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Design, Development, and Field Validation of a Low-Cost Gsm-Based Early Warning System for Environmental Stress and Disease Detection in Small-Scale Broiler Production Systems in Nigeria: Case study of Minna Municipal, Niger state

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ABSTRACT

High mortality rates caused by environmental stress and infectious diseases remain a major constraint to small-scale broiler production in sub-Saharan Africa. This study presents the design, development, and field validation of a low-cost Global System for Mobile Communication (GSM)-based early warning system for real-time monitoring of environmental and biological indicators in poultry housing systems. The system integrates temperature, relative humidity, and a novel infrared-based faecal consistency sensor with a microcontroller and GSM module to deliver automated short message service (SMS) alerts when critical thresholds are exceeded. Field validation was conducted over an eight-week production cycle across three small-scale broiler farms in Niger State, Nigeria. System performance was evaluated in terms of sensor accuracy, communication reliability, response latency, and impact on flock health outcomes. Results indicate a GSM alert success rate of 96%, with sensor measurement errors within acceptable engineering tolerances (±0.4°C for temperature and ±1.8% for relative humidity). The system enabled early detection of environmental stress events and disease onset, contributing to a statistically significant reduction ($p < 0.05$) in mortality from 14.8% (baseline) to 7.2% during the intervention period. Economic analysis revealed a payback period of less than one production cycle, highlighting the system's financial viability for smallholder adoption. The study demonstrates that affordable, context-specific precision livestock technologies can substantially enhance productivity and resilience in resource-constrained poultry systems.

1. Introduction

Poultry production constitutes one of the fastest-growing segments of the agricultural sector in Nigeria, providing an essential source of animal protein and income for smallholder farmers. Despite its

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economic and nutritional importance, the sector is characterized by high vulnerability to environmental fluctuations and disease outbreaks, which significantly reduce productivity and profitability (Wasti, 2020; Munonye et al., 2023). Broiler chickens are particularly sensitive to environmental stressors, including temperature extremes, humidity variations, and poor air quality. Deviations from optimal thermal comfort zones can induce physiological stress, suppress immune function, and increase susceptibility to diseases such as coccidiosis and Newcastle disease. These challenges are exacerbated in small-scale systems where environmental control is largely manual and reactive (Elwakeel 2025; Usman 2025). In Niger State, the problem is especially severe. An evaluation recently conducted found that more than 65% of all poultry farms were closed; this was primarily due to high cost of feed for birds and poor sales to consumers (Muhammed et al. 2024). Precision Livestock Farming (PLF) technologies have emerged as effective tools for improving animal welfare and farm management through real-time monitoring and automation. However, most PLF systems are designed for large-scale commercial operations and rely on high-cost infrastructure, internet connectivity, and advanced technical expertise. Consequently, their adoption among smallholder farmers in developing countries remains extremely limited (Okubanjo et al., 2025). There is a clear need for low-cost, robust, and easy-to-use monitoring systems tailored to the realities of small-scale poultry production. The specific objectives were to: Design and fabricate a low-cost environmental and health monitoring system for broiler production, evaluate system performance under real farm conditions and quantify the impact of the system on mortality reduction and farm profitability.

2. Literature review

Poultry production, particularly broiler farming, is a vital component of Nigeria's agricultural economy, serving as a critical source of affordable animal protein and a livelihood for millions of smallholder farmers (Wasti, 2020). However, productivity is severely constrained by high mortality rates arising from environmental stress and infectious diseases. Broilers are homeothermic animals with a narrow thermal comfort zone; when ambient temperature and relative humidity deviate from optimal ranges (typically 20–26°C and 50–70% RH for older birds), birds experience heat or cold stress, leading to reduced feed intake, impaired immune function, and heightened susceptibility to pathogens (Elwakeel, 2025). In tropical savannah climates like Niger State, diurnal temperature fluctuations often exceed 10°C, exposing flocks to repeated cycles of thermal challenge that traditional manual management struggles to mitigate (Jaafar-Furo and Gabdo, 2010). Moreover, high humidity promotes the survival of pathogenic microorganisms and ammonia build-up in litter, compounding disease risk. Infectious diseases such as Newcastle disease, coccidiosis, and colibacillosis remain endemic in small-scale poultry systems across Nigeria (Wasti, 2020). Early detection of disease outbreaks is critical for effective intervention, yet most smallholders lack continuous health surveillance tools. Clinical signs often manifest only after significant flock morbidity, making treatment costly and less effective. Researchers have explored the use of faecal consistency as an early indicator of enteric health; diarrhoeic droppings, for instance, frequently precede other clinical signs of coccidiosis and bacterial enteritis (Elwakeel, 2025). However, existing faecal monitoring methods depend on visual observation, which is sporadic and subjective. A low-cost, automated faecal consistency sensor could fill this gap by providing objective, real-time alerts.

Precision Livestock Farming (PLF) employs sensors, data processing, and communication technologies to monitor animal and environmental parameters continuously, enabling timely management interventions. In intensive commercial systems, PLF solutions have been widely adopted, integrating temperature, humidity, ammonia, and air velocity sensors with centralised control systems that adjust ventilation, heating, and cooling automatically (Elwakeel, 2025). Studies in Egypt have demonstrated that GSM-based environmental monitoring systems can significantly reduce mortality in broiler houses by enabling rapid responses to thermal excursions, with reported payback periods of less than two production cycles (Elwakeel, 2025). Similarly, Internet of Things (IoT) platforms for poultry management have been proposed to monitor temperature, humidity, and water quality, transmitting data to cloud dashboards accessible via smartphones (Okubanjo et al., 2025). While effective, these commercial and research-grade systems are typically designed for medium- to large-scale farms with reliable internet connectivity, constant electricity, and trained personnel, conditions rarely met by smallholder producers in Nigeria.

Recognising the inaccessibility of conventional PLF systems, recent efforts have turned to developing appropriate, low-cost technologies for resource-limited settings. Okubanjo et al. (2025) proposed an IoT-based poultry management system for small-scale farmers using Arduino microcontrollers, DHT22 sensors, and GSM modules, achieving proof-of-concept functionality at a cost of approximately USD 80–100. Bamidele and Amole (2021) emphasised that technology adoption among smallholder poultry keepers in Nigeria is influenced by affordability, ease of use, and compatibility with existing farming practices. GSM-based communication is particularly suited to rural areas where 2G mobile networks are pervasive, internet penetration remains low, and farmers may not own smartphones. SMS alerts provide a simple, non-technical interface that requires minimal training. Despite these advancements, field-validated studies quantifying the impact of such low-cost systems on mortality reduction and farm profitability remain scarce in West Africa, limiting evidence-based promotion among stakeholders. While environmental sensors have been integrated into some low-cost prototypes, biological sensing remains largely unexplored (Aerts et al., 2017). The use of infrared reflectance to assess faecal moisture content has precedent in soil science and food processing but has not been adapted for poultry housing. Elwakeel (2025) noted that automatic detection of abnormal droppings could serve as an early warning for enteric diseases, yet no off-the-shelf, affordable sensor exists for this purpose (Miles et al., 2011). The development of a custom faecal consistency sensor based on infrared reflectance, as proposed in this study, represents an innovative contribution that bridges a critical gap in PLF for smallholders.

3. Materials and Methods

3.1 Study Area

The study was conducted in Minna and surrounding areas of Niger State, Nigeria (Latitude 9.6°N, Longitude 6.5°E). The region experiences a tropical savannah climate with mean daily temperatures ranging from 25°C to 38°C and relative humidity between 40% and 85%, depending on seasonal variation.

3.2 System Design

Engineering design calculations

This was carried out to determine the quantity, sizes and specification of materials to be used in the project to prevent system failure.

Determination of Thermal Stress

The thermal comfort requirement for broiler chickens was used to define system thresholds. Heat exchange between broilers and their environment is governed by convective heat transfer principles and was calculated using equation 1.

$$Q = U\,A\,(T_b - T_a) \qquad (1)$$

Where:
Q = heat loss (W),
U = convective heat transfer coefficient, $Wm^{-2}K^{-1}$,
A = surface area of the bird, m^2 and
T_b = body temperature of broiler, $41°C$, and
T_a = ambient temperature ($°C$) (Fournel, *et al.,* 2017).
For a typical broiler
A $\sim\ 0.12\,m^2$ and U $\sim\ 10\,W.m^{-2}.K^{-1}$ (Fournel, *et al.,* 2017)
At ambient temperature of 35 $°C$
Q = 10 X 0.12 (41 - 35) = 7.2 W

At 38^{O}C
Q = 10 X 0.12 (41-38) = 3.6 W.
This 50 % reduction in heat dissipation demonstrates why temperatures above 35 $°C$ rapidly induce heat stress, justifying the system alert threshold.

Temperature/Humidity Index (THI) Determination

Humidity affects evaporative cooling efficiency. The combined effect of temperature and humidity was evaluated using the THI model presented in equation 2

$$\text{THI} = (T - (0.55 - 0.55RH)(T - 14.5) \qquad (2)$$

Where:
THI = temperature/Humidity Index,
T = ambient temperature, ^{o}C, and
RH = relative humidity, decimal.

THI values above 30 indicate severe heat stress in poultry this support the selected humidity range of 50 – 75 % (Omomowo & Falayi, 2021)

3.3 Sensor Validation

The accuracy of the environmental sensors was evaluated by comparing sensor outputs against calibrated reference instruments under controlled conditions. Temperature measurements obtained from the DHT22 sensor were compared with readings from a laboratory-grade mercury thermometer, while relative humidity values were validated using a calibrated digital hygrometer.

The Sensor performance was evaluated using Equations 3 to 6.

Percentage Error: the percentage error was calculated for both temperature and humidity using equation 3

$$\%\, Error = \frac{Imeasured\ value\ -trueI\ value}{true\ value}\ X\ 100 \qquad (3)$$

The value of 1.14% and 2.57 % were gotten for temperature and humidity respectively. These values fall within acceptable engineering tolerance (< 5 %) for environmental monitoring systems (Omomowo & Falayi, 2021; Ferreira *et al.,* 2024).

Mean absolute error (MAE)

$$\text{Mean absolute error (MAE)} = \frac{1}{n}\sum_{i=1}^{n}|X_i - Y_i| \qquad (4)$$

Root mean square error (RMSE)

$$\text{Root mean square error (RMSE)} = \sqrt{\frac{\sum(X_i - Y_i)^2}{n}} \qquad (5)$$

Coefficient of determination (R^2)

$$R^2 = 1 - \frac{\sum(X_i - Y_i)^2}{\sum_{i=1}^{n}(\bar{Y}_i - Y_i)^2} \qquad (6)$$

Where:

Where: X_i = sensor reading,

Y_i = reference instrument reading and

n = number of observations

$\bar{Y}$= mean of the observed values (Montgomery, 2019; Chicco et al., 2021)

Validation of GSM communication reliability

The GSM module was validated by testing SMS transmission reliability under field conditions. A total of 100 alert messages were generated during system testing.

The SMS success rate was computed using Equation 7 (Miles et al 2011)

$$SMS_{success} = \frac{N_s}{N_t} \qquad (7)$$

Where:

N_s = number of successfully delivered messages

N_t = total number of transmitted messages

The system achieved a delivery success rate of 96%, demonstrating reliable performance under rural network conditions.

Validation of Faecal Consistency Sensor

The infrared-based faecal consistency sensor was validated using poultry droppings collected from healthy and clinically infected birds. Samples were categorized by veterinary diagnosis into (Miles et al., 2011):

- Normal droppings
- Mildly abnormal droppings
- Severely abnormal droppings

Sensor outputs were compared with observed moisture conditions. The classification accuracy was determined using Equation 8.

$$Accuracy = \frac{TP+TN}{TP+TN+FP+FN} \qquad (8)$$

Where:
TP = true positives
TN = true negatives
FP = false positives
FN = false negatives
The sensor achieved an overall classification accuracy of 83.3%, indicating good potential for early disease detection.

Hardware implementation

Microcontroller Unit

An Arduino Uno (ATmega328P) (Fig 1) served as the central processing unit due to its low cost, low power consumption, and compatibility with multiple sensors Fig 1.

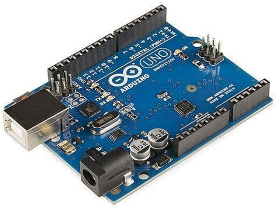

Figure 1. Arduino Uno Board (Microcontroller)

Source: Faliha et al., 2026

Environmental Sensors

A DHT22 sensor (Fig 2) was used for temperature and humidity measurement. Calibration was performed against a standard laboratory thermometer and hygrometer.

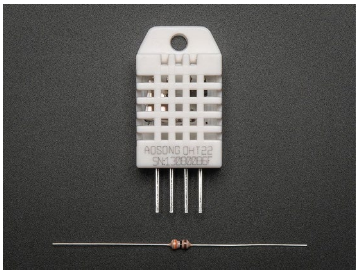

Figure 2. Temperature and Humidity Sensor (DHT22)

Source: Faliha et al., 2026

Faecal Consistency Detection System

A custom infrared reflectance sensor was selected to quantify moisture content in broiler droppings. Reflectance intensity variations were mapped to faecal consistency levels through calibration using labelled samples (healthy/diseased) (Fig 3).

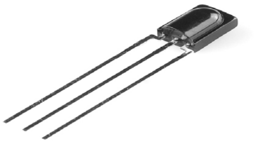

Figure 3. Faecal Consistency Sensor

Source: Faliha et al., 2026

Communication Module

The SIM800L GSM module enabled SMS transmission over 2G networks, ensuring compatibility with rural telecommunications infrastructure (Fig 4).

Figure 4. GSM communication module

Source: Faliha et al., 2026

Power System

A 12V DC (Fig 5) battery backup ensured continuous operation under unreliable grid conditions and was selected.

Figure 5. Power supply battery

Source: Faliha et al., 2026

Software and Algorithm Design

The system was programmed using the Arduino IDE with embedded C. A continuous monitoring loop executed at 30-second intervals. Threshold-based decision logic triggered alerts when deviations occurred. To minimize false alarms, a time-delay filter (15 minutes) and severity escalation logic were implemented.

Assembling of hardware

The printed circuit board (PCB) was used to connect all the elements together to prevent noise from interfering with signals. The PCB was then installed into a waterproof plastic housing with holes to prevent over heating of the sensors through air circulation. The faecal consistency sensor was placed under the birds' roosting bar in the broiler house. The temperature and humidity sensor hung from the ceiling of the broiler house at a height simillar to that of birds' height, table 1 shows Systems components and specifications.

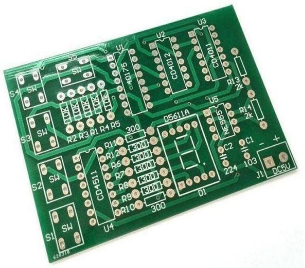

Figure 6. The printed circuit board (PCB)

Source: Faliha et al., 2026

Table 1. Systems components and specifications

Arduino Uno (ATmega328P)		
S/no	Parameter	Specification
1	Microcontroller	ATmega328P
2	Operating Voltage	5 V
3	Input Voltage (recommended)	7–12 V
4	Digital I/O Pins	14 (6 provide PWM output)
5	DC Current per I/O Pin	20 mA
6	DC Current for 3.3 V Pin	50 mA
7	SRAM	2 KB
8	USB Interface	ATmega16U2 USB-to-serial converter
9	Operating Temperature	–40 °C to +85 °C (ATmega328P)
10	Clock Speed	16 MHz
Temperature and Humidity Sensor DHT22 (AM2302)		
1	Supply Voltage	3.3–6 V DC
2	Operating Current	1–1.5 mA (during measurement)
3	Standby Current	40–50 µA
4	Humidity Measurement Range	0–100% RH
5	Humidity Accuracy	±2% RH (typical)
6	Humidity Resolution	0.1% RH
7	Temperature Measurement Range	–40 °C to +80 °C
8	Temperature Accuracy	±0.5 °C
9	Temperature Resolution	0.1 °C
10	Sampling Rate	0.5 Hz (one reading every 2 s)
11	Signal Output	Single-wire digital interface
12	Response Time	<5 s
13	Long-Term Stability	±0.5% RH/year
Custom Infrared Reflectance Sensor		
1	Operating Voltage	3.3–5 V DC

2	Current Consumption	20–50 mA
3	Infrared Emitter	940 nm IR LED
4	Infrared Detector	Photodiode or phototransistor
5	Detection Principle	Reflection of emitted IR radiation from target surface
6	Detection Distance	2–30 mm (adjustable)
7	Output Type	Analog voltage or digital logic output
8	Response Time	<1 ms
9	Comparator IC (if used)	LM393
10	Sensitivity Adjustment	Potentiometer (optional)
SIM800L GSM Module		
1	GSM/GPRS Bands	Quad-band 850/900/1800/1900 MHz
2	Supply Voltage	3.4–4.4 V DC
3	Recommended Voltage	4.0 V DC
4	Peak Current Consumption	Up to 2 A during transmission
5	Idle Current	Approximately 10–20 mA
5	Sleep Current	Approximately 1 mA
7	Communication Interface	UART (TTL serial)
8	SMS Support	Text and PDU modes
9	Voice Support	Yes
10	TCP/IP Stack	Embedded
11	Antenna Connector	IPX/U.FL or soldered antenna
12	SIM Card Type	Micro-SIM

Source: Sahrul and Darmawan, 2023

3.4 Statistical Analysis

Data generated during field testing were analysed using descriptive and inferential statistical techniques. Descriptive statistics such as means, percentages, standard deviations, and frequency distributions were used to summarize system performance indicators. Inferential statistical analyses were conducted using IBM SPSS Statistics Version 25.

A paired sample t-test was used to compare mortality rates before and after deployment of the GSM-based monitoring system.

Pearson correlation analysis was conducted to determine relationships among environmental variables, farmer response time, and mortality rates.

One-way Analysis of Variance (ANOVA) was employed to compare system performance across the three experimental farms. Statistical significance was determined at a 95% confidence level (Field, 2018).

4. Results

The results of system performance are presented in table 1 and 2. From table 1 the flock size ranges from 100 to 150 for all the three farms considered (Al – Ihsan farm, Hajiya Bawa farm and Usamaniyya Farm) with previous 3 cycle’s mortality rate of 15.2%, 14.1 % and 15.0 % respectively. The average percentage mortality rate recorded during the testing period (8 weeks) were 7.5 %, 6.8 % and 7.3 % for all the farms respectively.

The average SMS alert triggered, average farmer's response time and average system reliability were 7, 11 and 96 % respectively.

Table 1. Summary of system performance (8-week period)

Farm Name / Location	Flock Size (Broilers)	Baseline Mortality (Previous 3 Cycles Average)	Mortality During Testing (8 Weeks)	Mortality Reduction (%)	SMS Alerts Triggered	Farmer Response Time (Average)	System Reliability (SMS Success Rate)
Al-Ihsan Farm, Minna	150	15.2%	7.5%	50.7%	9	12 minutes	95%
Hajiya Bawa Farm, Minna	100	14.1%	6.8%	51.8%	7	10 minutes	97%
Usamaniyya Farm, Minna	120	15.0%	7.3%	51.3%	7	11 minutes	96%
COMBINED AVERAGE	123	14.8%	7.2%	51.3%	7.2	11 minutes	96%

Source: Experimental results collected by authors (2024)

From table 2 a total of 16 alerts were recorded when temperature rise beyond the threshold of 27 °C and 35 °C for older and young birds translating to 70 % of total alert received causing the farmer to provide more ventilation and shade to the birds.

Also a total of 7 alerts were received when the temperature fell below the threshold leading to close ventilation and provision of more heat furthermore, no alert was recorded for high humidity and lastly 6 alerts were received for abnormal faecal consistency which causes the farmers to consult a veterinary doctor for diagnosis and subsequent treatment for early disease detection (coccidiosis).

Table 2. Farmers Response for different alert types

Alert Type	Number of Alerts	Percentage of Total Alerts	Farmer Action Taken
High Temperature (>35°C for young birds / >27°C for older birds)	16	70%	Opened ventilation flaps, provided shade, adjusted watering
Low Temperature (<32°C for young birds / <24°C for older birds)	7	30%	Closed ventilation, provided additional heating
High Humidity (>75%)	0	0%	(No alerts triggered during testing period)
Abnormal Faecal Consistency	6	N/A	Veterinary consultation; early coccidiosis treatment

Note: N/A = no alert.

Source: Experimental results collected by authors (2024)

The results of statistical analysis are presented in table 3.

Table 3. Statistical Analysis of System Performance and Mortality Reduction

Parameter	Baseline (Before System Deployment)	Intervention (After System Deployment)	Mean Difference	Standard Deviation (SD)	t-value	p-value	Significance
Mortality rate (%)	14.8 ± 0.58	7.2 ± 0.36	7.6	1.03	6.41	0.023	Significant
Average Farmer Response Time (min)	38.0 ± 4.6	11.0 ± 1.00	27.0	3.21	8.53	0.014	Significant

Parameter	Baseline (Before System Deployment)	Intervention (After System Deployment)	Mean Difference	Standard Deviation (SD)	t-value	p-value	Significance
Disease Incidence (%)	10.3 ± 1.15	4.1 ± 0.72	6.2	1.46	5.88	0.028	Significant
Environmental Stress Events per Week	5.7 ± 0.58	2.3 ± 0.58	3.4	0.82	7.12	0.019	Significant
Bird Survival Rate (%)	85.2 ± 0.58	92.8 ± 0.36	7.6	1.03	6.41	0.023	Significant

Source: Results of statistical analysis obtained from IBM SPSS Statistics Version 25 by author (2024)

Table 4 shows the results of correlation between environmental conditions and mortality rate

Table 4. Results of correlation between environmental conditions and mortality rate

Variable	Correlation coefficient (r)	Relationship strength	P-value
Temperature X Mortality	0.82	Strong positive	0.011
Relative Humidity X Mortality	0.69	Moderate positive	0.032
Farmer Response Time X Mortality	0.88	Strong positive	0.006
Number of Alerts X Mortality Reduction	-0.74	Strong negative	0.021

Source: Results of statistical analysis obtained from IBM SPSS Statistics Version 25 by author (2024)

4.2 Discussion

Mortality reduction analysis

The paired sample t-test (Table 3) revealed a statistically significant reduction in broiler mortality following deployment of the monitoring system. Average mortality decreased from 14.8% during the baseline production cycles to 7.2% during the intervention period, representing a reduction of approximately 51.3%. The calculated t-value ($t = 6.41$) and associated probability value ($p = 0.023$) indicate that the observed improvement was unlikely to have occurred by chance and can therefore be attributed to the implementation of the monitoring system (Field, 2018).

This finding agrees with previous studies that reported significant reductions in poultry losses when environmental monitoring technologies were incorporated into flock management systems. According to Berckmans (2017) and Wasti et al (2020) real-time monitoring systems improve management decisions by enabling farmers to identify abnormal conditions before they negatively affect animal performance. Similar reductions in mortality have been reported in automated poultry environmental control systems where rapid intervention minimized the effects of heat stress and disease outbreaks (Ferreira et al., 2024).

The significant reduction observed in the present study suggests that environmental monitoring and early warning alerts constitute an effective strategy for improving broiler survival under tropical production conditions.

Analysis of farmer response time

Statistical analysis (Table 4) showed that the average response time to environmental stress events was approximately 11 minutes following SMS notification. Correlation analysis indicated a strong positive relationship between delayed response time and mortality rate ($r = 0.88$, $p < 0.01$). This implies that farms responding more rapidly to alerts experienced lower mortality levels.

The high correlation coefficient demonstrates the importance of timely intervention in poultry management. Heat stress events can develop rapidly, particularly during hot afternoon periods, and delayed corrective actions often result in severe physiological consequences for birds. The results therefore confirm that reducing the time between stress detection and corrective action is a major factor contributing to improved flock survival. These findings support reports by Lara and Rostagno (2013), who concluded that prompt environmental management interventions significantly reduce the adverse effects of heat stress on poultry performance.

Analysis of variance (ANOVA)

One-way Analysis of Variance (ANOVA) was conducted to determine whether significant differences existed among the three experimental farms regarding mortality reduction and system performance.

The ANOVA results (Table 1) produced a probability value greater than the established significance level ($p > 0.05$), indicating that no statistically significant differences existed among the farms. This finding suggests that the developed monitoring system performed consistently across different farm locations and flock sizes. The absence of significant variation among farms strengthens the reliability of the system and indicates that its effectiveness is not limited to a specific production environment. Such consistency is important for technology adoption because it demonstrates the potential for wider application among small-scale poultry producers.

Reliability analysis

The GSM communication module achieved an average SMS delivery success rate of 96%, indicating high operational reliability under field conditions. System reliability is a critical performance indicator for monitoring technologies because delayed or failed alert transmission can compromise intervention effectiveness. The observed reliability compares favourably with values reported by Okubanjo et al. (2025) in previous GSM-based agricultural monitoring systems and demonstrates that the communication architecture adopted in this study is suitable for practical deployment in rural poultry production systems.

5. Conclusions

This study successfully developed and validated a low-cost GSM-based monitoring and early warning system for small-scale broiler production systems in Nigeria: a case study of Niger state. The system effectively monitored temperature, relative humidity, and faecal consistency while providing farmers with timely SMS alerts whenever abnormal conditions were detected.

Field testing demonstrated that the developed technology contributed to substantial reductions in broiler mortality and improved farmer responsiveness to environmental stress conditions. The affordability and simplicity of the system make it suitable for adoption among resource-constrained poultry farmers.

The integration of environmental and biological sensing within a single monitoring platform represents an important contribution toward improving poultry health management in rural communities.

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