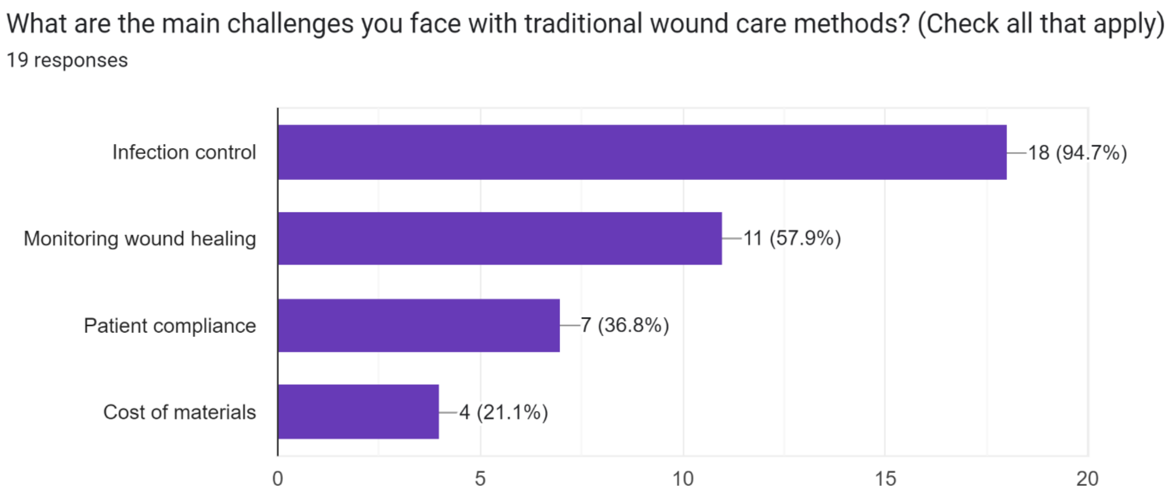


Figure 5.2 Challenges with Traditional Methods

Infection control (94.7%) and monitoring wound healing (57.9%) emerged as the major challenges with traditional wound care methods. This indicates a significant gap in current practices that smart bandages could potentially fill. The challenges in patient compliance (36.8%) and the cost of materials (21.1%) also highlight areas where smart bandages could provide improvements through better monitoring and potentially reducing the need for frequent dressing changes.

5.2.3 Effectiveness of Traditional Methods

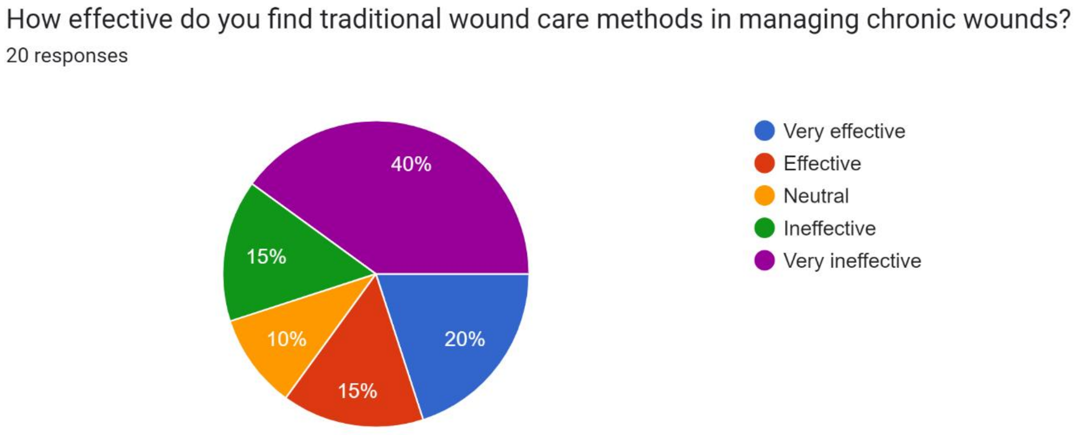


Figure 5.3 Effectiveness of Traditional Methods

A notable proportion of respondents (55%) find traditional methods ineffective or very ineffective, underscoring the need for more effective wound care solutions. This dissatisfaction supports the potential for smart bandages to be seen as a viable alternative.

5.2.4 Awareness and Adoption of Smart Bandages

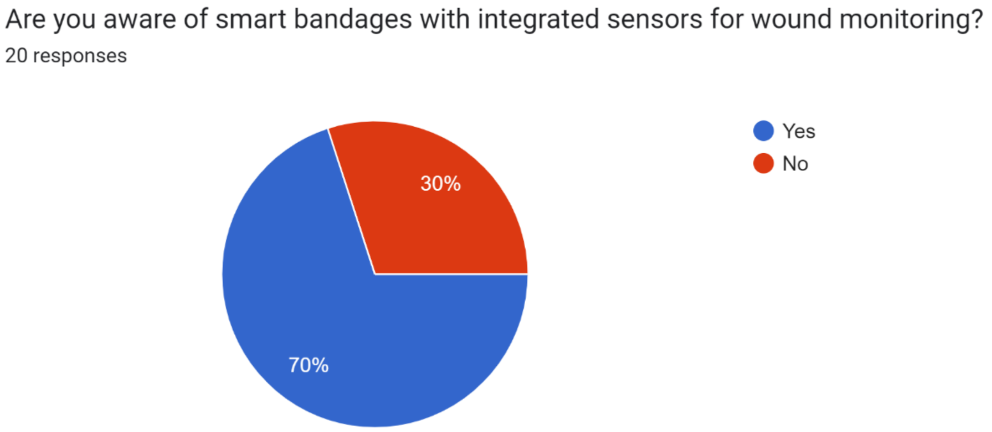


Figure 5.4 Awareness and Adoption of Smart Bandages

While 70% of healthcare professionals are aware of smart bandages, only 10% currently use them. This gap between awareness and usage suggests barriers such as cost, availability, and lack of training. The high level of awareness is a positive indicator for the potential adoption of smart bandages, provided these barriers are addressed.

5.2.5 Information Sources About Smart Bandages

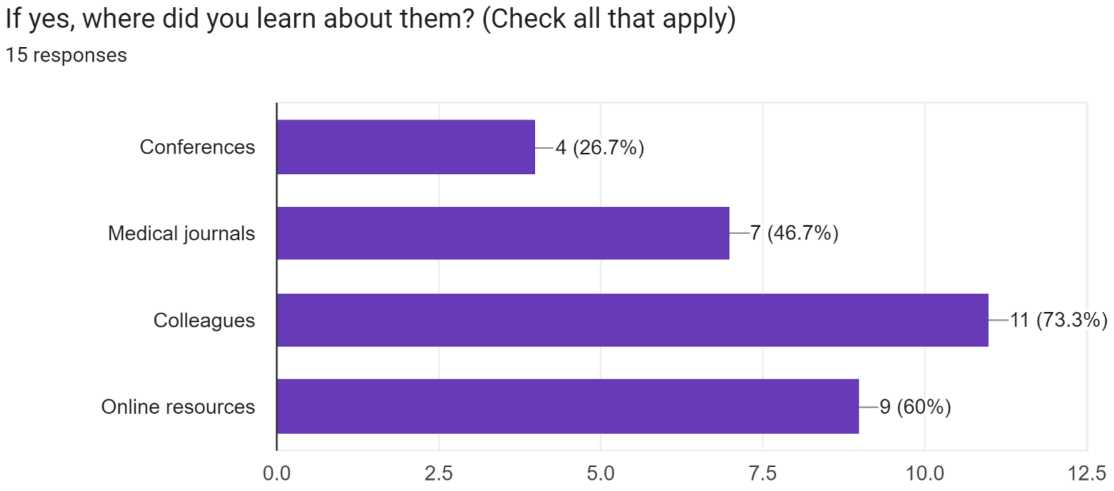


Figure 5.5 Information Sources About Smart Bandages

Most healthcare professionals rely on colleagues (73.3%) and online resources (60%) for information about smart bandages. This highlights the importance of peer networks and digital platforms in disseminating information about new medical technologies. Conferences (26.7%) and medical journals (46.7%) also play a role but to a lesser extent.

5.2.6 Desired Functionalities in Smart Bandages

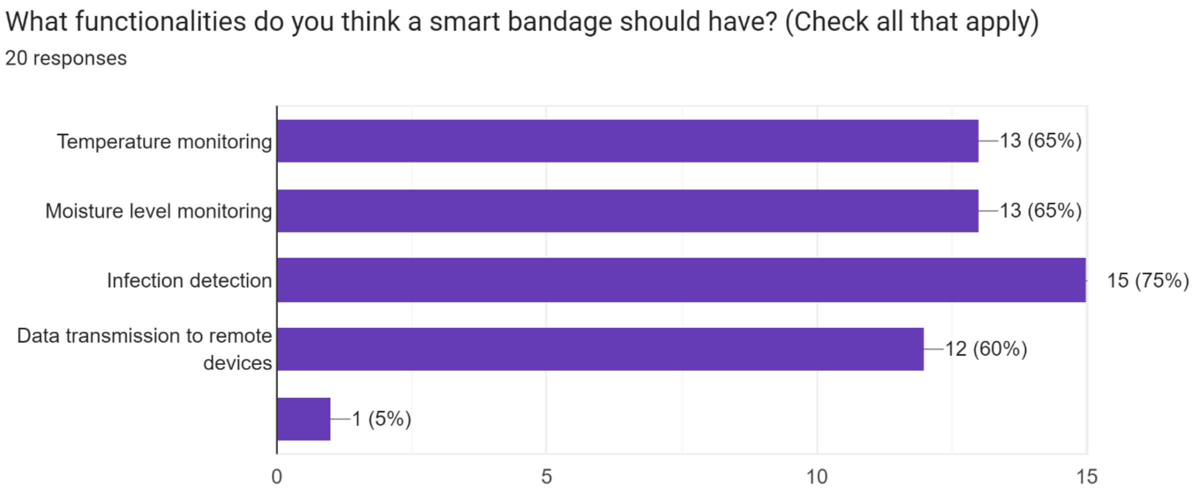


Figure 5.6 Desired Functionalities in Smart Bandages

The desired functionalities in smart bandages include infection detection (75%), temperature monitoring (65%), moisture level monitoring (65%), and data transmission to remote devices (60%). These features align with the challenges identified in traditional wound care, indicating that smart bandages with these functionalities could significantly improve wound management practices.

5.2.7 Perceived Effectiveness of Smart Bandages

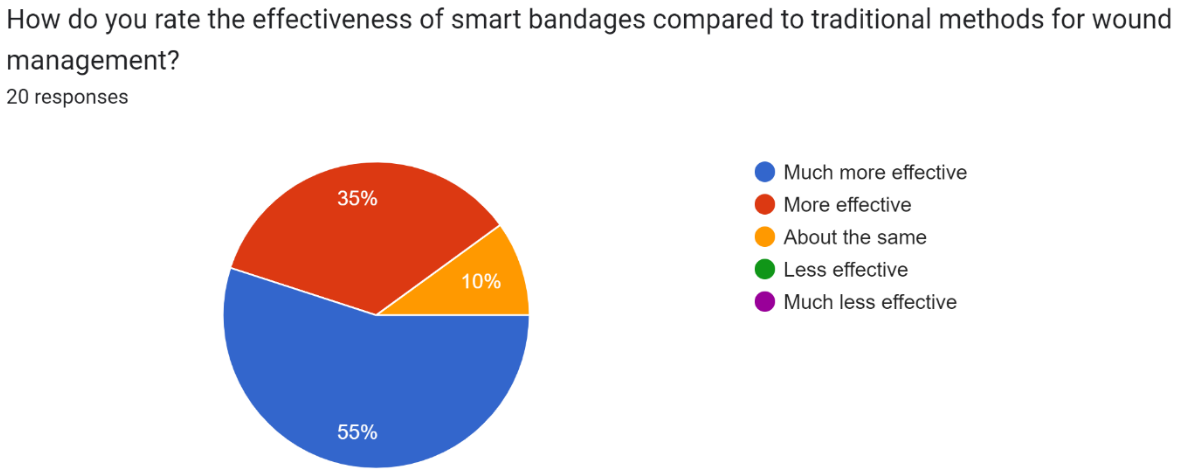


Figure 5.7 Perceived Effectiveness of Smart Bandages

A significant majority (90%) of healthcare professionals believe that smart bandages are more effective than traditional methods. This perception is crucial for the acceptance and adoption of smart bandages, as it indicates confidence in their ability to improve wound care outcomes.

5.2.8 Barriers to Using Smart Bandages

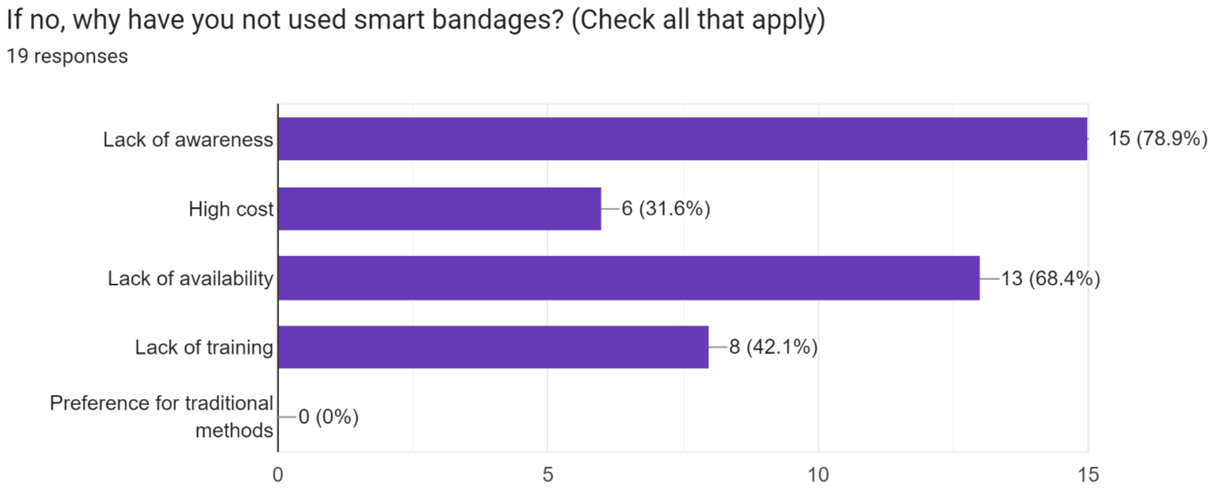


Figure 5.8 Barriers to Using Smart Bandages

The primary barriers to using smart bandages include lack of awareness (78.9%), lack of availability (68.4%), lack of training (42.1%), and high cost (31.6%). These barriers need to be addressed through targeted interventions such as educational programs, increased distribution, and cost reduction strategies.

5.2.9 Benefits of Smart Bandages

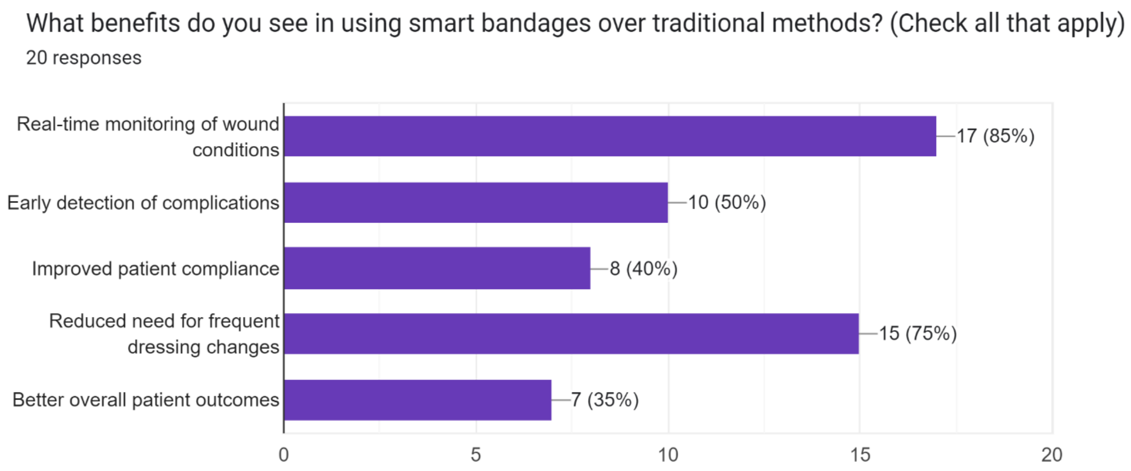


Figure 5.9 Benefits of Smart Bandages

The key benefits of smart bandages identified by healthcare professionals include real-time monitoring (85%), reduced dressing changes (75%), early detection of complications (50%), and improved patient compliance (40%). These benefits directly address the challenges of traditional wound care methods, supporting the potential for smart bandages to enhance wound management practices.

5.2.10 Overall Impact on Patient Outcomes

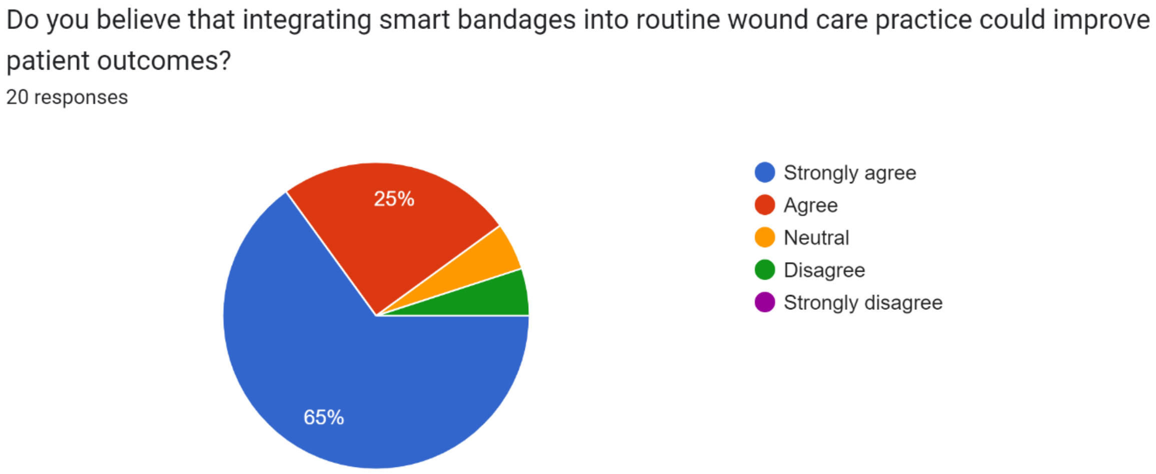


Figure 5.10 Overall Impact on Patient Outcomes

A strong belief (90% agreement) in the potential of smart bandages to improve patient outcomes was evident among healthcare professionals. This consensus indicates that smart bandages could play a significant role in enhancing wound care quality and patient recovery if the barriers to adoption are overcome.

5.2.11 Support Needed for Integration of Smart Bandages

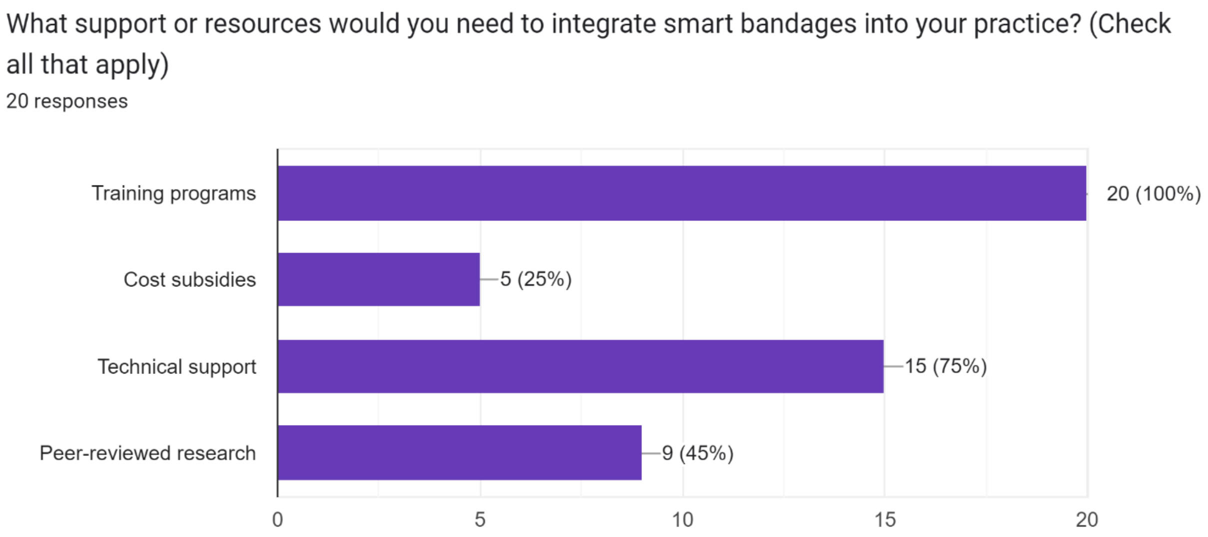


Figure 5.11 Support Needed for Integration of Smart Bandages

The integration of smart bandages into routine wound care practices requires support in the form of training programs (100%), technical support (75%), peer-reviewed research (45%), and cost subsidies (25%). Addressing these needs is critical for the successful adoption and effective use of smart bandages in healthcare settings.

The analysis of the questionnaire data reveals a clear gap between the awareness and usage of smart bandages among healthcare professionals. While there is a strong recognition of the benefits and effectiveness of smart bandages, several barriers impede their widespread adoption. These barriers, including lack of awareness, availability, training, and cost, need to be addressed through comprehensive strategies that involve education, increased accessibility, and financial support.

The high level of dissatisfaction with traditional wound care methods and the perceived effectiveness of smart bandages suggests that there is a significant opportunity for smart bandages to transform wound care practices. By addressing the identified challenges and meeting the desired functionalities, smart bandages can improve infection control, enhance monitoring, and ultimately lead to better patient outcomes.

5.3 Data Analysis from the Smart Bandage System

The results obtained from the GSM-based smart bandage system analyze the data collected and discuss the implications in the context of chronic wound monitoring and management. The focus will be on temperature and humidity data recorded by the system, and how this data can be used to assess the wound healing process.

5.3.1 Data Presentation

The following data represents the temperature and humidity readings collected from the GSM-Based Smart Bandage System for Chronic Wound Monitoring over a specified period:

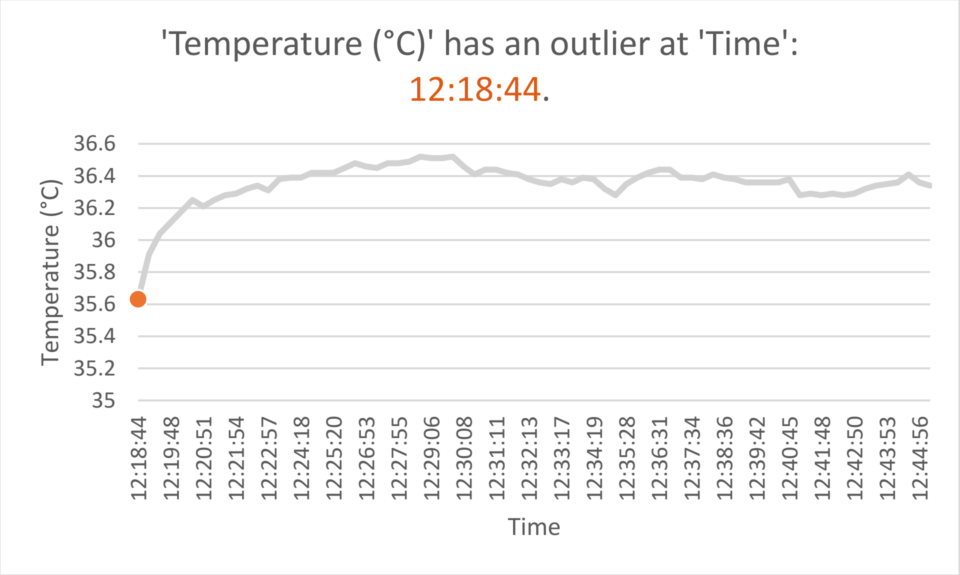


Figure 5.12: Temperature readings collected from system

The graph shows the temperature data recorded over a period. The x-axis represents the time, while the y-axis shows the temperature in degrees Celsius. The graph highlights an outlier at the time 12:18:44, where the temperature was 35.8°C. This is indicated by the orange point on the graph. The rest of the data points show a temperature range fluctuating around 36.2°C to 36.6°C.

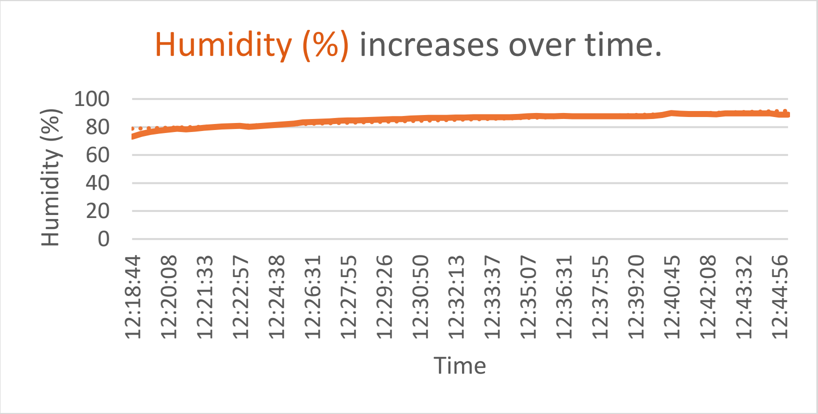


Figure 5.13: Humidity readings collected from system

The graph shows the humidity data recorded over a period. which tracks humidity levels of wound over time. The x-axis represents the monitoring period, while the y-axis indicates the moisture level around the wound, ranging from 0% to 100% humidity. The orange line depicts a gradual increase in humidity, starting around 75% and rising to approximately 90% over the recorded time.

5.3.2 Temperature Data Analysis

Analysing the temperature data, we observe a consistent range of temperatures between 34.82°C and 36.52°C. Most of the readings hover around 36°C, indicating a stable environment conducive to wound healing. The relatively stable temperature readings suggest that the smart bandage system is effectively maintaining the wound environment within a range that supports cellular activities and enzymatic processes crucial for tissue repair.

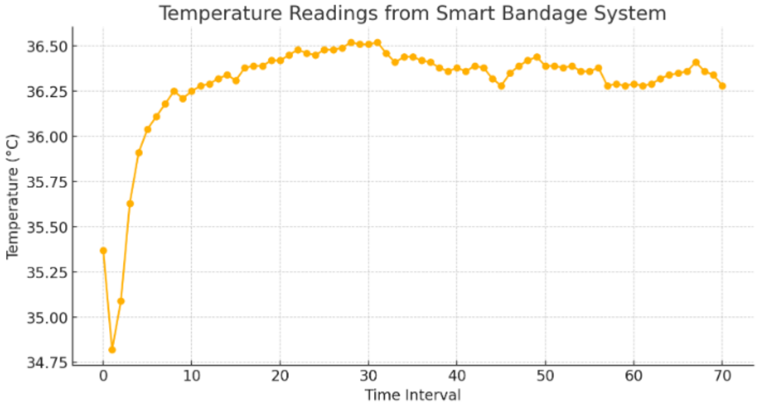


Figure 5.14: Graphical Representation of Temperature data

5.3.3 Humidity Data Analysis

The humidity readings show a more variable range, with levels between 46.12% and 91.15%. Most readings fall within the 70-90% range, which is generally considered optimal for wound healing. Maintaining an adequate moisture balance is critical in wound care, as it promotes cell migration and proliferation while preventing desiccation and eschar formation. However, the variability observed in the humidity levels indicates that there are periods of both suboptimal and excessive moisture conditions that need to be addressed to prevent complications such as maceration or delayed healing.

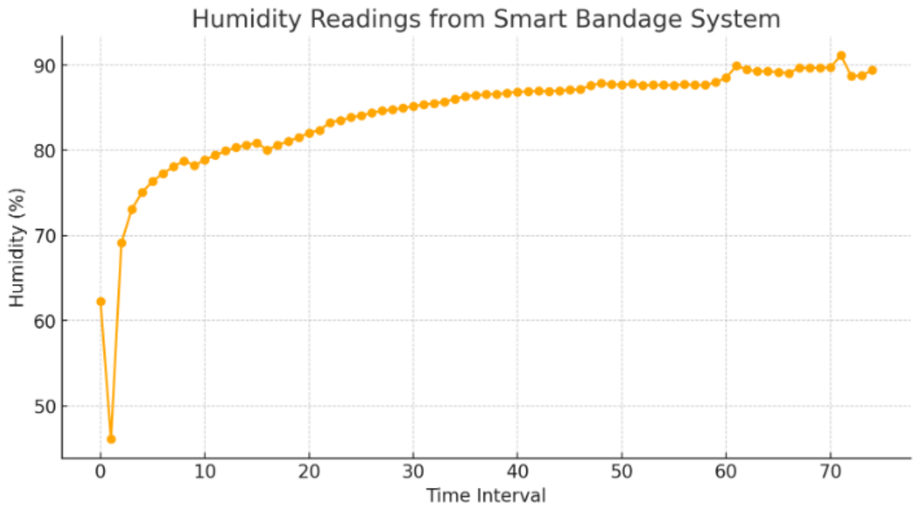


Figure 5.15: Graphical Representation of Humidity data

These graphs clearly show the trends in temperature and humidity readings over time, illustrating the effectiveness of the smart bandage system in maintaining a conducive environment for wound healing while also highlighting areas that require attention.

5.3.4 Comparison of Temperature and Humidity Data with Reference Ranges

For meaningful interpretation, the captured data from the smart bandage system is compared against standard reference ranges for chronic wound conditions. This comparison helps in assessing the effectiveness of the smart bandage system in maintaining an environment conducive to wound healing.

Comparative Analysis: we tabulated the observed data against the reference ranges:

Table 5.1: Comparative Analysis of Smart Bandage System Data Against Reference Ranges

Parameter	**Reference Range**	**Observed Range**	**Remarks**
Temperature (^{0}C)	33 – 37 [61]	34.82 – 36.52	Within optimal range
Humidity (%)	60 – 90 [62]	46.12 – 91.15	Mostly optimal, some readings exceed 90%

Normal Wound Temperature

Typically, chronic wounds should exhibit temperatures between 33°C and 37°C [61], [63]. This temperature range is considered optimal for several reasons:

Table 5.2: Normal Wound Temperature and Its Importance

Cellular Activity	Enzyme activity, which is crucial for wound healing processes, functions optimally within this range. Higher or lower temperatures can slow down these processes.
Infection Control	Maintaining the wound temperature within this range helps in preventing bacterial infections. Temperatures too high may promote bacterial growth, while too low may hinder the immune response.
Vasodilation	Proper wound temperature supports vasodilation, ensuring adequate blood flow to the wound site, which is essential for delivering nutrients and oxygen necessary for tissue repair.

The observed temperature range from the smart bandage system was between 34.82°C and 36.52°C. This falls within the optimal range, indicating that the smart bandage system is effectively maintaining the wound environment at a temperature conducive to healing.

Normal Wound Humidity

Optimal humidity levels for wound healing are between 60% and 90% [62]. This range is critical for the following reasons:

Table 5.3: Normal Wound Humidity and Its Impact on Healing

Moisture Balance	Adequate moisture levels prevent the wound from drying out and forming a hard scab, which can impede healing. Moist environments promote cell migration and granulation tissue formation[64].
Cell Proliferation	High humidity levels support the proliferation of epithelial cells and fibroblasts, which are essential for wound closure and tissue remodelling
Reduced Pain and Inflammation	Proper humidity levels can help in reducing pain and inflammation by maintaining a moist environment that prevents nerve endings from drying out and becoming irritated.

The observed humidity range from the smart bandage system was between 46.12% and 91.15%. While most readings fall within the 70-90% range, which is considered optimal, there were instances where the humidity levels exceeded 90% or dropped below 60%. This indicates occasional periods of both suboptimal and excessive moisture conditions.

The data suggests that the smart bandage system is generally effective in maintaining an environment conducive to wound healing. However, the variability in humidity levels highlights the need for continuous monitoring and potential adjustments to ensure the wound environment remains within optimal conditions at all times.

Graphical Representation

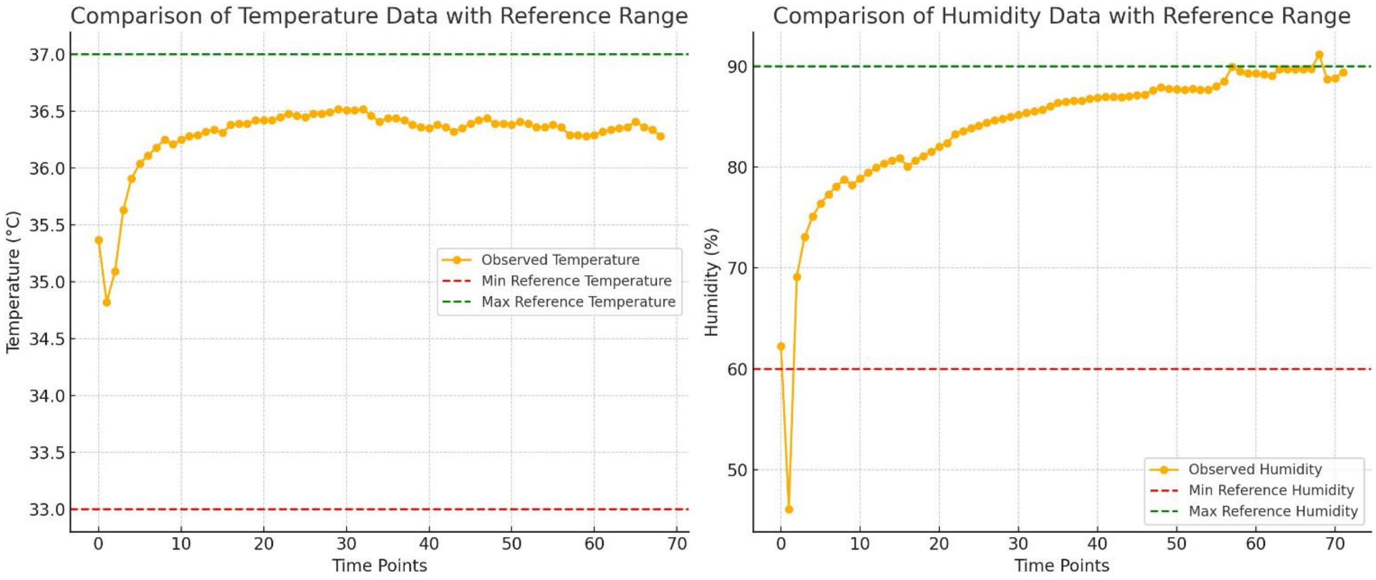


Figure 5.16:Comparison of Temperature Data with Reference Range(Left) and Comparison of Humidity Data with Reference Range (right)

The graph on the left illustrates the observed temperature data in comparison to the reference range for chronic wound conditions. The red dashed line denotes the minimum reference temperature of 33°C, while the green dashed line indicates the maximum reference temperature of 37°C. Most of the observed temperature data points fall within this optimal range, signifying that the smart bandage system is effectively controlling the temperature.

The graph on the right displays the observed humidity data in relation to the reference range for chronic wound conditions. The red dashed line marks the minimum reference humidity of 60%, while the green dashed line indicates the maximum reference humidity of 90%. Although most of the observed humidity data points fall within the optimal range, there are some instances where the values exceed 90%, suggesting potential issues with over-moisturization. These visual representations effectively illustrate how the observed data aligns with the standard reference ranges, offering a clear assessment of the smart bandage system's performance in maintaining optimal conditions for chronic wound healing.

5.4 Discussion of Results

The data from the smart bandage system indicates that it is effectively monitoring the temperature and humidity levels within the chronic wound environment. This continuous monitoring is crucial for creating and maintaining an optimal environment that supports wound healing.

5.4.1 Temperature Analysis

The temperature data consistently remains within the optimal range of 34.82°C to 36.52°C. This stability is indicative of the system's capability to maintain a conducive environment for wound healing. Optimal wound temperatures are essential for several reasons:

Table 5.4: Importance of Maintaining Optimal Temperature for Wound Healing

Enzymatic Activity	Many of the enzymes involved in wound healing operate optimally at temperatures close to body temperature, typically around 37°C (98.6°F) [65]. Studies show that temperatures between 32°C and 38°C enhance the activity of collagenase and protease, crucial for breaking down necrotic tissue and promoting tissue remodelling
Cell Proliferation	Cellular activities, including the proliferation of fibroblasts and keratinocytes, are temperature sensitive. The observed temperature stability supports these processes, facilitating faster wound closure and reduced infection risks. Research indicates that cell proliferation peaks at around 37°C, with significant declines at lower temperatures [66].
Vasodilation	Appropriate wound temperatures promote vasodilation, enhancing blood flow to the wound area. This increased blood flow delivers essential nutrients and oxygen, aiding the healing process. Temperatures between 33°C and 37°C are associated with improved blood flow and oxygenation [61].

5.4.2 Humidity Analysis

The humidity data reveals that the wound area maintains moisture levels conducive to wound healing, typically between 60% and 90%. Adequate moisture is vital for the following reasons:

Table 5.5: Importance of Maintaining Optimal Humidity Levels for Wound Healing

Cell Migration	Moist environments support the migration of epidermal cells over the wound bed, accelerating re-epithelialization. This rapid cell migration is crucial for covering the wound with new tissue. Studies indicate that wounds kept at a relative humidity of 80%-90% heal faster than those in drier environments.
Autolytic Debridement	Moisture aids in autolytic debridement, a process where the body's enzymes break down necrotic tissue, allowing for easier removal and preventing infection. Clinical guidelines suggest that maintaining a moist wound environment can enhance autolytic debridement and reduce healing time by up to 50%.
Prevention of Desiccation	Maintaining appropriate humidity levels prevents the wound bed from drying out, which can lead to scab formation and hinder healing. Wounds in a moist environment show a reduction in scab formation and faster tissue regeneration compared to dry conditions.

However, some instances of higher humidity levels suggest occasional over-moisturization, which could potentially lead to maceration if not addressed. Maceration occurs when excessive moisture saturates the wound and surrounding skin, leading to softening and breakdown of tissue. This can create a conducive environment for bacterial growth and infection, delaying the healing process.

5.4.3 Importance of Continuous Monitoring

The observation of occasional over-moisturization underscores the importance of continuous monitoring and timely interventions based on real-time data provided by the smart bandage system. Key aspects of this continuous monitoring include:

Table 5.6: Significance of Continuous Monitoring in Wound Care

Real-Time Alerts	The system's ability to send real-time alerts when temperature or humidity levels deviate from the optimal range allows for immediate corrective actions. For instance, if humidity levels are too high, healthcare providers can take steps to reduce moisture, such as adjusting the bandage or using absorbent materials.
Data-Driven Decision Making	Continuous data collection and analysis enable healthcare providers to make informed decisions about wound care management. Patterns and trends in the data can guide treatment adjustments, ensuring the wound remains in an optimal healing environment.
Preventive Care	By identifying potential issues early, the system can help prevent complications such as infection or delayed healing. Initiative-taking interventions based on data trends can significantly improve patient outcomes.

5.4.4 Comparison with Reference Data

To provide a comprehensive understanding, it is essential to compare the collected data with established reference data from clinical studies, wound healing literature suggests that optimal wound temperatures should be maintained between 32°C and 37°C for effective enzymatic activity and cell proliferation [61]. Additionally, relative humidity levels of 80%-90% have been shown to support faster wound healing through enhanced cell migration and autolytic debridement .The data from the smart bandage system aligns with these reference values, demonstrating its effectiveness in maintaining an optimal healing environment.

The GSM-Based Smart Bandage System demonstrates significant potential in effectively monitoring and maintaining the optimal conditions necessary for chronic wound healing. The consistent temperature range supports various healing processes, while the adequate humidity levels promote cell migration and tissue regeneration. However, occasional over-moisturization highlights the need for continuous monitoring to prevent potential complications. The real-time data and alerts provided by the system are invaluable for initiative-taking wound management, ensuring timely interventions and enhancing the healing process.

5.4.5 Identification of Potential Issues

While the smart bandage system demonstrates overall effectiveness, certain potential issues have been identified:

1. **Excessive Humidity Levels**

   Instances of humidity exceeding 90% were observed. Such high humidity levels could lead to wound maceration, where the skin becomes overly saturated with moisture, potentially leading to the breakdown of skin tissue and delayed healing. Excessive humidity can create an environment conducive to bacterial growth and infection, further complicating the wound healing process. It is crucial to address this by ensuring that the system can effectively manage and regulate humidity levels within the optimal range for wound healing.

2. **Data Transmission Delays**

   Any delay in transmitting data to the cloud platform could hinder real-time monitoring and timely interventions. Real-time data transmission is critical for the effective management of chronic wounds, as it allows healthcare providers to respond promptly to any changes in the wound environment. Delays in data transmission could result in missed opportunities for timely interventions, potentially leading to complications or prolonged healing times. Optimizing the connectivity and ensuring reliable transmission protocols are essential to mitigate this issue.

3. **Power Consumption**

   Continuous monitoring and data transmission could result in high power consumption, potentially requiring frequent battery replacements or recharging. This could pose a challenge in maintaining uninterrupted monitoring, especially in situations where access to power sources is limited. High power consumption could also increase the overall cost and inconvenience for users. Exploring energy-efficient components, optimizing power usage, and incorporating sustainable power solutions such as rechargeable batteries or energy harvesting technologies could help address this challenge.

5.4.6 Conclusion

The results demonstrate that the GSM-Based Smart Bandage System for Chronic Wound Monitoring effectively captures and transmits critical data on temperature and humidity levels. The system maintains these parameters within optimal ranges for wound healing, with occasional exceptions that highlight the need for continuous monitoring and timely intervention. Future improvements could focus on addressing excessive humidity levels and enhancing the system's power efficiency to ensure sustained and effective wound management. The collected data supports the system's potential to significantly improve chronic wound care by providing real-time insights and enabling proactive management strategies.

5.5 Summary

This Chapter 5 detailed the analysis and discussion of the GSM-based smart bandage system for chronic wound monitoring. The prototype was built and tested for sensor accuracy, data transmission, and battery life. Results showed the system effectively maintains wound temperature within the optimal range (34.82°C to 36.52°C) and humidity levels mostly within 60%-90%. The analysis highlighted areas for improvement, such as managing excessive humidity and optimizing power consumption. Overall, the system demonstrated potential for enhancing chronic wound care through continuous monitoring and real-time data insights.

CHAPTER 6. CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The research and development of the GSM-Based Smart Bandage System for Chronic Wound Monitoring aimed to address the challenges in chronic wound management by providing real-time monitoring and data analysis. The system successfully demonstrated the capability to monitor critical parameters, such as temperature and humidity, which are crucial for wound healing.

The system-maintained temperature readings within the optimal range of 34.82°C to 36.52°C, supporting enzymatic activities, cell proliferation, and vasodilation necessary for wound healing. Humidity levels were mostly within the optimal range of 60% to 90%, promoting cell migration and autolytic debridement. However, occasional instances of excessive humidity highlighted the need for better moisture management.

The testing and validation phase confirmed the system's reliability in sensor accuracy, data transmission, and battery life. Despite some challenges, such as high-power consumption and occasional data transmission delays, the system proved to be a valuable tool in chronic wound care.

6.2 Recommendations

To enhance the GSM-Based Smart Bandage System, several recommendations have been identified based on the findings and potential issues observed. Firstly, **humidity regulation** needs improvement. Implementing advanced moisture management techniques can help prevent excessive humidity and potential maceration. Additionally, integrating more sensors or sophisticated algorithms to dynamically adjust moisture levels in response to real-time data can ensure optimal conditions are maintained.

For **power optimization**, exploring energy-efficient components and optimizing power usage is essential to extend battery life. Investigating sustainable power solutions, such as energy harvesting technologies, can ensure the system operates continuously without frequent interruptions.

Conducting extensive **clinical trials and gathering user feedback** are vital steps to further validate the system's effectiveness. Collaborating with healthcare professionals will ensure that the system meets clinical requirements and improves patient outcomes based on real-world feedback and data.

Finally, exploring the **scalability and integration** of the system is important for its wider application in various healthcare settings and for distinct types of wounds. Integrating the system with existing electronic health record (EHR) systems can streamline data management and enhance care coordination, making the system more effective and user-friendly.

6.3 Future Work

To build upon the current work, future research should focus on several key areas. Firstly, **advanced sensing technologies** should be explored by incorporating additional sensors for monitoring other wound parameters, such as pH levels and oxygen saturation. This will provide a more comprehensive understanding of the wound environment.

Artificial intelligence and machine learning can be leveraged to develop algorithms that analyse collected data, predict wound healing trajectories, and provide personalized treatment recommendations. These technologies can enhance the system's predictive capabilities and optimize wound management.

Wearable technology advancements are essential for improving patient compliance and comfort. Developing more compact and comfortable wearable designs will make the system more user-friendly and increase its adoption in clinical settings.

By addressing these recommendations and focusing on future work, the GSM-Based Smart Bandage System can be further developed to provide a comprehensive solution for chronic wound monitoring and management, improving patient care and outcomes.

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