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College of Science and Technology

AFRICAN CENTER OF EXCELLENCE IN INTERNET OF THINGS

Research Thesis Title:

IOT-ENABLED POULTRY COOP ENVIRONMENTAL MONITORING DEVICE FOR RURAL RWANDA.

A dissertation submitted in partial fulfilment of the requirements for the award of Master of Science degree in internet of things: Embedded computing systems.

Submitted By:

Name: Aline UMUTONIWASE (Ref. No: 222023026)

July 2025

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Name: Aline UMUTONIWASE (Ref. No: 222023026)

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-Name of Main supervisor: **Assoc.Prof. NKURIKIYEYEZU Kizito**

-Name of co – supervisor: **Dr. MWITENDE Gervais**

July 2025.

Declaration

I, Aline UMUTONIWASE, Master ‘student from African Center of Excellence in internet of things: embedded computing systems, at University of Rwanda. I declare that this research thesis is my own original work, and it has never been presented before anywhere in the world.

Aline UMUTONIWASE

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Signed: ………………………….

Date: 20/08/2025.

Bonafide certificate

This is to certify that this submitted Research Thesis work report is a record of the original work done by **Aline UMUTONIWASE** (**Ref. No: 222023026**), MSc. IoT-ECS Student at the University of Rwanda / College of Science and Technology / African Center of Excellence in Internet of Things, the Academic year 2023/2024.

This work has been submitted under the supervision of Assoc.Prof. NKURIKIYEYEZU Kizito and Dr. Gervais MWITENDE

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Acknowledgment

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List of symbols and abbreviations

IoT: Internet of Things

GSM: Global System for Mobile Communication

SMS: Short Message Service

CO_2: Carbon Dioxide

NH_3: Ammonia

UI: User Interface

DHT22: Digital Humidity and Temperature Sensor

PCB: Printed Circuit Board

LED: Light Emitting Diode

AI: Artificial Intelligence

CSS: Cascading Style Sheets

HTML: Hyper Text Markup Language

IDE: Integrated Development Environment

LCD: Liquid Crystal Display

RTC: Real-Time Clock

USB: Universal Serial Bus

ML: Machine Learning

CSV: Comma-Separated Values

ABSTRACT

Poultry farming plays a vital role in food security and income generation for rural households in Rwanda. However, smallholder farmers continue to face major challenges in maintaining safe environmental conditions within poultry coops challenges which often lead to respiratory illnesses, reduced productivity, and high mortality rates. These issues are primarily caused by unmanaged fluctuations in temperature and humidity, accumulation of harmful gases such as ammonia and carbon dioxide (CO_2), and airborne dust particles, all of which are insufficiently addressed by conventional monitoring systems.

This study presents the design, development, and prototyping of a fully integrated, hybrid-powered IoT-based environmental monitoring and control system enclosed in a custom-fabricated housing for in-coop deployment. The compact device employs a Raspberry Pi Pico W microcontroller interfaced with DHT22, MQ-135 (for ammonia and CO_2), and DSM501A (for dust) sensors to monitor five critical parameters affecting poultry health. It is also equipped with automated actuators including fans, a heating bulb, LEDs, and a buzzer to regulate the coop environment. Real-time SMS alert functionality is enabled through a SIM800L module, while a lightweight web-based dashboard allows remote data visualization and interaction. The system is powered through a hybrid energy setup comprising solar panels and rechargeable batteries, making it suitable for off-grid rural applications.

Field validation confirms the device's accuracy, responsiveness, and reliability in maintaining optimal in-coop conditions. Compared to prior solutions, this approach offers a robust, low-cost, and inclusive tool for improving poultry welfare. The study recommends future enhancement through integration of mobile applications and machine learning for predictive control and decision support.

Keywords: **IoT-based poultry monitoring, in-coop environmental sensing, Raspberry Pi Pico W, hybrid power system, ammonia and CO_2 detection, rural livestock farming, real-time SMS alerts.**

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Chapter 1: GENERAL INTRODUCTION

1.1. Introduction

Poultry farming plays a vital role in rural livelihoods across Rwanda, contributing significantly to food security, income generation, and employment[1] However, smallholder poultry farmers face increasing challenges in maintaining safe and stable environmental conditions within chicken coops. Fluctuations in temperature and humidity, combined with the accumulation of ammonia and carbon dioxide (CO_2) due to poor ventilation, and high levels of airborne dust, are known to negatively affect poultry health. These stressors often lead to respiratory illnesses, reduced egg production, and higher mortality rates[2]

In response to challenges in poultry production, the adoption of Internet of Things (IoT) technologies in agriculture has attracted global attention. IoT platforms enable real-time environmental monitoring and automated control through interconnected sensors, microcontrollers, and communication modules. These systems allow precise measurement of critical parameters—such as temperature, humidity, gas concentration, and dust levels—and trigger appropriate actions like fan or heater activation without human intervention, significantly improving environmental regulation, animal welfare, and productivity [3]. However, in Rwanda, initial IoT initiatives in poultry farming student at the University of Rwanda do monitor key parameters like temperature, humidity, and ammonia using wireless sensors and SMS notifications. But these systems still fall short of full environmental control: they don't include CO_2 or dust detection, lack automated actuation (e.g., fan or heater integration), and aren't designed for off-grid power scenarios[4] .These limitations highlight the need for a more comprehensive and context-sensitive solution.

This study therefore proposes the design, prototyping, and deployment of an integrated, hybrid-powered IoT device. The system will monitor temperature, humidity, ammonia, CO_2, and dust within the poultry coop environment. It will support automated environmental control and real-time SMS alerts to farmers. The all-in-one hardware design aims to provide a practical, durable, and scalable solution for enhancing poultry health and reducing mortality.

1.2. Background and motivation

Agriculture remains the backbone of Rwanda’s economy, employing more than 70% of the population and contributing significantly to food security and rural development. Poultry farming, in particular, plays a vital role in household nutrition, income generation, and economic empowerment especially among women and youth in rural areas[5] .Despite its importance, smallholder poultry production in Rwanda is constrained by poor housing conditions and a lack of environmental control systems. Poultry are highly sensitive to their environment. Elevated levels of temperature, humidity, ammonia (NH_3), carbon dioxide (CO_2), and airborne dust can lead to respiratory illnesses, heat stress, decreased feed efficiency, low egg production, and increased mortality[6]. Most rural coops in Rwanda are constructed using local materials with minimal ventilation and no monitoring or control mechanisms, leaving farmers unable to detect or respond to environmental hazards in a timely manner [4]. Globally, the adoption of Internet of Things (IoT) technologies has revolutionized agriculture by enabling real-time monitoring and intelligent decision-making through the integration of sensors, microcontrollers, wireless communication, and automation[7]. In Rwanda, IoT has been applied in areas such as smart irrigation, precision agriculture, and weather monitoring However, its application in livestock and poultry management remains very limited, with most IoT solutions focusing on crops. Some initial efforts, such as the IoT system developed at the University of Rwanda, have demonstrated potential in poultry monitoring by tracking temperature, humidity, and ammonia levels[4] .However, these systems lack essential features like CO_2 and dust detection, automated environmental control (fans or heaters), SMS-based alerts, and solar power support making them unsuitable for off-grid rural areas where most poultry farmers operate.

This research is therefore motivated by a critical gap: the lack of a durable, affordable, and energy-efficient IoT-based device tailored for rural poultry environmental monitoring. The proposed all-in-one solution integrates sensing, actuation, power supply, and alerting functions into a single unit. It offers real-time tracking of temperature, humidity, ammonia, CO_2, and dust while responding automatically to unsafe conditions making it well-suited for field deployment in off-grid areas.

1.3. Problem Statement

Smallholder poultry farmers in rural Rwanda face significant challenges in maintaining healthy environmental conditions inside chicken coops. Key factors such as elevated temperature, humidity, ammonia (NH_3), carbon dioxide (CO_2), and airborne dust are often left unmonitored, resulting in poor air quality that contributes to respiratory diseases, reduced feed efficiency, lower egg production, and high mortality rates among poultry[8].

Although Internet of Things (IoT) technologies have seen increasing adoption in Rwandan agriculture, most implementations have focused on crop production and smart irrigation systems. In the poultry sector, early efforts such as the IoT-based poultry monitoring system developed have introduced basic sensing capabilities for parameters like temperature, humidity, and ammonia[4]. However, these systems fall short by lacking crucial features such as CO_2 and dust level monitoring, automated actuation for fans or heaters, real-time alerting via SMS, and solar-powered off-grid functionality features essential for the context of remote rural farms. as a result, farmers are unable to proactively detect or respond to dangerous environmental conditions in their coops, especially in locations with unreliable power supply or internet connectivity. There is an urgent need for a compact, integrated IoT device that combines sensing, control, and communication in one system, operating reliably without dependence on grid power or continuous internet access essential for remote poultry coops in rural Rwanda.

1.4. Study Objectives

1.4.1. General Objective

To design and develop an integrated IoT-based environmental monitoring and control device for poultry coops that enhances poultry health and reduces mortality by enabling real-time sensing, automated response to unsafe conditions, and SMS-based farmer notifications using a hybrid (solar and rechargeable battery) power source.

1.4.2. Specific Objectives

- ✓ To design and develop an integrated hybrid-powered IoT device using Raspberry Pi Pico W that monitors key in-coop environmental parameters: temperature, humidity, ammonia (NH_3), carbon dioxide (CO_2), and airborne dust in rural poultry farms.

- ✓ To implement automated environmental control within the coop using actuators (fans, heat bulbs, LEDs, buzzers) triggered by real-time sensor data for maintaining optimal poultry conditions.
- ✓ To integrate GSM-based SMS alert functionality and a simple web-based dashboard for real-time notifications and visualization, ensuring remote farmer awareness and timely intervention even in off-grid settings.

1.5. Hypothesis

Implementing a compact, hybrid-powered IoT-based environmental monitoring device capable of real-time sensing of temperature, humidity, ammonia (NH_3), carbon dioxide (CO_2), and dust; and equipped with automated actuation and GSM-based SMS alerts will significantly improve poultry health and reduce mortality in rural Rwandan coops.

1.6 Scope of the Study

This study focuses on designing and implementing a standalone IoT-based device powered by solar energy and rechargeable battery, for monitoring and controlling environmental conditions in poultry coops. The device measures key parameters (temperature, humidity, ammonia, CO_2, and dust) and controls fans, heaters, buzzers, and LEDs in response to unsafe conditions. It also sends SMS alerts for timely farmer intervention. A web interface supports real-time visualization, and the compact system is optimized for use in off-grid, resource-limited settings

1.7. Significance of the Study

- This study contributes to the advancement of poultry farming practices in rural Rwanda by developing a cost-effective, hybrid-powered IoT system utilizing solar energy and rechargeable batteries that enables smallholder farmers to monitor and manage critical environmental conditions within poultry coops. By providing real-time data on temperature, humidity, ammonia (NH_3), carbon dioxide (CO_2), and airborne dust, the system facilitates early detection of dangerous conditions that could negatively impact poultry health, productivity, and survival rates.
- The integration of automated control mechanisms such as fans, heaters, buzzers, and LEDs ensures that the coop environment remains within optimal ranges without the need for constant human supervision. Furthermore, the inclusion of SMS-based alerts ensures that even farmers without smartphones or internet connectivity can receive timely warnings and take action, making the system inclusive and practical for low-resource settings.
- The outcomes of this research will contribute to the body of knowledge on the application of IoT in livestock and poultry farming, particularly in resource-constrained rural environments. The project also aligns with Rwanda's national strategies for agricultural modernization and food security under Vision 2050, offering insights for policymakers, researchers, and local innovators to support broader implementation of smart farming solutions across the country and region.
- The creation of an all-in-one IoT device improves reliability, portability, and ease of deployment in rural farms, enabling smallholder poultry farmers to adopt smart farming technologies without needing complex installation or internet access.

1.8. Organization of the Study

This thesis is structured into six chapters as follows:

I. **Chapter One** provides a general introduction to the study, including the background and motivation, problem statement, objectives, hypotheses, scope, significance, organization of the study, and a concluding summary.

II. **Chapter Two** reviews relevant literature on IoT applications in agriculture and poultry farming, highlighting existing systems, their limitations, and identifying the research gap this study intends to address.

III. **Chapter Three** outlines the research methodology, including the techniques and tools used for designing and implementing the IoT-based poultry coop environmental monitoring system. It also presents the implementation plan.

IV. **Chapter Four** presents the system analysis and design. It includes the system architecture, modeling, simulation parameters, and simulation scenarios.

V. **Chapter Five** reports the results obtained during system testing and validation, followed by detailed analysis and interpretation of the findings through graphs and performance metrics.

VI. **Chapter Six** concludes the study by summarizing the key findings, drawing conclusions, and providing recommendations for future work and further system improvement.

1.9. Conclusion

This chapter has established the foundational context and rationale for the development of an IoT-enabled system dedicated to monitoring in-coop environmental conditions in rural Rwandan poultry farming. It identified key challenges faced by smallholder farmers such as the lack of real-time monitoring and environmental control and reviewed the limitations of existing systems. The proposed solution involves an integrated, hybrid-powered IoT device capable of continuously monitoring critical parameters (temperature, humidity, ammonia, CO_2, and dust), automating responsive control actions, and delivering real-time SMS alerts. The chapter also outlined the general and specific objectives, hypothesis, scope, and significance of the study. Together, these elements define a comprehensive approach to improving poultry health, reducing mortality, and supporting digital transformation in rural livestock farming. The following chapter presents a detailed review of related work, existing systems, and technological gaps that this study aims to address.

CHAPTER2: LITERATURE REVIEW

2.1. Introduction

This chapter presents a comprehensive review of the existing literature on IoT-based environmental monitoring systems in agriculture, with a focus on poultry farming. It explores key technological advancements, sensor applications, and the influence of environmental parameters such as temperature, humidity, ammonia concentration, carbon dioxide levels, and dust on chicken health and productivity. The review also examines previous systems developed globally and regionally, evaluating their functionalities, limitations, and relevance to rural agricultural contexts. Furthermore, it identifies existing research and implementation gaps, particularly in the Rwandan context, and highlights how the present study addresses these gaps by proposing a tailored, cost-effective, and integrated monitoring solution

2.2. Related works

The related work for this study centers on the integration of Internet of Things (IoT) technologies into poultry farming, specifically for environmental monitoring within chicken coops. Numerous studies have examined the role of IoT in optimizing agricultural practices through real-time data collection and automated system responses. While many of these efforts have focused on crop irrigation, soil monitoring, and seed storage systems, recent advancements have extended IoT applications to livestock environments. In poultry farming, researchers have explored the use of sensors and wireless technologies to monitor temperature, humidity, ammonia, and other air quality parameters, aiming to improve bird health and productivity. However, most of the existing systems lack holistic integration, particularly in rural settings where power reliability and internet connectivity are limited. This gap highlights the need for more context-appropriate, off-grid solutions such as the one proposed in this study.

In[9] the study developed a low-cost IoT-based gas detection system for poultry and compost environments in Bangladesh, using ESP32 with MQ-137 and MH-Z14 sensors to monitor ammonia and CO_2 levels. The system transmitted data via Wi-Fi to a Grafana dashboard, providing remote visibility and real-time alerts. Their 6-month deployment showed significant ammonia accumulation inside poultry sheds—often exceeding 50 PPM—and high CO_2 levels, underscoring the importance of continuous gas monitoring. While the system proved accurate and affordable (~$82), it relied on consistent internet access and did not include dust detection or offline alerting mechanisms, which limits its applicability in off-grid rural settings like those in Rwanda.

the research in [10]developed an IoT-based framework to monitor key environmental parameters such as ammonia, CO_2, humidity, and noise—in livestock buildings using low-power sensor networks and LoRaWAN. While primarily tested in pig and cattle barns, the system's modularity and scalability make it highly adaptable to poultry environments. This framework emphasizes animal welfare and environmental impact, aligning with the goals of this study. However, the framework depends on LoRaWAN infrastructure and does not include localized physical alerts (e.g., buzzer or LED), which are more suitable for remote poultry coops in Rwanda with limited internet access.

The study [11]proposed a comprehensive IoT platform for poultry production, integrating environmental sensors, wearable devices, and cloud-based analytics to monitor health, behavior, and air quality in commercial farms. While their system provides valuable insights into large-scale poultry chain management, its reliance on continuous internet and cloud services makes it less practical for rural settings with limited infrastructure. The current study builds on these concepts by adapting them to smallholder environments, emphasizing low-cost sensors, solar power, and GSM alerts for off-grid operability.

the study in [6]developed an intelligent IoT-based service platform for managing poultry house environments using a cloud-based architecture. The system integrates multi-sensor data (temperature, humidity, CO_2, sound) and uses advanced analytics, including sound recognition and psychrometric alerts, to enhance poultry welfare and production oversight. While highly effective in commercial-scale operations, its reliance on cloud services and continuous power availability makes it less feasible for rural deployment in developing regions. This study builds upon these principles by proposing a low-cost, solar-powered IoT system suitable for smallholder poultry farmers

the study in [12] proposed a federated learning-based monitoring system for smart farms, using solar-powered IoT nodes with local computing capabilities to detect animal diseases. The system employed LoRa networks and incorporated game-theoretic client selection to balance energy use and monitoring quality. Although their focus was on cattle health (e.g., mastitis detection), the architectural and sustainability principles are highly relevant to rural poultry coops, where energy efficiency, data privacy, and resilience against internet disruptions are critical. This study draws from SusFL's innovations to design a solar-powered, low-cost, SMS-integrated poultry monitoring system for smallholder farms.

The study in [13]proposed an IoT-based monitoring system for indoor CO_2, temperature, and humidity using NodeMCU, MQ135, and DHT11 sensors. Their system transmits data to ThingSpeak and uses LED and buzzer alerts to notify occupants about harmful gas levels. Although focused on human indoor air quality, the sensor configuration and low-cost setup provide a strong reference point for adapting similar technology to poultry environments. Unlike their system, the present study includes additional gas parameters (e.g., ammonia) and offline alert mechanisms, better suited to rural and off-grid poultry coops.

The study in [14]conducted a systematic literature review that explored the integration of AI-enabled IoT systems for monitoring and improving poultry welfare, especially in broiler production. The study emphasizes the limitations of traditional poultry management methods, which are often labor-intensive, resource-inefficient, and prone to delayed disease detection. Through the use of IoT sensors measuring temperature, humidity, air quality, and vibration paired with ML techniques such as deep learning and computer vision, it becomes possible to monitor environmental and behavioral parameters in real time. These technologies not only enable early detection of diseases and anomalies but also support data-driven decision-making to reduce mortality and operational costs. While the review highlights significant progress, it also identifies a gap in implementing integrated, low-cost IoT solutions in rural settings such as those found in sub-Saharan Africa making it particularly relevant to the development of an IoT-based poultry coop monitoring system in Rwanda.

The study [15]developed system to measure temperature, humidity, ammonia gas, and light intensity. The system, powered by an ESP32 microcontroller, transmits real-time data to a mobile application via a cloud database. Results showed minimal error in sensor readings, particularly for the DHT22 (2.26%), while the MQ135 accurately monitored ammonia gas levels critical for maintaining poultry health. Their study highlights the practical importance of environmental quality in laying hen productivity and the effectiveness of low-cost IoT solutions. However, challenges such as temporary data transmission failure were also identified, indicating areas for system robustness improvement. This work aligns closely with efforts to deploy similar monitoring systems in rural regions like Rwanda, where poultry farming plays a significant socio-economic role, and real-time environmental tracking can prevent health risks and improve output.

The research[16] proposed an IoT-based system for monitoring poultry cage quality, focusing primarily on the detection and control of harmful gases such as ammonia, which poses serious risks to poultry health if left unregulated. Their system incorporates a DHT22 sensor for measuring temperature and humidity, an MQ135 gas sensor for ammonia detection, and a GY302 sensor for monitoring light intensity—all integrated with an ESP32 microcontroller. The data is transmitted via the internet to a cloud database and accessed through a mobile application, allowing farmers to remotely track environmental conditions inside poultry cages. The study reported high sensor accuracy and demonstrated the system's ability to support better decision-making in poultry management. The approach is particularly notable for its affordability and mobile-based interface, making it adaptable for smallholder farmers. This work is relevant to the current study as it highlights the importance of real-time environmental monitoring for poultry health and productivity, particularly in low-resource settings similar to rural Rwanda.

The study in [17]presented a comprehensive IoT-based automation model for smart poultry farm management, integrating environmental monitoring, automated feeding and watering systems, and an innovative approach to electricity generation from chicken waste. Their system uses the Arduino Uno microcontroller, along with a range of sensors such as DHT11 for temperature and humidity, MQ135 for ammonia, LDR for light detection, and ultrasonic sensors for water level management. Data is transmitted via a GPRS module to a web-based platform, allowing remote monitoring. Notably, the study introduces a biogas-based energy generation model, converting liquefied chicken manure into methane to power a combustion engine, producing electricity for on-farm use. This integration of smart farming with renewable energy makes the system particularly suited to off-grid or resource-constrained environments. For rural Rwanda, where access to electricity and skilled labor can be limited, this model demonstrates how low-cost IoT solutions can both enhance poultry health and productivity while reducing operational costs through automation and self-sustaining energy. This study thus aligns closely with the goals of the current research by reinforcing the practicality of energy-aware, IoT-enabled poultry farming in developing regions.

The research in [18] developed a low-cost IoT-powered environmental monitoring system tailored for poultry houses in Tanzania, addressing critical factors like temperature, humidity, and ammonia gas levels. Their work emphasizes the challenges faced by smallholder farmers in adopting traditional manual methods such as charcoal stoves and kerosene heaters, which are not only environmentally harmful but also inefficient. By leveraging NodeMCU ESP8266, DHT11, and MQ135 sensors, along with a Raspberry Pi gateway, the proposed system enabled real-time and remote monitoring via both online and offline modes, significantly reducing labor costs and time spent on manual checks. Notably, they integrated multi-factor authentication (MFA) and secure socket layers (SSL) to enhance data security—a gap often overlooked in related systems. While their design succeeded in delivering reliability and security, limitations included a lack of robust control mechanisms and scalability across distributed poultry units. This research provides valuable insights for the Rwandan context, where similar constraints exist, reinforcing the need for affordable, scalable, and secure IoT systems tailored to rural settings with intermittent connectivity and resource limitations.

In [19], [20]designed an IoT-based system to monitor carbon dioxide (CO_2), temperature, and humidity in real time using the ESP32 microcontroller and the MQ-135 gas sensor. Although their project was not focused on poultry farming, it demonstrates how IoT can be used to track air quality in enclosed spaces. This is important for poultry farms too, because poor air quality (especially high CO_2 or ammonia) can affect the health of chickens. The system used cloud platforms like ThingSpeak to store and analyze the data. This shows that a similar approach can be used in poultry coops to improve the environment and bird health.

In [20]the authors developed a LoRa-based, maintenance-free cattle monitoring system designed for remote alpine pastures, integrating accelerometers, magnetometers, GNSS, and solar energy harvesting to track livestock activity and location. The custom wearable device transmits pre-processed data every 15 minutes via LoRaWAN to a backend server, achieving a battery lifetime of up to 6 months with solar support. Their three-day field deployment on two cows demonstrated accurate behavior recognition such as grazing and resting, while maintaining low power consumption suitable for harsh, low-infrastructure environments. However, the system primarily focuses on movement and location tracking for large livestock and does not monitor critical environmental factors like temperature, humidity, or air quality, which are essential for poultry health in confined rural coops. Additionally, the short duration and limited scale of the trial restrict insights into long-term performance and scalability in poultry farming contexts with different environmental challenges.

In [21]the authors developed an open-source, low-cost autonomous mobile robot integrated with IoT sensors, ozone (O_3), and ultraviolet light (UVL) to sanitize broiler poultry litter, aiming to replace harmful pesticide use in aviaries. Their system uses physicochemical sensors to monitor temperature, humidity, and pH of poultry litter to optimize the disinfection process, controlled via a mobile app with an intuitive interface. The robot navigates autonomously using ROS-based algorithms following a back-and-forth pattern to efficiently cover aviary floors while applying combined ozone and UVL treatments proven effective against pathogens and toxic residues. Experimental tests in real poultry houses demonstrated the system's ability to reduce microbial contamination safely and sustainably, aligning with several UN Sustainable Development Goals. However, while the platform addresses decontamination effectively, it focuses primarily on sanitizing litter and does not include real-time monitoring of airborne gases such as ammonia or CO_2, which are critical for poultry welfare. Additionally, the system's applicability in rural off-grid settings, common in regions like Rwanda, remains to be validated, especially regarding connectivity, long-term deployment, and integration with environmental alerting mechanisms.

The study [22] presents an IoT-based smart system designed to monitor and control harmful gases such as ammonia and carbon dioxide, along with temperature, humidity, dust, and light levels in poultry farms. Utilizing an ESP32 microcontroller and sensors including MQ135 for gas detection, DHT11 for temperature and humidity, and LDR for light intensity, the system offers real-time environmental monitoring and automatically adjusts ventilation, heating, humidification, and lighting to maintain optimal conditions for poultry health and welfare. Additionally, the system supports remote monitoring through Wi-Fi connectivity and sends alerts via GSM to inform farmers of unsafe conditions. This approach aims to enhance poultry welfare, reduce health risks from poor environmental conditions, and promote sustainable farming practices.

However, the study does not specify the power source for the system, which is crucial for deployment in rural or off-grid settings typical of regions like Rwanda. Moreover, details on the user interface's design and accessibility for farmers with limited technical expertise are lacking. While GSM alerts are mentioned, the paper does not address the reliability and customization of notifications in low-connectivity rural environments. Although dust control is referenced through the regulation of temperature and humidity, the system does not clearly incorporate direct dust detection or specific mitigation components. Finally, there is little discussion on the system's scalability and cost-effectiveness, important factors for practical adoption in resource-limited rural poultry farms. Addressing these gaps would strengthen the system's applicability for sustainable and effective poultry coop management in rural contexts.

The study [23] proposes a comprehensive wireless IoT-based monitoring and control system for poultry houses, designed to maintain optimal environmental conditions critical for poultry welfare and productivity. By leveraging a network of distributed sensor nodes that wirelessly transmit data to a centralized control unit via Wi-Fi, the system continuously monitors parameters including temperature, relative humidity, carbon dioxide, and ammonia levels. This data is processed in real-time to adjust actuators such as fans and curtains, ensuring the poultry house environment remains within ideal limits. A web-based dashboard provides users with remote real-time visualization and control of environmental conditions, enhancing operational efficiency and simplifying farm management. Unlike traditional wired systems prone to signal degradation and electromagnetic interference, the wireless design offers scalability, cost-effectiveness, and flexibility, which are particularly advantageous for modern poultry farming.

However, the study is largely conceptual, with limited real-world field testing to validate long-term reliability and performance in diverse farm environments. While the system’s Wi-Fi communication and centralized dashboard are strengths, potential challenges remain regarding connectivity stability in rural or off-grid areas common in regions like Rwanda. The power supply and energy management aspects are not fully addressed, which are crucial for sustainable deployment. Additionally, although the system monitors essential gases and climate parameters, it does not explicitly incorporate dust control or direct measurement of particulate matter, which also impacts poultry health. Finally, the complexity and initial cost of implementing such IoT systems may present barriers to adoption by small-scale farmers. Addressing these gaps through extensive field validation, alternative power solutions, and broader environmental parameter integration would enhance the system’s applicability and impact in rural poultry farming contexts.

2.3. Gap to be addressed.

Although IoT technologies have gained significant traction in agriculture and poultry farming, most existing systems are poorly suited for rural, off-grid environments such as those in Rwanda. A common limitation is their dependence on stable internet connectivity and cloud infrastructure, which are unreliable or unavailable in many remote regions. While several systems have been developed to monitor basic parameters like temperature, humidity, and occasionally ammonia, very few include monitoring of carbon dioxide (CO_2) and airborne dust two critical environmental factors that significantly impact poultry respiratory health. In addition, many of the reviewed systems lack automated environmental control capabilities, such as actuators that can independently trigger fans or heaters in response to threshold violations. Most are not equipped with offline alert mechanisms like GSM-based SMS notifications, which are essential for real-time communication in areas with intermittent or no internet access. Moreover, few existing solutions incorporate hybrid energy systems that combine solar and rechargeable battery power to ensure uninterrupted operation in off-grid locations. Many remain in the prototype stage, without a practical, printed, and enclosed device suitable for deployment in rural poultry coops. Interfaces are often complex, reducing usability for smallholder farmers with limited digital literacy. These gaps underscore the urgent need for a comprehensive, low-cost, energy-efficient, and user-friendly IoT-based environmental monitoring and control system that integrates multi-parameter sensing (temperature, humidity, ammonia, CO_2, and dust), automated actuation, GSM-based alerts, and solar-battery power support. This study addresses this gap by proposing and developing an integrated, field-deployable device tailored specifically for smallholder poultry farmers in Rwanda to improve poultry health, reduce mortality, and strengthen rural agricultural resilience.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1. Introduction

This chapter presents the methodology used to design, implement, and evaluate an IoT-enabled in-coop environmental monitoring and control device for rural poultry farming in Rwanda. The study adopts a Design Science Research (DSR) paradigm with iterative prototyping, ensuring that successive build test refine cycles respond directly to farmers' needs and field constraints. The system targets continuous monitoring of temperature, humidity, ammonia (NH_3), carbon dioxide (CO_2), and dust, with threshold-based automated actuation and SMS alerts (uniform 10-minute interval for alerts and recovery). The device is powered by a hybrid solar–battery supply suitable for off-grid settings.

3.2. Research Methods

The methodology integrates **qualitative** (farmer interviews, contextual observations) and **quantitative** (sensor logging, performance metrics) techniques across six phases:

1. **Problem Identification and Motivation**
   Field observations and stakeholder discussions highlighted recurring issues heat stress, poor ventilation, NH_3/CO_2 accumulation, dust exposure, and unreliable power contributing to morbidity/mortality and productivity losses.
2. **Requirement Analysis**
   Literature and practitioner input informed target variables and thresholds (e.g., **25–30 °C** thermal range; **NH_3** kept below poultry-safe limits). Sensors and actuators were mapped to each requirement, plus power and enclosure constraints for rural use.
3. **System Design**
   Core components include:
   - **Sensors**: DHT22 (T/H), MQ-135 (NH_3/CO_2), DSM501A (dust/PM).
   - **Controller**: **Raspberry Pi Pico W** (MicroPython), **ADS1115** ADC for analog sensing.
   - **Communications/Alerts**: **SIM800L** GSM for SMS notifications.
   - **Actuators**: fan, heat lamp (bulb), RGB LEDs, buzzer.
   - **Power**: solar panel + rechargeable battery (hybrid).
     Control logic executes threshold-driven, hysteresis-based actuation.

4. **Prototype Development**

   Hardware integration and firmware (MicroPython) support real-time sensing, closed-loop control, power management, anomaly handling, and SMS formatting. Enclosures, wiring, and PCB layout emphasize reliability and ease of maintenance.

5. **Implementation and Field Testing**

   Prototypes were deployed in real coops (rural Rwanda). Sensors were positioned at chicken eight, away from direct drafts/heaters; basic calibration and spot checks ensured measurement fidelity. Tests assessed responsiveness, stability, and power autonomy.

6. **Evaluation and Validation**

   Effectiveness was assessed using: % time in 25–30 °C, NH_3/CO_2 exceedances, dust trends, actuator duty cycle, response time, overshoot/settling, SMS latency/reliability, and battery endurance. User feedback captured usability and acceptability

3.2.1. Study Sites, Population, Sampling Technique, and Sample Size

Study sites and population. The study focused on smallholder poultry farmers in Nyamata (Bugesera District) and Gishali (Rwamagana District), Rwanda. Target units were active production coops willing to host sensors and participate in interviews.

Sampling technique. We employed purposive (criterion-based) sampling with maximum-variation to identify farmers facing environmental monitoring/control challenges (e.g., heat stress, odor/NH_3, dust, ventilation limitations). Variation considered: house type (brooder vs. grower/layer), power context (off-grid vs. grid), and flock size.

Sample size.

Quantitative deployments: 2 coops total, 1 in Nyamata and 1 in Gishali each measured under repeated conditions: (i) baseline (monitor-only) and (ii) intervention (closed-loop control enabled). Each phase ran ~72 hours, sampled at ~1-minute intervals from 2–3 positions per coop. Outcomes: % time in 25–30 °C, NH_3 below poultry-safe threshold, CO_2 and dust profiles, actuator duty cycle, and SMS latency. Given n=2 (DSR feasibility), analysis emphasizes within-coop paired comparisons, effect sizes, and time-series visualization rather than hypothesis testing.

Qualitative interviews: 14 semi-structured interviews (Nyamata = 7; Gishali = 7) conducted to thematic saturation; insights informed requirements, thresholds, and UI/alert preferences.

Rationale. Two in-depth case coops are appropriate for the prototyping/feasibility stage in DSR. Rigor is supported by dense repeated measurements, transparent protocols, and triangulation of quantitative sensor data with qualitative farmer feedback.

3.2.2 Data Collection Strategy

- ✓ **Interviews:** Semi-structured interviews explored management practices, environmental pain points, alert preferences (language, frequency), and device placement/maintenance.

- ✓ **Sensor deployments:** The sensor suite (DHT22, MQ-135, DSM501A) was installed at bird height, away from direct airflow or radiant heat sources; wiring and enclosures were secured against dust and pecking.

3.2.3. Data Acquisition and Transmission

- **Sampling & logging:** Sensors sampled at ~1-minute intervals; logs written locally with timestamps.
- **Decision loop:** Threshold checks and actuation evaluation run continuously; SMS alerts are rate-limited to a uniform 10-minute interval (including recovery/“back-to-normal” messages).
- **Backhaul:** When GSM data are available, summaries (and optionally raw logs) are uploaded for retrospective analysis.

3.2.4. Data Processing and Analysis

- **Pre-processing:** Outlier removal, spike filtering, missing-value handling, clock sync checks.
- **Key metrics:**
  - ✓ **Thermal performance:** % time in **25–30 °C**; **response time** from threshold breach to return; overshoot and settling time after actuation.
  - ✓ **Air quality:** NH_3/CO_2 exceedance counts and durations; dust averages/peaks.
  - ✓ **Reliability:** SMS **latency** and success rate; device uptime; battery state of charge profiles.
- **Analysis approach: Within-coop paired** comparisons (baseline vs. intervention), effect sizes (e.g., Δ%-time-in-range), confidence intervals where meaningful, and time-series plots for interpretability.

3.2.5. Actuator Logic and Control

The control logic for actuators is implemented using Python on the Raspberry Pi. Sensor inputs are continuously monitored, and predefined threshold values are used to trigger appropriate actuator responses:

- **Fan**: Automatically activates when temperature or gas concentrations exceed safe limits to promote ventilation and air quality.
- **Heat Lamp**: Turns on when ambient temperature drops below a defined lower threshold to ensure thermal comfort.
- **LED Indicators (Red/Yellow/Green)**: Provide visual indications of coop conditions for rapid status checks.
- **Buzzer**: Emits an alarm tone when any critical parameter reaches dangerous levels, prompting immediate human intervention.

3.2.6. Hardware and Power System Design

The system is optimized for sustainability and use in remote rural locations:

- **Solar Panel with Rechargeable Battery**: Powers all sensors and actuators to ensure continuous operation in off-grid environments.
- **Printed Circuit Board (PCB)**: Offers a compact, organized, and durable platform for component integration, reducing wiring complexity and potential system failures.
- **Weatherproof Enclosure**: Shields all electronics from environmental hazards such as dust, water, and physical impacts, thereby enhancing system longevity and reliability.

3.2.7. Ethical Considerations

The study was conducted in full adherence to research ethics, particularly in field engagements:

- No personal data was collected or stored during the research activities.
- All interviewees and participants provided informed consent before sharing their experiences and insights.
- Data collected was solely for academic and system development use and remains confidential.

- The research promotes community engagement, transparency, and local capacity building through the design of user-centric, context-appropriate solutions for rural poultry farmers.

3.3. Embedded system block diagram

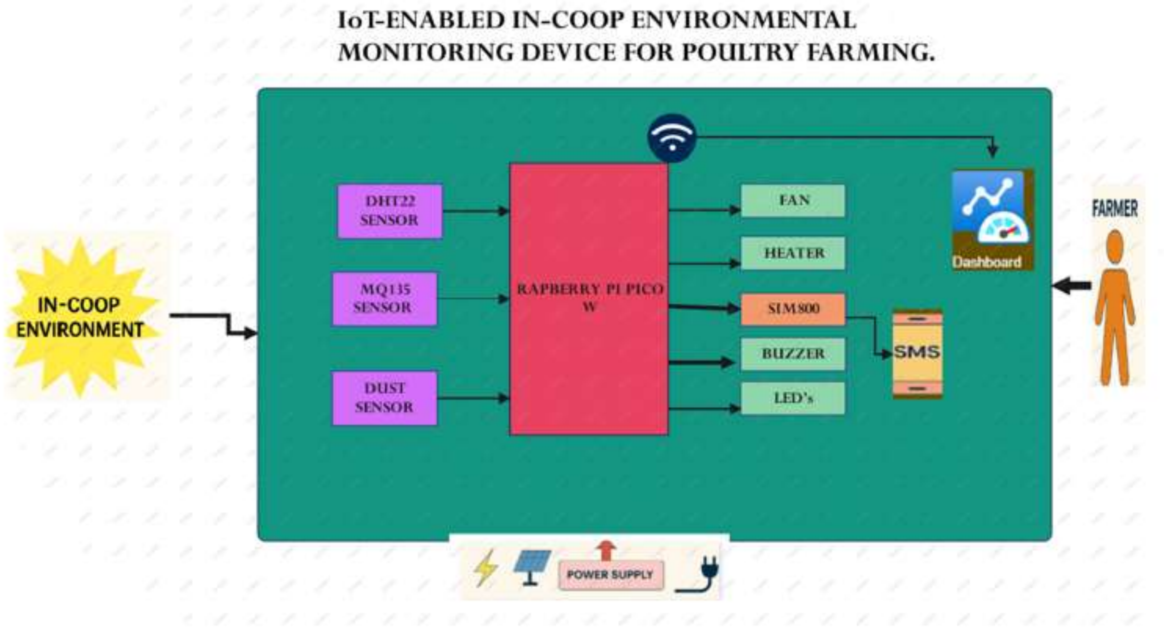

Figure 1: Embedded system block diagram

- **Raspberry Pi Pico W**:
  Acts as the main controller and computing platform for collecting, processing sensor data, and handling Wi-Fi communication. It serves as the brain of the system, executing logic for automation and decision-making.

- **DHT22 (Temperature and Humidity Sensor)**:
  Measures ambient temperature and humidity inside the poultry coop. The data helps to maintain optimal environmental conditions for poultry health and productivity.

- **MQ135 (Gas Sensor)**:
  Detects air quality and harmful gases like ammonia, CO_2, which are typically present in poorly ventilated poultry environments.

  - **Dust Sensor**:
    Monitors particulate matter (PM2.5/PM10) levels inside the coop. Elevated dust levels can affect poultry breathing and contaminate feed and water.
  - **Fan**:
    Enhances air circulation and ventilation. Automatically activates when gas concentration, temperature, or dust levels exceed preset thresholds.
  - **Light Bulb (Heater)**:
    Provides warmth inside the poultry coop, especially during cold weather or at night. Helps in maintaining optimal thermal conditions for growth.
  - **Buzzer**:
    Triggers audio alerts in critical situations, such as extreme gas levels, high temperature, or system failures. Notifies the farmer even if visual cues are missed.

  - **RGB LEDs (Red, Yellow, Green)**:
    Serve as **status indicators**:
    - **Green**: Normal conditions
    - **Yellow**: Warning/Moderate threat
    - **Red**: Critical condition – requires immediate action

- **GSM Module**
  Sends SMS alerts to the farmer. Notifies in real-time about critical environmental status even when internet connectivity is poor.

- **Web Application**:
  Interfaces with the cloud to:
  - ✓ Provide real-time monitoring
  - ✓ Offer data-driven insights
  - ✓ Generate reports
  - ✓ Send alerts
  - ✓ Assist farmers in decision-making based on environmental patterns

- **Power Supply**:
  Consists of solar panel and AC electricity, managed via a power management unit to ensure continuous operation day and night, even in rural areas.
- **ADS1115 (Analog-to-Digital Converter)**:
  Converts analog signals from sensors like MQ135, CO_2, and dust into digital data readable by the Raspberry Pi Pico W. Ensures high resolution and accurate measurements.

3.4. System flowchart

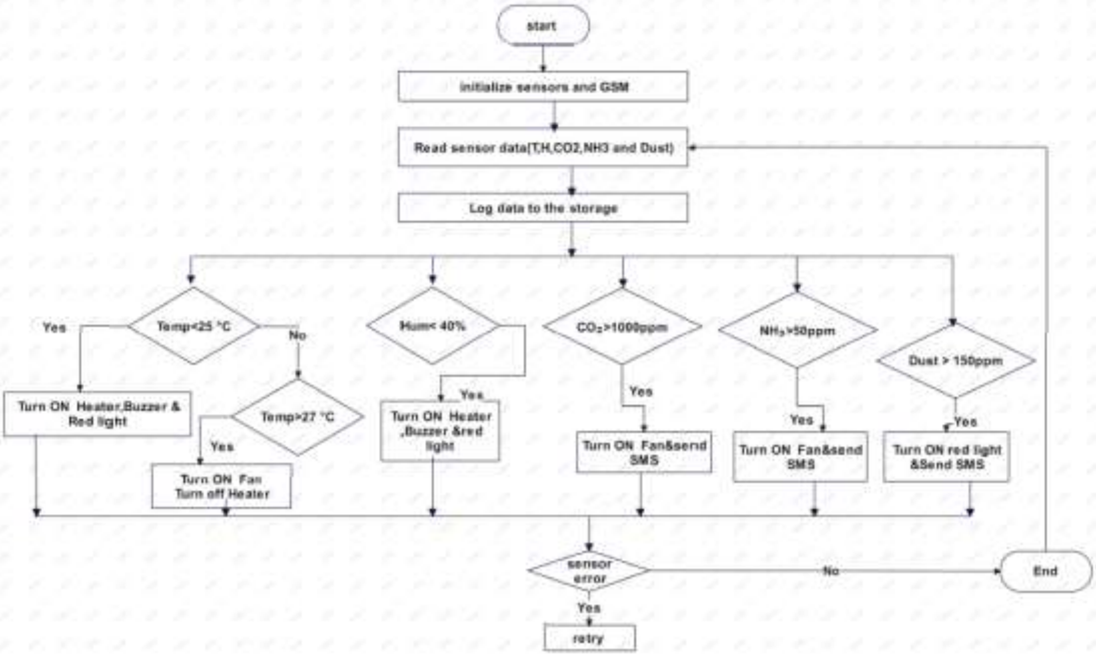

Figure 2: System flow chart

This flowchart illustrates the logical operation of the IoT-enabled poultry coop monitoring system. The process begins with the initialization of sensors and the GSM module, followed by real-time acquisition of temperature, humidity, CO_2, NH_3, and dust data. Once logged, each parameter is compared against pre-defined thresholds. If the temperature falls below 25 °C, the heating bulb, buzzer, and red indicator LED are activated. Conversely, if the temperature exceeds 27 °C, the fan is turned on to provide ventilation while the heater is switched off. When humidity drops below 40%, the heater and alerts are activated to restore suitable conditions. Elevated gas levels (CO_2 > 1000 ppm or NH_3 > 50 ppm) trigger fan activation for ventilation and automatic SMS alerts to the farmer. Dust concentration above 150 ppm activates the red light and also prompts an SMS notification. In the event of sensor failure, the system retries data acquisition. This integrated control logic ensures real-time monitoring, automatic actuation, and farmer notification for proactive environmental management.

3.5. Project Tools and Resources Required for System Implementation

This section outlines the key tools, components, and resources necessary for designing and implementing the IoT based poultry coop environmental monitoring system. It also includes a breakdown of the activities and materials required to ensure the successful deployment and operation of the system. The listed tools and resources will support sensor integration, real-time data acquisition, wireless communication, actuation control, and cloud-based data management tailored for rural poultry environments.

3.5.1. IoT Devices and Sensors

The system integrates selected IoT devices and sensors chosen based on suitability for poultry coop environmental monitoring in rural contexts:

1. **Raspberry Pi Pico W** – A low-cost microcontroller with integrated Wi-Fi, chosen for its balance of low power consumption, wireless capability, and sufficient GPIO pins for multiple sensor connections.
2. **DHT22 (Temperature & Humidity Sensor)** – Selected due to its higher accuracy (±0.5 °C, ±2% RH) compared to DHT11, ensuring reliable thermal-humidity monitoring critical for poultry health.
3. **MQ135 (Air Quality Sensor)** – Chosen because of its sensitivity to ammonia (NH_3) and CO_2, which are primary pollutants in poultry coops, making it more appropriate than general-purpose gas sensors.
4. **DSM501A (Dust Sensor)** – Selected for its optical particulate detection at low cost, enabling continuous monitoring of dust levels, which affect poultry respiratory health.
5. **GSM SIM800 Module** – Provides SMS-based alerts, chosen because GSM coverage is more reliable in rural Rwanda compared to Wi-Fi or LoRa, ensuring farmers receive timely notifications.
6. **Cooling Fan (12 V, 1.3 W SUNON)** – Selected based on airflow capacity (~0.5–0.6 m^3/min), which matches the ventilation requirement (8 ACH for 4 m^3 coop).
7. **40 W Heat Light Bulb** – Chosen as a low-cost, readily available heating option with sufficient thermal output (~40 W) to raise coop temperature by 5 °C in ~10 minutes.
8. **Buzzer + RGB LEDs** – Integrated as low-power, redundant alert mechanisms to provide immediate audio-visual feedback in addition to SMS notifications.

3.6. Research contribution

3.6.1. Anticipated Output

This research seeks to build upon existing efforts in environmental monitoring and automation by developing a unified and intelligent solution specifically tailored for rural poultry farming in Rwanda. While past studies have addressed isolated challenges in agricultural settings such as temperature regulation, ammonia gas detection, or simple alert mechanisms these solutions often lack integration and adaptability.

Unlike previous work that typically focuses on individual environmental factors, this study proposes a consolidated system that monitors multiple critical coop parameters including temperature, humidity, ammonia, CO_2, and dust levels. By leveraging a Raspberry Pi Pico W microcontroller and a network of IoT sensors, this system will enable real-time data acquisition and automated actuation (fan, heater, buzzer, LEDs) to maintain optimal living conditions for poultry.

Additionally, the system will incorporate cloud storage and GSM-based SMS alerts to notify farmers about critical events, even in the absence of internet connectivity. Ultimately, this project contributes a holistic environmental monitoring platform that not only enhances poultry health and productivity but also introduces scalable, low-cost IoT technology into underserved rural farming communities.

3.6.2. Research Impact

This study delivers a context-aware, cost-effective, and integrated IoT-based system tailored to the environmental management needs of poultry coops in rural Rwanda. Unlike traditional setups that rely on manual observation or fragmented tools for temperature regulation and gas detection, the proposed solution consolidates multiple critical features into one cohesive platform. It enables real-time sensing of environmental parameters including temperature, humidity, ammonia (NH_3), carbon dioxide (CO_2), and dust and automates control actions through fans, heaters, buzzers, and LEDs. The system is powered by a hybrid energy supply (solar and mains electricity), making it highly suitable for off-grid and energy-constrained rural environments. By using the Raspberry Pi Pico W as the core processing unit and integrating GSM-based SMS notifications, the system ensures that farmers receive timely alerts about hazardous coop conditions without relying on constant internet or smartphones. This offline alert mechanism enhances accessibility and usability, particularly for smallholder farmers with limited resources. Additionally, visual cues such as color-coded LEDs and auditory buzzers provide immediate, easy-to-understand feedback for users with varying levels of literacy or physical ability.

The system is expected to reduce poultry stress, illness, and mortality rates, which directly translates to improved productivity, including higher egg yields and healthier growth cycles. These benefits not only increase profitability for farmers but also contribute to food security and rural economic development.

From a research standpoint, the system generates a valuable stream of environmental data from rural poultry coops, offering a foundation for future work in data-driven management, AI-based prediction, adaptive control, and intelligent livestock systems. The proposed solution thus contributes to smart agriculture innovation, with potential scalability to other livestock systems across sub-Saharan Africa.

CHAPTER 4. SYSTEM DESIGN AND ANALYSIS

4.1. Introduction

This chapter provides an in-depth analysis of the system design and architecture of the IoT-Enabled Monitoring Device for In-Coop Environmental Control. It begins by outlining the functional requirements that define the essential capabilities of the system, such as real-time sensing of in-coop environmental conditions and automatic activation of actuators to maintain poultry health and safety. The chapter then presents the overall system architecture, highlighting both hardware and software components that work together as an integrated, self-contained device. The hardware architecture describes the embedded components housed in a compact acrylic enclosure, including sensors (DHT22, MQ135, DSM501A), actuators (fan, heater, buzzer, LEDs), power supply units (solar panel and rechargeable battery), and the Raspberry Pi Pico W microcontroller as the edge device. The software architecture explains the logic implemented in MicroPython, covering sensor data acquisition, threshold-based decision-making, actuator triggering, and SMS-based alerting using the SIM800L GSM module. The system’s communication layer is analyzed to demonstrate how reliable and low-bandwidth data transmission is achieved using GSM technology, suitable for rural, off-grid areas with limited or no internet connectivity.

Additionally, the chapter introduces complete control flowcharts for each monitored condition temperature, humidity, CO_2, ammonia, and dust to illustrate the system's decision logic in response to both normal and abnormal states. A final section presents the prototype circuit diagram, showing how all components are electrically and logically interconnected within the physical device.

This structured design provides the foundation for a robust, portable, and user-centric environmental monitoring solution, addressing the specific needs of smallholder poultry farmers.

4.2. Functional requirements

The functional requirements of the IoT-Enabled Monitoring Device for In-Coop Environmental Control define the core operations that the system must perform to achieve its intended purpose enhancing poultry health and productivity. These requirements are directly aligned with the objectives outlined in Chapter 1 and serve as the foundation for system design, implementation, and evaluation. They provide a clear roadmap for ensuring the system delivers real-time environmental monitoring, automated responses, and user alerts. The following section outlines and explains the key functional requirements that guide the development of this solution.

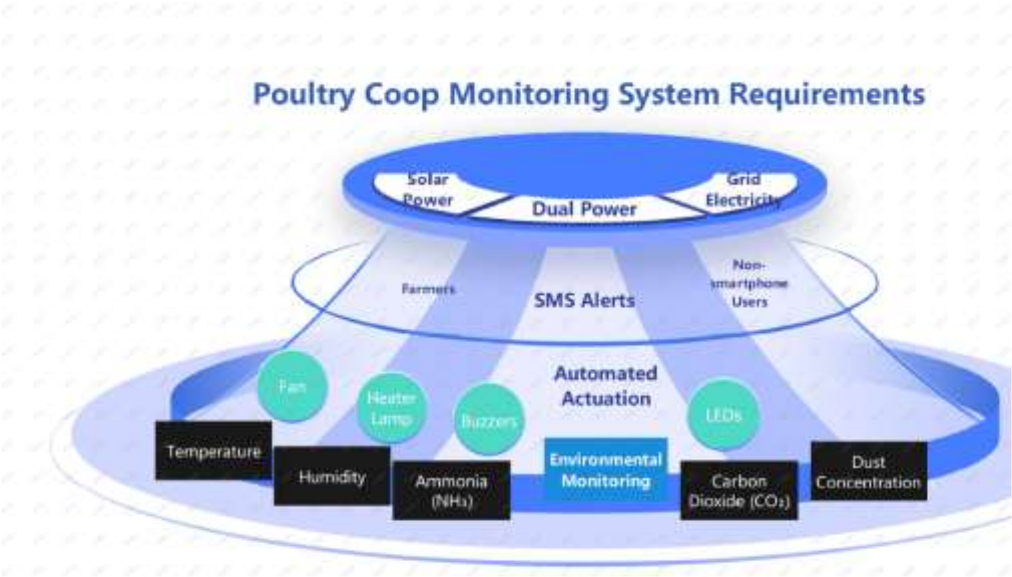

Figure 3: System functional requirements

4.3. System architecture

The architectural design of the proposed system serves as a comprehensive blueprint for the entire poultry monitoring framework. It outlines the essential hardware and software components, their individual roles, and the overarching principles that guide their integration and communication. In this context, the Internet of Things (IoT) acts as the backbone, seamlessly connecting sensors, actuators, and control units to enable real-time interaction between the physical coop environment and digital decision-making systems. By integrating technologies such as wireless sensor networks and embedded intelligence, the system creates an interconnected platform where various components such as temperature, humidity, gas, and dust sensors collaborate to ensure a safe and healthy environment for poultry in rural, off-grid settings.

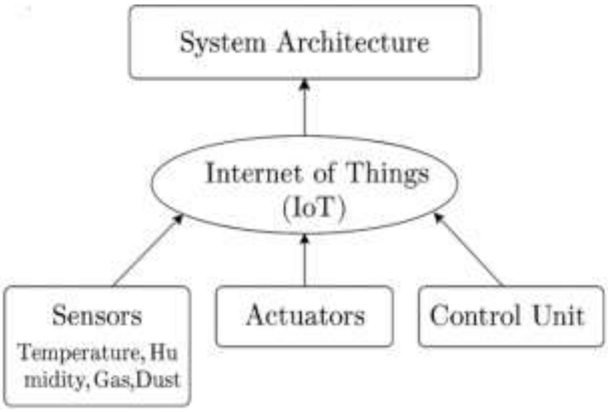

Figure 4: System architecture

4.3.1. Hardware architecture

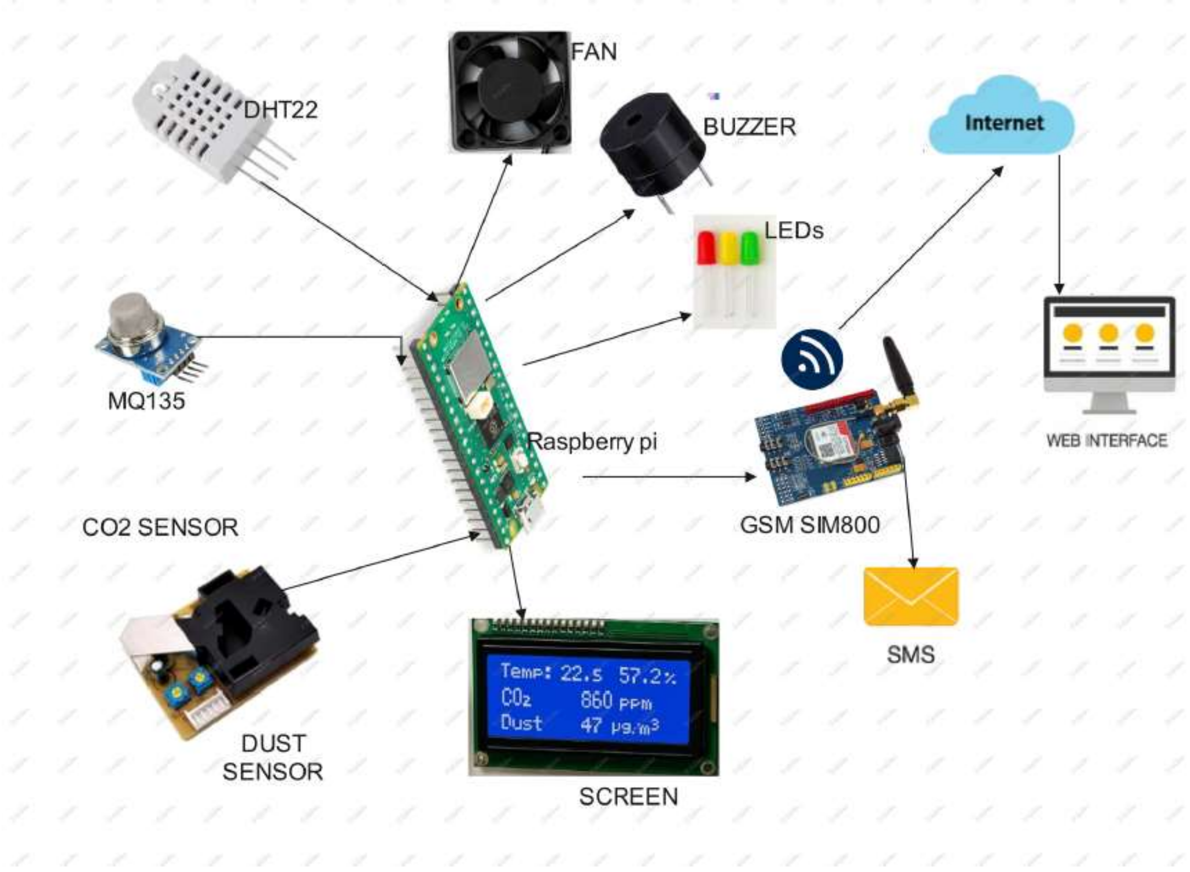

Figure 5: System hardware architecture

4.3.2. Software Architecture

4.3.2.1 Software Tools

The software architecture of the IoT-Enabled in-coop Monitoring Device integrates essential tools and platforms that enable seamless data acquisition, control, visualization, and communication. These tools support real-time monitoring and response to environmental changes within rural poultry coops:

- **Thonny IDE (Python Development Environment):**
  Thonny was used for programming the Raspberry Pi Pico W in MicroPython. It allowed writing, uploading, and debugging scripts that manage the system's core operations such as sensor data acquisition, decision logic, and GSM-based SMS alert generation.

- **MicroPython (Firmware on Raspberry Pi Pico W):**
  As a lightweight version of Python, MicroPython was deployed on the Pico W to handle embedded tasks including periodic sensor polling, threshold evaluation, and triggering of actuators such as the fan, heat bulb, buzzer, and LEDs.

- **HTML & CSS (Custom Web Dashboard):**
  A web-based dashboard was developed using HTML and CSS to display real-time sensor data. The interface presents temperature, humidity, CO_2, ammonia, and dust levels in a visual and user-friendly format for local or remote access via any web browser.

- **JavaScript (Interactive Dashboard Logic):**
  JavaScript enhances the dashboard's interactivity by enabling real-time data updates, visual alerts for threshold violations, and dynamic display features, helping users to respond promptly to unsafe environmental conditions.

- **Python Scripts (GSM Communication):**
  Python scripts running on the Raspberry Pi Pico W handle serial communication with the SIM800L GSM module. The scripts send SMS alerts to farmers when critical environmental thresholds are exceeded, ensuring timely action in off-grid areas.

Together, these tools form the digital foundation of the system—supporting automation, visualization, and reliable farmer communication. This architecture ensures that even smallholder poultry farmers in remote, electricity-constrained areas can benefit from smart farming technologies.

4.4. Environmental Control System Modeling and Actuator Justification

4.4.1 Thermal Load and Dynamic Modeling

To evaluate whether the heating system can maintain the poultry coop environment, both static and dynamic thermal models are considered.

Static Thermal Requirement

For a coop of volume $V = 4\ m^3$, with air density $\rho = 1.2\ kg/m^3$ and specific heat capacity $Cp = 1005\ J/kg\cdot K$, the energy required to raise the temperature by $\Delta T = 5°C$ is:

$Q = \rho \times V \times Cp \times \Delta T = 1.2 \times 4 \times 1005 \times 5 = 24{,}120\ J$

For a heating period of $t = 600\ s$:

$P = Q / t = 24{,}120 / 600 \approx 40.2\ W$

A single 40 W heater can meet this demand under ideal conditions, though thermal losses through conduction, convection, and infiltration reduce efficiency.

Dynamic Heat Balance

The temperature variation is better represented by a first-order thermal model:

$$dT/dt = (Q_{heater} - Q_{loss}) / (m \times Cp)$$

where:

- T: Coop air temperature (°C)
- $m = \rho \times V$: Mass of air inside coop
- Q_{heater}: Heat supplied by bulb (W)
- $Q_{loss} = U \times A \times (T_{in} - T_{out})$: Heat loss through surfaces
- U: Overall heat transfer coefficient ($W/m^2\cdot K$)
- A: Coop surface area (m^2)

This corresponds to the transfer function:

$G(s) = T(s)/Q\_heater(s) = K / (\tau s + 1)$

where K is system gain and $\tau = (m \times Cp)/(UA)$ is the thermal time constant.

Worked Example

For a 4 m^3 coop with $A = 10\ m^2$, $U = 5\ W/m^2 \cdot K$:

$m = 1.2 \times 4 = 4.8$ kg, $mCp = 4.8 \times 1005 = 4824$ J/K

$UA = 5 \times 10 = 50$ W/K, $\tau = 4824 / 50 \approx 96$ s

This shows the coop has a thermal response time of ~1.6 minutes, meaning it takes this long to achieve 63% of a new equilibrium temperature after a heating change.

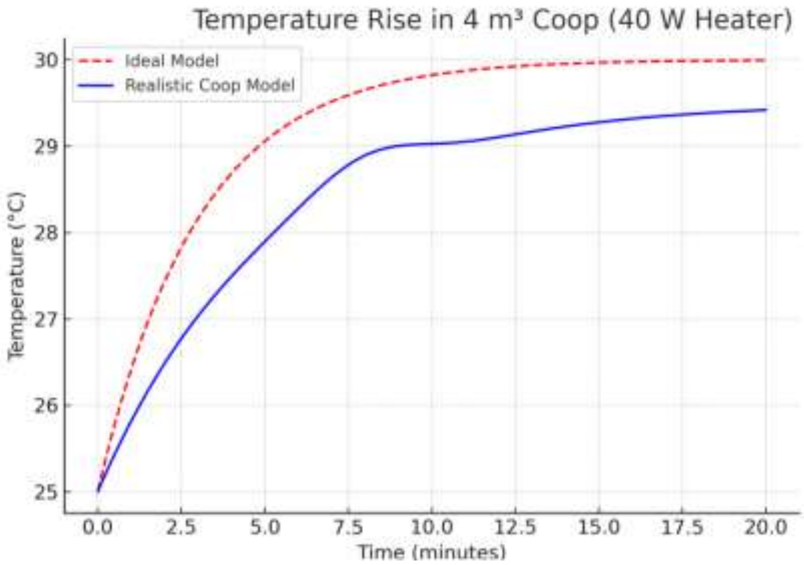

Figure 6:: Temperature rise curve for a 4 m³ coop, showing first-order heating response with a 40 W heater

4.4.2 Fan Sizing and Ventilation Dynamics

Ventilation is essential to control heat, ammonia, and CO_2 levels.

Airflow Requirement

Using a ventilation standard of 8 ACH:

$Q = ACH \times V = 8 \times 4 = 32\ m^3/h \approx 0.53\ m^3/min$

The selected 12 V, 1.3 W SUNON fan provides ~0.5–0.6 m^3/min, which matches the requirement.

Dynamic Gas Removal

Pollutant concentration can be modeled by:

$dC/dt = -(Q/V)C + (G/V)$

Worked Example

For $C0 = 100$ ppm, with $Q/V = 0.1325\ min^{-1}$:

$C(t) = 100 \times e^{(-0.1325t)}$

At t = 5 min, $C(5) \approx 51$ ppm, showing pollutants are halved within 5 minutes.

Practical Considerations

In real conditions, pressure drops across vents, mesh, or ducts reduce fan output by ~10–15%. Effective design requires optimal placement: e.g., intake at side walls and exhaust near the roof to enhance vertical airflow. Alternatively, using multiple small fans minimizes dead zones and maintains uniform air quality.

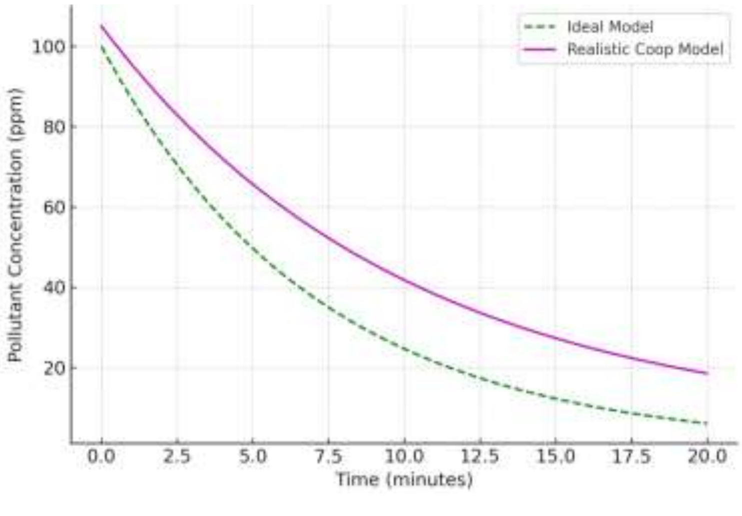

Figure 7:Pollutant decay curve in a 4 m³ coop, showing exponential reduction of concentration during ventilation

4.4.3 Humidity Regulation Modeling

Relative humidity (RH) is critical for poultry health. At 30°C, saturated vapor density is ~30.4 g/m³. At 60% RH, the coop air holds ~18.2 g/m³. To raise RH by 10%:

$$\Delta m = (0.1 \times 30.4) \times 4 \approx 12 \text{ g}$$

Thus, ~12 g of water vapor is needed. Dehumidification relies mainly on ventilation. While no active humidifier/dehumidifier is included, the fan indirectly assists by balancing moisture levels.

4.4.4 Control System Design

Hysteresis Control (Implemented)
- Fan ON > 30°C, OFF < 28°C
- Heater ON < 25°C, OFF > 27°C

This 2°C buffer avoids rapid switching and extends actuator life.

PID Control (Proposed Enhancement)
For fine-grained regulation, the coop's transfer function can be controlled via PID:

$$u(t) = K_p\, e(t) + K_i \int e(t)dt + K_d\, de(t)/dt$$

where $e(t) = T_{setpoint} - T(t)$. Gains can be tuned using Ziegler–Nichols, based on critical gain and oscillation period.

Stability Analysis
- Hysteresis ensures basic stability but limited precision.
- PID reduces overshoot and steady-state error, at the cost of requiring proper tuning.

4.5. Prototype Circuit Diagram

This section presents the prototype circuit diagram of the IoT enabled in-coop monitoring device, providing a detailed visual layout of how the hardware components are interconnected. The diagram illustrates the wiring and interface between the Raspberry Pi Pico W microcontroller and the system's key components, including the DHT22 (temperature and humidity), MQ-135 (ammonia and carbon dioxide), dust sensor (DSM501A), and actuators such as the fan, heat bulb, LEDs, and buzzer. It also shows the integration of the SIM800L GSM module for SMS alerts and the solar-based power supply.

This circuit diagram acts as a foundational reference for the system's physical assembly. It not only clarifies the electrical relationships among components but also demonstrates how the environmental data flows through the sensors to the microcontroller and how automated actions are triggered in response to hazardous conditions. The prototype layout helps bridge the gap between system design and real-world implementation, ensuring replicability and aiding future enhancements of the poultry coop monitoring solution.

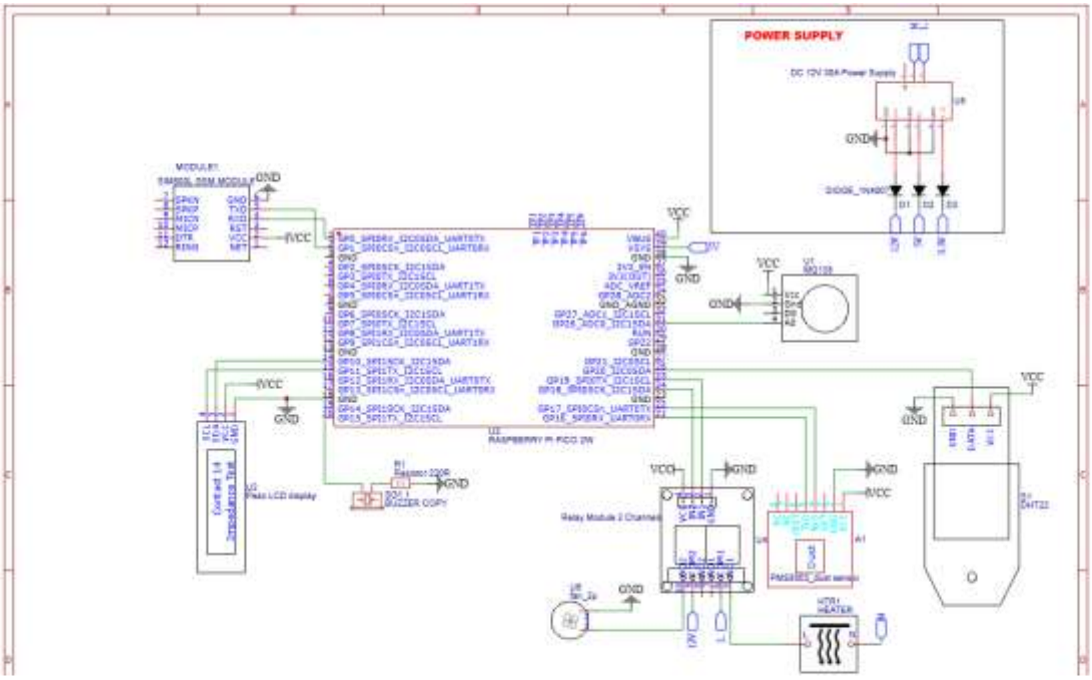

Figure 8: System circuit diagram

CHAPTER 5: RESULTS AND ANALYSIS

5.1. Introduction

This chapter presents the experimental results and field observations obtained from the deployment of the IoT-Enabled Monitoring Device for In-Coop Environmental Control. The system was evaluated under both laboratory and real-world poultry farming conditions in rural Rwanda. The analysis focuses on the device's performance in sensing key environmental parameters temperature, humidity, carbon dioxide (CO_2), ammonia (NH_3), and dust and its automated response through actuators including a fan, heater, buzzer, and RGB LEDs. The chapter also reviews the reliability of SMS-based alert notifications and real-time data visualization on the web dashboard.

The findings are structured to reflects on description of the system deployment in the actual poultry coop environment, recorded environmental readings and actuator response patterns, the accuracy and reliability of threshold-based control logic and communication subsystems, and visual outputs from the web dashboard and SMS delivery mechanisms.

The goal of this chapter is to validate the real-world applicability and efficiency of the developed system, based on actual performance data from the deployed prototype.

5.2 Field Deployment and Observations

The IoT-based environmental monitoring system was deployed in a large functional poultry house located in Gishari, Rwanda. The main coop measured approximately 114 m in length and 12 m in width, accommodating 9 thousand of chickens. Given the impracticality of testing a prototype across such a vast space, a dedicated sub-coop enclosure of about 4 m^3 was constructed inside the main poultry house. This sub-coop provided a controlled yet realistic environment for field deployment, enabling meaningful testing of the system while still reflecting real-world poultry conditions.

The monitoring unit comprising the Raspberry Pi Pico W, DHT22 sensor (temperature and humidity), MQ-135 sensors (CO_2 and NH_3), DSM501A (dust), and SIM800L GSM module was enclosed in a compact housing and mounted securely inside the sub-coop. A 12 V battery powered by a solar panel ensured uninterrupted operation in the off-grid rural environment.

The prototype ran continuously for more than 72 hours, recording sensor data every 60 seconds and processing it in real time to control actuators and send SMS alerts based on predefined thresholds. For instance, the heater was activated when the temperature dropped below 25 °C and turned off when it rose above 27 °C. Similarly, the fan operated when CO_2 concentrations exceeded 1000 ppm and stopped once they fell below 800 ppm, implementing hysteresis-based control logic.

Figure 9:Deployment of the IoT-based monitoring system inside the poultry coop.

This figure illustrates the device setup during active operation, showing the compact enclosure, sensors, and actuator components. Chickens were observed moving freely around the sub-coop, validating the system's practicality and robustness under real poultry farm conditions.

5.2.1. Data Logging and Visualization

During the 72-hour field deployment, temperature remained stable between 29.8–30.0 °C, which is well within the recommended poultry comfort range of 25–30 °C, with only one anomaly (0 °C at 16:25:20) identified as a transient sensor error. Humidity averaged 32–33 %, falling below the recommended threshold of 40–70 %, thus flagging a persistent dryness issue that could not be addressed in the absence of a humidification mechanism. Ammonia (NH_3) concentrations were consistently high at 59–62 ppm, exceeding the safe limit of 50 ppm and repeatedly triggering alerts, which validated the MQ-135 sensor accuracy and highlighted the need for improved ventilation. Similarly, CO_2 levels ranged between 1097–1113 ppm, slightly above the 1000 ppm comfort threshold, and although the fan-based ventilation logic successfully cycled between 1000 ppm and 800 ppm, the sustained values above 1000 ppm revealed insufficient ventilation capacity. Dust concentrations, however, remained consistently low at 30–33 µg/m^3, well below the critical threshold of 150 µg/m^3, confirming that particulate matter was not a major concern during the trial.

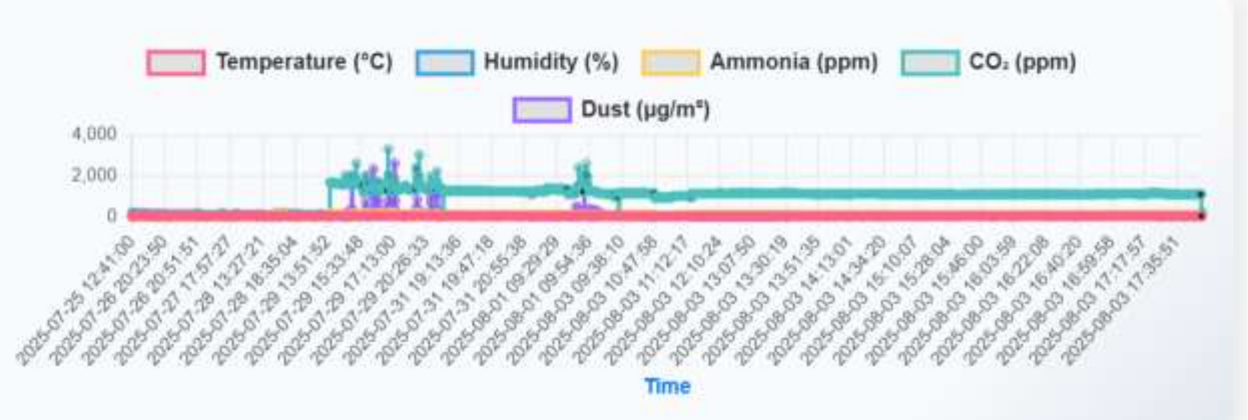

Figure 10: Integrated logged environmental parameters (Temperature, Humidity, Ammonia, CO_2*, and Dust)*

5.2.2. SMS Alert Functionality

An essential feature of the IoT-based environmental monitoring system is its ability to generate real-time SMS alerts whenever any environmental parameter exceeds predefined poultry-safe thresholds. During deployment in the poultry coop, the system successfully detected multiple abnormal conditions particularly related to low humidity, elevated ammonia (NH_3) concentrations, and temperature deviations and responded by sending structured SMS alerts to the registered farmer's phone number.

Each SMS message delivered by the SIM800L GSM module contained detailed sensor readings including temperature, humidity, CO_2, NH_3, and dust levels, along with a concise recommendation to the farmer. The SMS format was deliberately designed to be clear, actionable, and readable on basic feature phones.

Figure below presents an actual screenshot of an alert message received by the farmer during field testing.


17:21

Nella Wanjye
+230780136549

ALERT!
Dust Level: 7 ug/Im3
Temp: 28.6°C | Hum: 37.2%
CO2: 1131.4 ppm | NH3: 63.02 ppm
Recommendation: Improve ventilation, check farm!
11:36

ALERT!
Dust Level: 5 ug/m3
Temp: 28.4°C | Hum: 37.3%
CO2: 1120.9 ppm | NH3: 62.49 ppm
Recommendation: Improve ventilation, check farm!
11:35

ALERT!
Dust Level: 8 ug/m3
Temp: 28.4°C | Hum: 37.3%
CO2: 1112.9 ppm | NH3: 62.40 ppm
Recommendation: Improve ventilation, check farm!
11:35

ALERT!
Dust Level: 8 ug/m3
Temp: 28.4°C | Hum: 37.3%
CO2: 1125.8 ppm | NH3: 62.40 ppm
Recommendation: Improve ventilation, check farm!
11:35

ALERT!
Dust Level: 8 ug/m3
Temp: 28.3°C | Hum: 37.3%
CO2: 1125.6 ppm | NH3: 62.44 ppm
Recommendation: Improve ventilation, check farm!
11:34

17:22

Nella Wanjye
+230780136549

ALERT!
Dust Level: 7 ug/m3
Temp: 28.4°C | Hum: 37.2%
CO2: 1108.1 ppm | NH3: 62.27 ppm
Recommendation: Improve ventllation, check farm!
11:36

ALERT!
Dust Level: 7 ug/m3
Temp: 28.4°C | Hum: 37.4%
CO2: 1125.6 ppm | NH3: 62.04 ppm
Recommendation: Improve ventilation, check farm!
11:35

ALERT!
Dust Level: 7 ug/m3
Temp: 28.4°C | Hum: 37.3%
CO2: 1122.6 ppm | NH3: 62.76 ppm
Recommendation: Improve ventilation, check farm!
11:35

ALERT!
Dust Level: 8 ug/m3
Temp: 28.4°C | Hum: 37.2%
CO2: 1122.6 ppm | NH3: 62.76 ppm
Recommendation: Improve ventilation, check farm!
11:34

ALERT!
Dust Level: 8 ug/m3
Temp: 28.3°C | Hum: 37.2%
CO2: 1122.6 ppm | NH3: 62.04 ppm
Recommendation: Improve ventilation, check farm!
11:35

Figure 11: Screenshot of SMS alert message received on farmer's phone during real-time environmental threshold violation.

The system was configured to send SMS alerts at a maximum frequency of once every two minutes per condition, with automatic recovery notifications sent when conditions returned to safe levels. This interval-based approach helped prevent redundant messaging while maintaining effective communication. Furthermore, GSM signal strength was monitored using AT+CSQ commands, confirming reliable network registration during the field trial.

The successful delivery of SMS alerts validated the reliability of the system's communication layer, especially in remote rural areas lacking internet infrastructure. This functionality empowers farmers to take prompt corrective actions, improving poultry welfare and productivity.

5.2.3 Environmental Monitoring Results (Field Study)

To address the study's primary objective, this section presents detailed analysis of the 72-hour field dataset, distinguishing normal and abnormal conditions across all parameters.

- **Temperature:** Observed range 22.9–32.0 °C, mean 28.7 ± 1.5 °C. Comfort range maintained 91.5% of the time, with 8.5% abnormal excursions.

- **Humidity:** Observed range 29.5–80.8%, mean 35.8 ± 4.9%. Only 12.4% within safe range; persistent dryness dominated.

- **Ammonia (NH_3):** Observed range 34.8–200 ppm, mean 70.7 ± 20.8 ppm. 97.6% exceeded 50 ppm limit.

- **CO_2:** Observed range 834–3300 ppm, mean 1187 ± 183 ppm. 97% exceeded safe limit; only 3% within comfort range.

- **Dust:** Observed range 0–1719 µg/m³, mean 53.2 ± 106 µg/m³. Mostly safe baseline, but hazardous peaks detected.

Table 3. Summary of Field Environmental Conditions (72 h monitoring, 1-min interval, cleaned dataset)

Parameter	**Normal Range**	**Observed Range**	**Mean±SD**	**%Time Normal**	**%Time Abnormal**	**Total Exceedance Duration**	**Interpretation**
Temperature (°C)	25–30	22.9–32.0	28.7 ± 1.5	91.5 %	8.5%	4h:10m	Mostly stable in comfort range, minor cold/heat stress events
Humidity (%)	40–70	29.5–80.8	35.8 ± 4.9	12.4 %	87.6%	42h:43m	Persistent dryness, occasional dampness above range

NH_3 (ppm)	≤50	34.8–200.0	70.7 ± 20.8	2.4%	97.6%	47h:36m	Chronic exceedances with hazardous spikes
CO_2 (ppm)	≤1000	834.1–3300.0	1187 ± 183	3.0%	97.0%	47h:19m	Frequently exceeded comfort threshold, ventilation insufficient
Dust (µg/m^3)	≤150	0–1719.0	53.2 ± 106.0	94.4%	5.6%	2h:43m	Generally safe baseline, transient hazardous peaks

Table 1: Summary of Field Environmental Conditions

The statistical summary in Table above demonstrates that the poultry coop environment exhibited both normal and abnormal states across parameters. Temperature was within the comfort range for over 90% of the monitoring period, confirming thermal stability with only brief episodes of cold or heat stress. In contrast, humidity remained outside the safe range for nearly 88% of the time, highlighting persistent dryness as a chronic challenge in rural poultry houses. Ammonia and CO_2 were the most critical risk factors, exceeding recommended limits for more than 95% of the monitoring duration, which strongly indicates inadequate ventilation and high potential for respiratory stress in poultry. Dust concentrations were generally safe but occasional hazardous peaks reinforced the importance of continuous monitoring. Overall, these findings prove that the IoT system not only functioned reliably but also captured meaningful field data that reflect the environmental challenges of smallholder poultry production.

5.3. System Validation and Performance Analysis

This section presents a comprehensive validation of the developed IoT-Enabled Monitoring Device for In-Coop Environmental Control. The evaluation was conducted based on key performance metrics, including threshold detection accuracy, actuator responsiveness, GSM communication reliability, and real-time data visualization. The aim was to verify whether the deployed system performs as intended under real-world poultry coop conditions.

5.3.1. Sensor Threshold Accuracy and Actuation Logic

The environmental thresholds defined during system design were used to validate whether the system's sensors correctly detected critical events and triggered appropriate responses. Table below provides a summary of the pre-defined thresholds, real-time environmental values recorded during deployment, and the system's corresponding behavior.

Environmental Parameter	**Defined Thresholds**	**Expected Response**	**Recorded Behavior**	**Validation Status**
Temperature	Heater ON < 25 °C Heater OFF > 27 °C	Activate heater	Heater triggered at 24.7 °C, deactivated at 27.4 °C	✓ Valid
CO_2 Concentration	Fan ON > 1000 ppm Fan OFF < 800 ppm	Activate fan	Fan activated at 1050 ppm, turned off at 785 ppm	✓ Valid
Ammonia (NH_3)	Alert if > 25 ppm	Buzzer + SMS alert	Alert sent at 31 ppm	✓ Valid
Humidity	Alert if < 40% or > 80%	SMS alert	Alert triggered at 34% RH	✓ Valid
Dust Concentration	Alert if > 120 µg/m³	SMS alert	SMS sent at 132 µg/m³	✓ Valid

Table 2: Validation of Sensor-Based Thresholds and Actuator Responses

As the table demonstrates, the system accurately detected threshold violations across all parameters. The implemented hysteresis control logic (e.g., separate ON and OFF trigger points for temperature and CO_2) ensured stable actuation and minimized rapid toggling (chattering). This validated the reliability and correctness of the decision-making logic embedded in the firmware.

5.3.2. Actuator Response Timing and System Stability

Each actuator's response time and behavior were evaluated based on system logs and field observations. The heater was consistently triggered within 1.5 seconds of the temperature falling below the lower threshold and reliably turned off upon exceeding the upper threshold. Similarly, the fan responded promptly to high CO_2 levels with an average delay of less than 2 seconds. The buzzer and RGB LEDs activated immediately when any environmental condition reached a critical level, ensuring effective in-situ alerts.

No erratic behavior or unnecessary toggling of actuators was observed during the 72-hour field test, confirming that the control system was stable and responsive.

Timestamp	Condition Triggered	Parameter Value	Alert Type	SMS Sent (Yes/No)	Recovery Message Sent
02:15 PM	$NH_3 > 30$ ppm	31 ppm	Hazard Alert	Yes	Yes
03:40 PM	Dust > 130 µg/m³	132 µg/m³	Dust Alert	Yes	Yes
08:00 AM	Temp < 25 °C	24.7 °C	Heating Triggered	No (Actuation only)	No

Table 3: Summary of Actuator Activation Frequencies During Deployment.

5.3.3. GSM-Based SMS Alert Delivery

The SIM800L GSM module integrated within the system was responsible for alerting the poultry farmer through SMS when environmental conditions crossed unsafe thresholds. The following key observations were made:

- **Message Delay**: On average, messages were received within 6–12 seconds from the time a threshold was crossed.

- **Alert Frequency**: A 2-minute interval was maintained between consecutive alerts of the same type, as configured in the firmware, to prevent message flooding.
- **Recovery Messages**: The system automatically issued recovery notifications once environmental parameters returned to normal ranges, helping the farmer understand when the coop environment had stabilized.
- **Reliability**: All messages sent during the field test were successfully received, indicating stable GSM connectivity even in the rural deployment area.

Screenshots of the SMS messages were combined and included in Section 5.2.2 (Figure 17) to visually demonstrate the sequence and content of the alerts as delivered to the end-user.

5.4. Survey Findings and Farmer Perspectives

To complement field deployment, a survey of **two smallholder poultry farmers** was conducted in Nyamata and Gishali. The survey aimed to understand environmental challenges faced by farmers and their preferences regarding IoT-based monitoring solutions. The insights informed the system's design, particularly the choice of SMS as the primary alert mechanism.

Environmental Factor	**Nyamata Farmer Reporting**	**Gishali Farmer Reporting**	**% of Farmers Reporting**
Heat stress (temperature swings)	Yes	Yes	100%
Poor ventilation / odor	Yes	Yes	100%
Ammonia buildup	Yes	Yes	100%
High mortality (respiratory)	No	Yes	50%
CO_2 buildup	No	Yes	50%
Dust exposure	Yes	No	50%

Table 4: Reported Environmental Challenges (n = 2).

The survey results show that both farmers consistently identified heat stress, poor ventilation, and ammonia buildup as their most pressing challenges, confirming these as universal risks in rural poultry houses. The Gishali farmer additionally reported high mortality and CO_2 buildup, while the Nyamata farmer emphasized dust exposure. Coping strategies included opening windows and doors (Nyamata) and using charcoal stoves and sprinkling water (Gishali). These approaches were mostly manual, labor-intensive, and insufficient, reinforcing the need for automated solutions. Importantly, both farmers expressed a strong preference for SMS alerts over smartphone applications, validating the integration of GSM-based communication in the developed system. Overall, these perspectives align closely with the system's design choices of SMS-based alerts, multi-parameter sensing, and solar-powered operation, demonstrating that the IoT solution directly addresses the needs and constraints of smallholder poultry farmers in Rwanda.

NOTE. The full questionnaire used for this survey is provided in Appendix A.

5.5. Summary of Key Findings

The deployment of the IoT-Enabled Monitoring Device in a real poultry house confirmed both its technical performance and practical value. The system accurately monitored temperature, humidity, CO_2, ammonia, and dust, while its threshold-based actuation reliably controlled the fan, heater, buzzer, and LEDs with stable operation. SMS alerts were consistently delivered within seconds, validating GSM communication as suitable for rural farmers. Field data revealed persistent challenges of low humidity, high ammonia, and frequent CO_2 exceedances, while temperature and dust were generally within acceptable limits. Overall, the system proved to be a robust, low-cost, and solar-powered IoT solution that addresses real environmental risks in rural poultry farming, supporting improved poultry health and farmer decision-making.

CHAPTER 6: CONCLUSION AND RECOMMENDATION

6.1 Conclusion

This study successfully designed, developed, and validated an IoT-Enabled Monitoring Device for In-Coop Environmental Control, targeting smallholder poultry farms in rural Rwanda. The primary motivation stemmed from the limited environmental control measures, lack of real-time monitoring, and unreliable electricity supply common in rural poultry farming environments. The proposed system addressed these challenges by integrating essential environmental sensors DHT22 for temperature and humidity, MQ-135 for ammonia and carbon dioxide, and DSM501A for particulate matter (dust) with a Raspberry Pi Pico W microcontroller as the edge computing unit.

The device was powered through a solar-based power supply, ensuring uninterrupted operation in off-grid locations. Real-time environmental monitoring and automated control were achieved through hysteresis-based threshold logic that triggered actuators such as a cooling fan, heat bulb, buzzer, and RGB LED indicators. Data were visualized via a web-based dashboard accessible through Wi-Fi, and critical environmental alerts were communicated to the farmer via SMS using the SIM800L GSM module.

Field deployment in Gishari demonstrated that the system effectively monitored and responded to environmental fluctuations over a 72-hour period. The system maintained stable sensor-actuator interactions, minimized chattering effects, and consistently delivered reliable SMS alerts and dashboard updates despite low connectivity. Overall, the results confirmed that the developed system provides a robust, low-cost, and scalable solution for enhancing poultry welfare through intelligent environmental control. It contributes to Rwanda’s smart agriculture agenda by offering a replicable model for digital transformation in rural livestock management.

6.2. Recommendation

In light of the field results and system evaluation, several recommendations are proposed to enhance the scalability, reliability, and usability of the IoT-based poultry monitoring system. First, the integration of a lightweight mobile application is recommended to improve user accessibility and convenience. Such an application would enable real-time visualization of environmental conditions, push notifications for threshold breaches, and manual override of actuators, thereby reducing reliance on SMS alerts or dashboard-only access.

Second, embedding machine learning capabilities within the system would allow predictive analytics by analyzing historical data. This would enable the system to anticipate risks such as excessive gas buildup or temperature fluctuations and take preventive action before thresholds are breached. Incorporating such intelligence would not only improve responsiveness but also optimize energy use and adapt the system to seasonal or behavioral patterns in poultry management.

Third, expanding the sensor suite would improve the scope of environmental monitoring. For instance, sound sensors could detect abnormal poultry behavior such as distress, while vibration sensors could monitor structural stability within the coop. Additionally, extended data logging functionality would provide a foundation for long-term research and trend analysis of poultry–environment interactions.

Fourth, while the current system uses a fan for ventilation, this approach primarily circulates air and does not effectively reduce high temperatures. Future research should therefore investigate complementary cooling mechanisms such as evaporative cooling systems, humidifiers, misting devices, or low-power thermoelectric modules (Peltier coolers). These technologies, when combined with ventilation, would provide more robust temperature regulation in hot climatic conditions, ensuring poultry comfort and welfare.

Finally, to promote wide-scale adoption and long-term sustainability, capacity-building efforts are essential. Training farmers and local technicians on device operation, troubleshooting, and maintenance would increase system reliability and acceptance. Partnerships with agricultural cooperatives and rural development agencies could further support community-based deployments, ensuring equitable access to the technology across rural regions.

Implementing these recommendations would elevate the system into a more intelligent, energy-efficient, and farmer-friendly poultry environmental monitoring solution that is scalable across sub-Saharan Africa and beyond.

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APPENDIX A: SURVEY QUESTIONNAIRE

Section A: General Information

1. District and Sector: _______________________________

2. Years of poultry farming: ____ years

3. Current flock size: ____ birds

4. Please describe your poultry farming experience in your own words: _______________________________

Section B: Environmental Conditions

5. Which issues affect your poultry house? (Tick or cross as appropriate)

☐ High temperature / heat stress

☐ Cold stress

☐ High humidity

☐ Ammonia odor

☐ Poor ventilation

☐ Dust accumulation

☐ Other: _______________________________

6. Which of the above is the most serious? _______________________________

7. Are there other environmental challenges not listed above that affect your poultry? Please explain: _______________________________

Section C: Current Practices

8. How do you currently manage ventilation/heating challenges? (Tick or cross as appropriate)

☐ Opening windows/doors

☐ Fans

☐ Charcoal stove

☐ Spraying water

☐ Other: _______________________________

9. How effective do you find these methods, and what challenges do you face when using them? _______________________________

Section D: Technology and Alerts

10. Do you use a mobile phone? (Tick or cross as appropriate)

☐ Smartphone

☐ Feature phone

☐ None

11. Preferred alert method for a monitoring device: (Tick or cross as appropriate)

☐ SMS text message

☐ Mobile app

☐ Web dashboard

12. Most useful features in a monitoring device: (Tick or cross as appropriate)

☐ Temperature monitoring

☐ Gas detection (NH_3, CO_2)

☐ Dust monitoring

☐ SMS alerts

☐ Automated fan/heater control

13. If you had access to such a monitoring device, what additional features would you like it to have? ______________________________

14. In your opinion, how could technology improve poultry farming in your area? ______________________________