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# *An IoT Architecture For Automated Microclimate Control In Smallholder Poultry Brooder Cages*

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**Abstract: High mortality rate of nursery poultry birds is a big problem particularly for small holder farmers in most sub-urban regions of Nigeria due to unfavourable climatic conditions and inadequate infrastructure. To tackle these problems, this paper presents the development of an innovative smart poultry cage framework that features a novel integrated air quality and climate control system. The proposed system features sensors to track the internal temperature, humidity and air quality of the cage and provide feedback to farmers in real-time. The system also features a robust communication infrastructure that provides resilience in case of poor network access. The smart cage firmware allows for series of autonomous operations that involves actuation of fans when temperature of air quality degrades to sub optimal levels. Performance analysis of the prototype reveals the system's high reliability in maintaining preset environmental setpoints within 98 percent of target values. The autonomous ammonia gas buildup mitigation control loop also successfully maintained the air quality to within acceptable standards to ensure chicks' safety. This integrated smart cage solution offers a technological lifeline to small and medium-scale poultry farmers in rural Nigeria, the opportunity to improve their business economy and scale appropriately by enhancing productivity, reducing mortality and promoting sustainable resilient agricultural practices at affordable cost.**

**Keywords: Smart cage, poultry birds, brooding, IoT, environmental monitoring**

## I. INTRODUCTION

Poultry production is an important component of the Nigerian agriculture industry. This is because it offers a relatively cheap and affordable source of animal protein. It also provides employment opportunities for farmers as well as a low barrier entry point for small-scale agricultural enterprises. However, productivity and profitability in this industry is dependent on a number of factors. One crucial factor is the quality of the brooding environment for the chicks particularly during their nursery stage when they are most vulnerable to heat stress among other pathological challenges due to their fragile immune system. More studies in precision-poultry designs now treats the poultry house less like just a housing unit and more like an instrumented system with sensors, networks, controllers, and decision support layered together to keep birds comfortable and farms productive [1]. This shift in design is an important step especially in the rural regions of the world where farmers rarely have the capital, labour, or technical backup to run commercial climate-control equipment.

The most important variable that affects the chicks the most when it goes wrong is temperature. A chick that gets too cold in its first days struggles to feed and grow; one that gets too hot suffers physiological stress, immune suppression, and in the worst cases, dies [2]. Humidity is another sensitive parameter. When it is too much, the litter turns wet, breeding microbes and releasing harmful gases, and when it is too little, dust and dehydration become the problem. Another important variable to monitor is the air quality. This is because manure and litter constantly release ammonia and $CO_2$ into the poultry enclosed space which if not monitored actively and ventilated continuously, causes severe damage to the health of the chicks [3]. Earlier experimental work backs this up directly, that is, birds exposed to elevated atmospheric ammonia simply perform worse, which makes air-quality control a production issue, not a comfort add-on [4].

Manual heater, fan for air control, and lighting switching as well as sporadic human supervision are key components of conventional poultry care. These approaches are susceptible to uneven assessment, delayed action, and the practical difficulties of ongoing oversight. Early automation research demonstrated that integrated controllers and wireless sensors could monitor poultry-house conditions and automate basic activities [5], while subsequent IoT-based systems provided remote monitoring and internet-connected warnings [6]. In a broader sense, IoT-enabled agriculture supports continuous measurement and data-driven control by integrating sensors, edge processing, communication protocols, cloud services, and actuators [7]. This design makes it possible to identify and address environmental abnormalities in poultry housing before the birds are harmed by extended exposure.

These techniques have been used to resource-constrained chicken farming in recent research. For Tanzanian poultry producers with limited resources, Lufyagila et al. created an Internet of Things (IoT) environmental monitoring system and reported labour and monitoring time reductions [8]. An ESP32-based system for tracking and managing temperature, humidity, and air quality was introduced by Orakwue *et al.* [9]. Additionally, behavioural monitoring has been added to sensor networks, enabling anomalous activity patterns to help management and health choices [10]. Although calibration, drift, cross-sensitivity, and sensor location continue to be significant practical concerns, low-cost sensing systems are also being assessed for continuous indoor air quality measurement in poultry operations [11].

Despite these advancements, a lot of systems still rely on reliable energy and continuous internet access. In impoverished countries, where power outages, poor network coverage, expensive data, and little technical assistance are frequent, these presumptions restrict direct adoption. When connection is available, a cloud-only system could show helpful information, but during an outage, it might not provide critical alerts. In a similar manner, a monitoring-only system can detect danger but fail to address it. Therefore, inexpensive integrated systems that integrate environmental sensing with temperature, humidity, ammonia, water, and lighting management have been the focus of Nigerian research for small-scale farmers [12]. Poultry-house microclimate assessment may be supported by modular microcontroller-based sensor nodes, according to recent rapid-prototyping work [13], and low-cost automated units with GSM connection indicate the importance of early-warning services [14].

Considering these challenges, this study develops an IoT-enabled smart cage for nursery birds that integrates redundant farmer notification, distant data logging, closed-loop environmental control, and local sensing. The central processing unit is an ESP32 microcontroller. A digital sensor measures temperature and humidity, and a MQ-series gas sensor detects declining air quality. Direct-current fans offer ventilation and cooling, while a heater with a positive temperature coefficient provides warmth. Higher-current actuators were operated by the low-power controller thanks to MOSFET switching stages, and direct human contact is supported by a local display and push-button interface. The firmware uses hysteresis or threshold-based decision-making to engage ventilation when temperature or air-quality data above predetermined limitations and to initiate heating below the targeted brooding range.

There are two channels in the communication architecture. Under typical circumstances, the ESP32 uses Wi-Fi to send time-stamped measurements to the ThingSpeak cloud platform for storage and visualisation. A SIM800L GSM module offers a different SMS alert channel if internet access is unavailable or a critical threshold is surpassed. By separating local control from distant connectivity, the farmer maintains an autonomous warning system while the cage continues to sense and actuate during cloud disruption. Because automation must continue to work under the infrastructure settings under which it is deployed, such resilience is crucial.

The contribution of this research is the design and controlled evaluation of a low-cost, modular smart-cage architecture tailored to environmental and infrastructural challenges in developing regions. The prototype has multi-parameter sensing, automated heating and ventilation, local display, cloud recording, and GSM fallback notification in contrast to systems that are restricted to passive monitoring or a single communication channel. The precision of temperature regulation, actuator responsiveness, air quality mitigation, communication dependability, and continuous system stability are all assessed. Additionally, it creates a basis for calibrated gas detection, long-term energy evaluation, live-bird validation, and predictive analytics. [15]. These kinds of locally adaptive systems can convert breakthroughs in sensing and connection into useful gains in bird welfare, farm resilience, and smallholder productivity as intelligent technologies continue to transform precision poultry production

## II. LITERATURE REVIEW

Temperature, relative humidity, ventilation, and gaseous pollutants interact to affect bird comfort, respiratory health, development, and survival; hence, environmental control is essential to chicken production. Ammonia and odour emission in laying-hen housing are influenced by temperature, moisture conditions, and ventilation, as demonstrated by Nimmermark and Gustafsson [16]. This suggests that these factors should be controlled as a system rather than as discrete observations. Because nursery birds have a limited ability to regulate their body temperature, they are particularly susceptible to sudden changes in temperature. As a result, continuous sensing, networked data collecting, and automatic actuation have replaced periodic manual observation in poultry-control studies.

The viability of integrating sensors, integrated controls, and wireless communication was demonstrated by early research on smart poultry. A wireless system for monitoring temperature, humidity, light, and water level in poultry farms was developed by Amir *et al*. [17]. In their proposal for a real-time temperature controller for grill houses, Detsch *et al.* [18] proposed a real-time temperature controller for broiler houses and demonstrated the importance of formal control logic in maintaining a prescribed thermal environment. An IoT-based laying hen environment monitoring system was introduced by Zhai *et al.* [19], expanding local sensing to distant data access. Even though these systems were major advancements, multi-parameter control, communication redundancy, and infrastructure resilience were not completely addressed since they often focused on specific variables or monitoring functions.

Pereira *et al.* [20] developed an inexpensive hardware linked system for continuous microclimatic data collecting and designed an IoT sensor for environmental monitoring on chicken farms. Their system offered a useful substitute for sporadic manual measurements, but it focused more on monitoring than autonomous correction. To monitor poultry in real time, Debauche *et al.* [21] used edge computing, artificial intelligence, and open-hardware wireless sensors. To enable data validation and automation, their design used predictive models and collected environmental measurements on a regular basis. In addition to demonstrating the analytical utility of high-frequency data, their study also indicated that representative datasets, steady communication, and sensor quality are necessary for reliable prediction.

An IoT-based smart chicken cage that tracked temperature, humidity, ammonia, carbon monoxide, and carbon dioxide was developed by Syahrorini *et al.* [22]. Their study's combination of various environmental sensors and remote access makes it closely connected to this research work. However, it lacked an independent warning channel in the event of an internet outage and was mostly relied on Wi-Fi. Lufyagila *et al.* [23], in their investigation of IoT environmental monitoring for Tanzanian poultry houses, focused on low-cost technology for farmers with limited resources. While emphasising cost, maintainability, network availability, and user accessibility as crucial design factors in poor countries, their analysis proved that linked monitoring could minimise ongoing physical inspection.

A low-cost remote poultry management system for small and medium-sized farmers was presented by Chigwada *et al.* [24] It was based on a Wi-Fi-enabled ESP8266 and used a web site to monitor and control water level, temperature, humidity, ammonia, lighting, and security features. Although web access was still reliant on internet connectivity, its combination of sensing and actuator control outperformed monitoring-only systems. Orakwue *et al.* [25] developed an IoT-based system to monitor and regulate the environmental conditions of chicken farms, verifying that embedded controllers are appropriate for combining readings of temperature, humidity, and air quality. These studies allow for communication designs that maintain farmer notification in the event of a disruption in cloud connectivity, but they also enable low-cost microcontroller platforms.

Liu *et al.* [26] developed an intelligent IoT service platform for poultry-house environmental management. The system demonstrated the transition from discrete sensor nodes to more comprehensive farm-management platforms by integrating environmental data, communication infrastructure, and centralised services. Although these systems enhance long-term data storage and visualisation, they may make deployment more difficult. To demonstrate the value of continuous gas sensing for identifying temporal emission patterns, Bhattad *et al.* [27] developed an IoT-based system to measure the gas emissions from laying hens throughout the day. Additionally, their findings highlight the necessity of separating indicative outputs generated by broad-response semiconductor sensors from calibrated gas concentrations.

Another important factor is communication technology. A low-cost IoT and LoRaWAN system for family poultry farms was developed by Finistrosa et al. [28], demonstrating that dispersed monitoring and centralised data access may be supported by long-range, low-power communication. LoRaWAN improves range and energy efficiency but may require gateway infrastructure unavailable to small farms [29-32]. Godinho *et al.* [33] used dispersed measurement nodes, Wi-Fi, automated actuators, a centralised control unit, and a web dashboard to develop a wireless monitoring and control system. In addition to finding reliable power and wireless coverage as viable criteria, their field testing showed synchronised sensing and actuation.

Elwakeel [34] developed a low-cost automated device that included GSM early alerts, Wi-Fi connectivity, solar-powered operation, and measurements of temperature, humidity, ammonia, and methane in addition to activating ventilation and cooling equipment. Because it solves affordability, infrastructural constraints, and instant farmer notifications, the system is particularly pertinent. However, more live-bird testing is still required because a large portion of its validation was carried out in restricted laboratory settings. Cloud reliance, inadequate gas-sensor calibration, restricted backup communication, imperfect integration of heating, cooling, ventilation, and lighting, and inadequate validation in smallholder settings are common deficiencies found throughout the examined studies.

The present study responds through an ESP32-based nursery-bird smart cage combining temperature–humidity sensing, air-quality indication, PTC heating, forced ventilation, adjustable lighting, ThingSpeak logging, local display, and GSM-based SMS alerts. In addition to gathering environmental data, its goal is to preserve local closed-loop control and offer a backup communication channel in the event of an internet outage. Therefore, by focusing on low-cost integration, autonomous operation, communication resilience, and appropriateness for poultry production under infrastructure restrictions in developing regions, it expands related systems.

## III. Methodology

This study adopts an applied experimental engineering approach to develop and evaluate the microclimate control system for poultry nursery birds. The system hardware and software framework were designed to function specifically in an operational constraint environment and is thus optimized for energy efficiency and resilient communication

### A. System Architecture and Design Overview

The overall architecture is as shown in Figure 2 and operates as a closed-loop feedback control system centred around the 32-bit dual-core Tensilica Xtensa LX6 processor. The system continuously polls ambient temperature, relative humidity and air quality. The sensor data from these three key parameters are processed locally and compared with preset thresholds to drive real-time actuation through switching circuits. The data are also sent to the cloud in real time to facilitate remote access and control for technology savvy users.

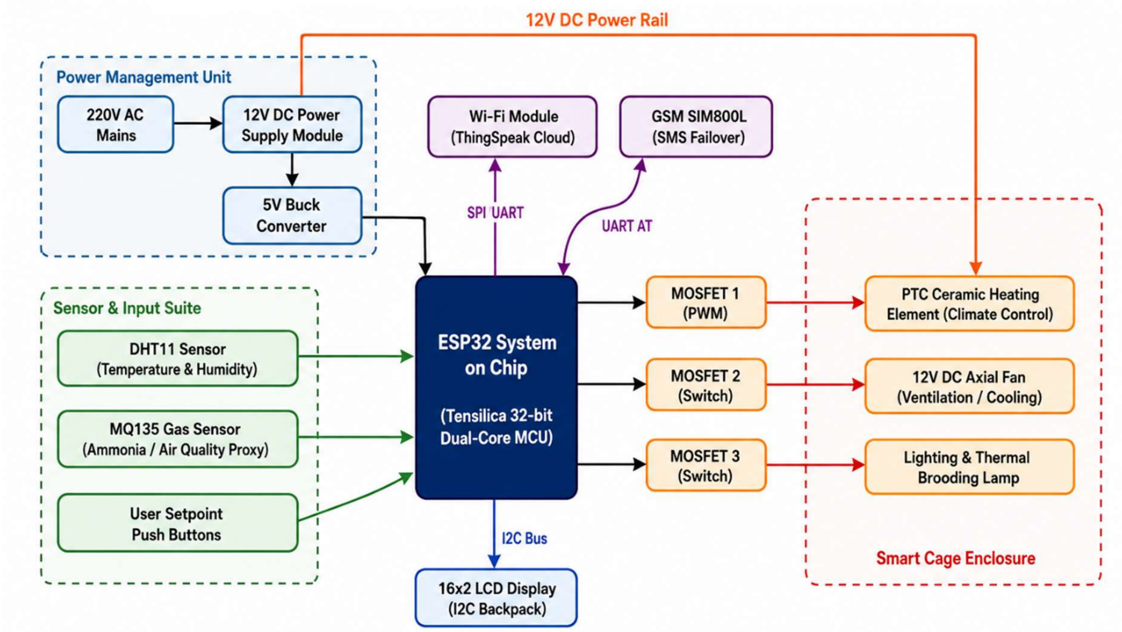


Fig. 1. Functional Block Diagram of the Proposed Smart Poultry Cage Framework

In order to mitigate the challenge of intermittent rural network coverage, the architecture incorporates a dual-channel communication infrastructure. Under normal operating conditions, telemetry packets are transmitted over a local Wi-Fi link to a cloud platform for continuous data logging and remote monitoring. If Wi-Fi connectivity is lost or internet access becomes unavailable, the system seamlessly transitions to a cellular network to issue immediate SMS alert notifications to mobile devices particularly when critical environmental thresholds are violated.

B. Hardware Integration

The components for the study were chosen to ensure low power consumption requirements as well as mechanical durability and stability particularly in high humid agricultural environment. The core sensor suite was built around the DHT22 for temperature and humidity measurement. For the air quality measurement, the MQ135 gas sensor was used. The sensor was able to monitor toxic volatile organic compounds and ammonia gas. To achieve this, the sensor output voltage was measured across a load resistance of 10k and converted to sensor resistance using Eq. 1.

$$RS = \frac{(3.3 - V_{\mathrm{RL}}) \times R_L}{V_{\mathrm{RL}}} \quad (1)$$

Where RS is the sensor resistance, $V_{\mathrm{RL}}$ the sensor output voltage, $R_L$ the road resistor. A pre-calibrated baseline resistance $R_0$ of $1600\,\Omega$ was used to establish a clean air baseline. Finally, the equivalent ammonia gas concentration in part per million was calculated using regression modeling as shown in Eq. 2.

$$\mathrm{PPM}_{\mathrm{NH3}} = a \times \left(\frac{RS}{R_0}\right)^b \quad (2)$$

Where a and b are the power-law parameters which were determined by applying logarithmic regression analysis to two data points that were obtained from the manufacturer's sensitivity characteristic curve for ammonia. The helps to linearize the sensors traditional non-linear response curve on a log-log scale thus enabling real-time ppm estimation with the smart cage directly from within the firmware.

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3.2.1 Power Architecture

The smart cage features a dual power source to ensure functionality even in an off-grid environment. The main system power is derived from a stabilized 12v DC power supply from a power supply module which can take input from an AC to DC converter or from solar PV module. Lower voltage rails, specifically 5V DC and 3.3V DC for logic circuits are supplied using a LM2596 step-down buck converter to maintain high thermal efficiency.

Since nursery birds require elevated room temperature, heating is achieved through a ceramic positive temperature coefficient (PTC) heating element. The system microcontroller modules power to the element using 5 kHz pulse width modulation signal via logic-level N-channel MOSFET switches. The inherent self-limiting thermal property of PTC ceramic materials helps to prevent any form of catastrophic thermal runaway in case of software locking. To ensure proper ventilation and air circulation within inside the cage, a 12V DC axial fan was employed. The fan served dual purpose. First, it ensures air cooling during over-temperature events and secondly ensured dynamic air exchange during periods of excessive harmful gas build up. Supplemental lighting was also included to provide constant illumination as well as a liquid crystal display to improve user experience.

**C. Firmware Design and Control Logic**

The firmware was developed in C++ with the core control algorithm executing a non-blocking loop with continuous feedback control. Hysteresis control was also implemented to prevent rapid actuator cycling around setpoints. The thermal control system of the smart cage routinely evaluates the real-time temperature $T_{\text{air}}$ against a user-configurable brooding target $T_{\text{set}}$ which was defaulted to 34.0°C for day 0 to day 7 chicks. The temperature control setpoint for heating and cooling is as shown in Eq. 3 and 4.

$$\text{Heater State (PWM Duty)} = \begin{cases} 128\ (50\%\ \text{Duty}), & \text{if } T_{\text{air}} < T_{\text{set}} \\ 0\ (0\%\ \text{Off}), & \text{if } T_{\text{air}} \geq T_{\text{set}} \end{cases} \quad (3)$$

$$\text{Cooling Fan State} = \begin{cases} \text{HIGH (ON)}, & \text{if } T_{\text{air}} > T_{\text{set}} \\ \text{LOW (OFF)}, & \text{if } T_{\text{air}} \leq T_{\text{set}} \end{cases} \quad (4)$$

For the air quality control system, the code logic thread evaluates the $\text{PPM}_{\text{NH3}}$ against an established safe biological limit of 15.0 ppm. If the gas level exceeds this set threshold, the ventilation fan is forced into a HIGH state to purge the air pollutant in the cage. At this time also a one-time pre-programmed SMS alert is sent to the farm manager telephone number.

**D. Experimental Setup and Validation Method**

To empirically validate system performance prior to full live-bird trials, the smart cage prototype was placed in an environmental test chamber under different controlled evaluation scenarios. First, the cage was tested for brooding thermal stability. For this test, the system setpoint was configured to $T_{\text{set}}$ of 34.0°C, thereafter, cold air currents were introduced around the enclosure exterior to evaluate the heater activation time, thermal ramp rates and steady-state setpoint overshoot and hysteresis stability. Ambient external temperature was also raised to approximately 38.0°C to evaluate thermal recovery time, over-temperature fan response, and steady-state cooling performance. The functionality of the air quality sensor was also pre-evaluated to ensure safety for nursery birds. Finally for remote access and monitoring, data was continuously logged at update intervals of 20 seconds via HTTP GET request directly to a cloud server

## IV. RESULTS

The results of our findings are as discussed in this section. The prototype smart cage underwent rigorous testing and empirical evaluation under a controlled environment to determine is climate control capabilities under highly dynamic environmental and resource constrained environment it will be made to operate in. Testing was done to measure temperature regulation ability, humidity control and air quality purging capability. The system was also tested for dynamic switching latency as well as telemetric reliability. All sensor logs and actuator states were transmitted in real-time to a cloud server during operation and also captured locally via serial connection monitor to validate the integrity of the transmitted data.

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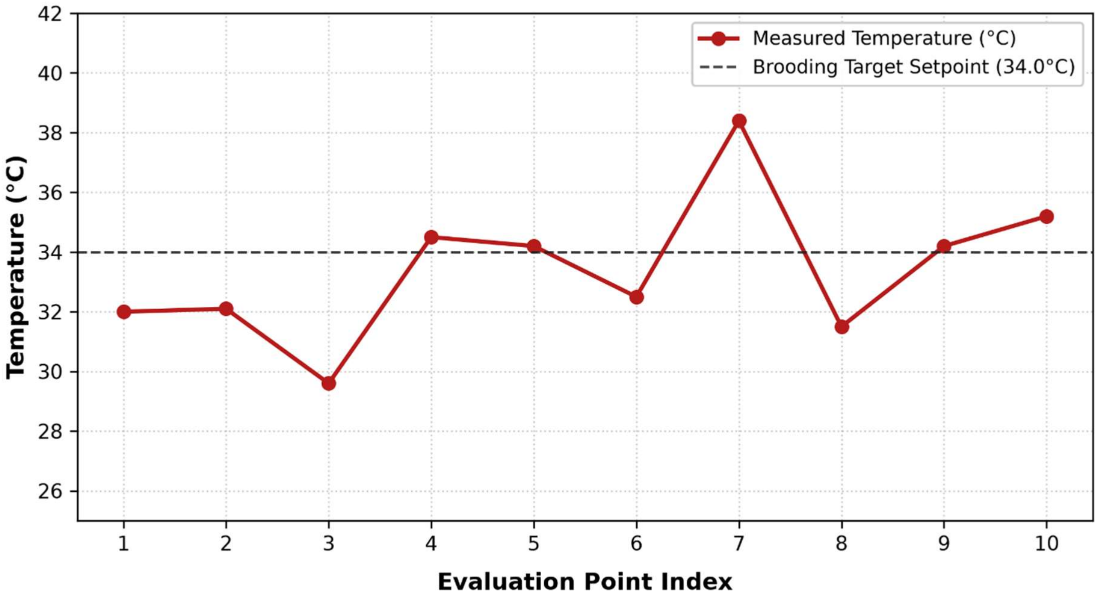


Fig. 2. Real-time temperature profile of the smart cage enclosure during brooding and heat stress testing

A. Microclimate Thermal Regulation

Temperature control is one of the main priorities during early-stage brooding of poultry birds particularly during the first 7 days of the chick's life. Consequently, maintaining a stable temperature around the recommended target setpoint of 34.0°C is central to the chicks' survival. Figure 2 presents the temperature response profile of the cage internal environment with the evaluation points 1 through 10 representing the discrete steady state sampling windows during the thermal testing process. Figure 2 reveals the smart cage attempt at stabilizing the internal temperature index. For instance, when ambient conditions were artificially depressed to 29.6°C, the closed-loop controller activated the PTC heating element via PWM driver switching. The system successfully elevated the cage temperature to the 34.0°C target setpoint, thereby maintaining the thermal stability within a tight ±1.5°C boundary during steady-state operation.

In other to evaluate the thermal override performance of the smart cage, a relatively high-heat stress condition was simulated by inducing an artificially elevated external ambient temperature of approximately 38.0°C. The result presented in Figure 2 reveals that the controller was able to identify the positive temperature deviation and initiate two major activities to mitigate this. First the heating element is immediately deactivated while the air-cooling fan is engaged. The combination of these two activities successfully forced the excessive internal temperature of the cage down to the set safe zone.

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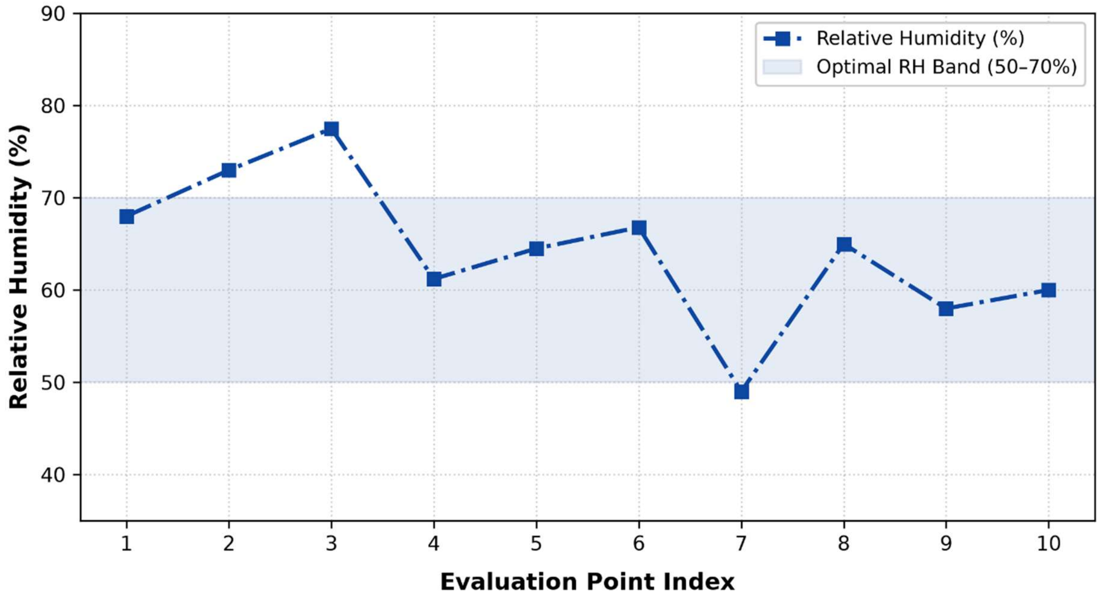


Fig. 3. Relative humidity response curve across temperature ramp and ventilation cycles

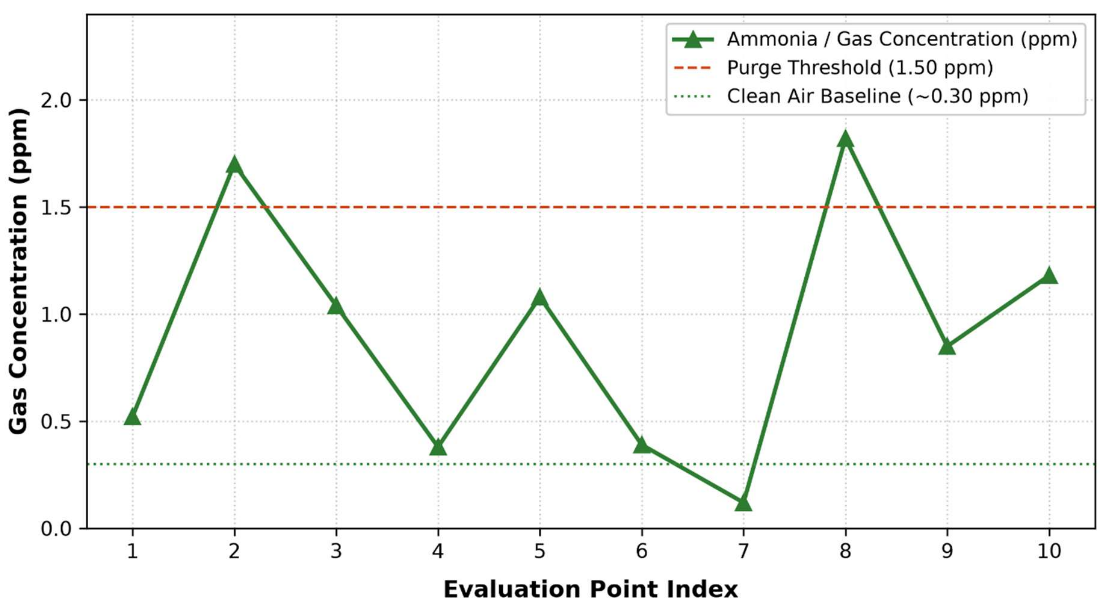


Fig. 4. Ammonia/Gas concentration plot for air quality improvement

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B. Dynamic Relative Humidity Control

Figure 3 shows the relative humidity response curve within the smart cage environment and how it's impacted by temperature change. The sensor data validated the inverse thermodynamic relationship that exists between the ambient temperature and the indoor relative humidity. During initial pre-conditioning at 29.6°C, baseline relative humidity recorded an elevated 78%. However, as the PTC heating element elevated the internal temperature to 34.0°C, the relative humidity systematically decreased from 78% to a stabilized equilibrium range of 58%--59%. Throughout subsequent forced-cooling cycles, the result shows that active ventilation remains a reliable way of keeping relative humidity within the recommended range of between 50% to70%. This essentially helps in suppressing moisture buildup without causing significant air dehydration to the poultry birds.

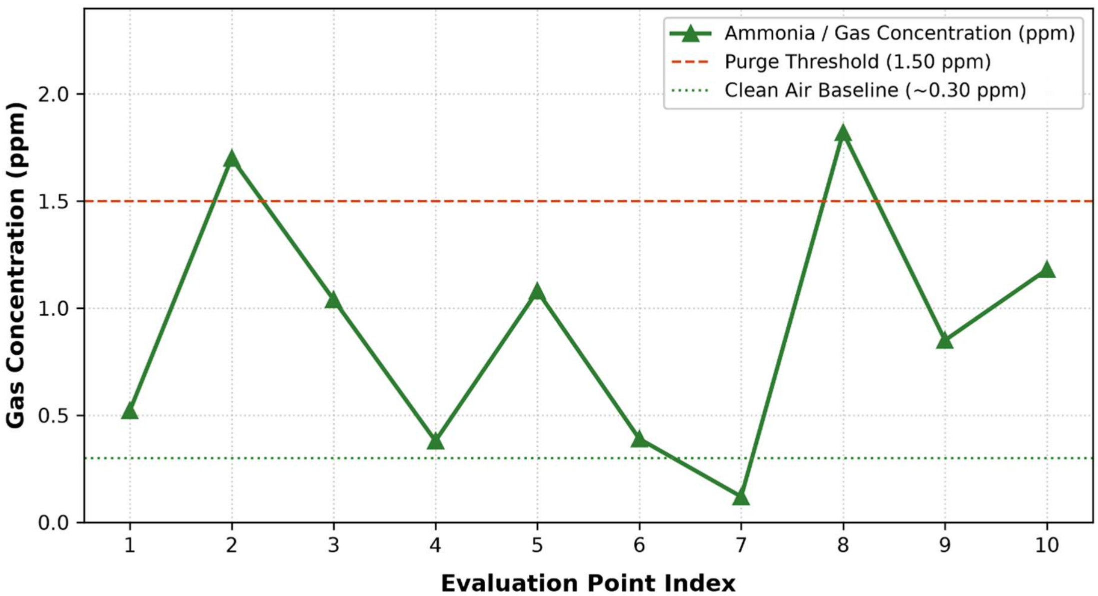


Fig. 5. Gas Concentration and Purge Response Across Test

C. Air Quality Measurement and Control

Figure 4 shows the indoor air quality condition of the smart cage. The figure demonstrates the efficacy of the closed-loop threshold control logic in mitigating volatile organic contaminants like ammonia gas build-up within the nursery cage environment. During the baseline operation as indicated in the evaluation point 1, the indoor gas concentration was stable at 0.52 ppm. When unventilated conditions were allowed to gradually advance, volatile organic accumulation caused gas levels to surge to a level slightly higher than the pre-configured safety threshold (1.50 ppm) at point 2 (1.70 ppm) and point 8 (1.82 ppm). Whenever threshold violation is recorded, the smart cage control firmware executes an actuator override and immediately energizes the DC ventilation fan to extract harmful gases from the cage. The impact of this is evident between evaluation points 3 and 7 where the gas concentration level was clearly below the purge threshold.

## V. Discussion

The empirical results from this study confirm that the developed smart poultry cage could successfully translate automated control logic in precise microclimate regulation. This precise control was able to address key biological and operational challenges particularly in small holder farmers who operate majorly in resource-constrained environments.

The system's ability to maintain thermal stability within 34.0°C ± 1.5°C directly addresses the challenge of heat stress which is the primary cause of early chick mortality in tropical regions. This challenge is even more devastating for neonatal chicks that are usually characterized by undeveloped physiological thermoregulation. Consequently, exposure to temperatures below 30°C induces lethal hypothermia, whereas exposure above 36°C causes rapid dehydration and heat stress death. By maintaining the enclosure strictly within the thermoneutral zone, chicks expend minimal metabolic energy on thermoregulation. This maximizes energy conversion that leads to better tissue growth and better feed conversion ratio. Since temperature and humidity control and closely related, proper temperature control ensure the relative humidity will mostly stay within a safe range.

Since the effectiveness of the smart cage is not only dependent on temperature control alone, a successful air quality control ensures a comprehensive safe atmosphere for the birds. In poultry brooding, sustained exposure to high level of atmospheric ammonia or nitrogenous faecal gas can lead to severe physiological impairment in small chicks. Concentrations exceeding 20 ppm is can cause ciliated mucosal paralysis in the upper respiratory tract of poultry birds. This oftentimes can lead to keratoconjunctivitis, and reduced feed conversion ratios. In this design, by enforcing aggressive localized purge trigger at 1.50 ppm, the smart cage system ensures that harmful gases are evacuated long before reaching pathologically harmful thresholds.

Through the implementing multiple parameters monitoring and control system, the smart cage prototype demonstrated excellent technical efficacy. Also, the implementation of a dual Wi-Fi/GSM communication architecture ensure that real time alerts are available to farmers over both cellular and Wi-Fi to ensure prompt notification and intervention from farmers when anything goes wrong. This ensures that problems that could threaten the welfare of the poultry birds are promptly attended to before they worsen.

## VI. Conclusion and Future Work

This study proposed an autonomous microclimate control system for nursery poultry beds to combat the challenge of high nursery bird mortality arising from heat stress and excessive exposure to high level of atmospheric ammonia or nitrogenous faecal gas. The smart cage design was particularly target at small holder farmers to operate exclusively under resource-constrained environment. The development utilizes an ESP32 microcontroller with sensors to track temperature, humidity and air quality. The system implements a robust firmware for precise thermal regulation, dynamic relative humidity control and automated air quality purging. The smart cage offers a scalable, robust engineering solution to mitigate early chick mortality and improve brooding output among poor farmers in remote areas

While the prototype evaluation confirmed robust technical efficiency, future studies can focus on long-term field deployments with live chicks to evaluate direct impact on several physiological outcomes like mortality rates, daily body weight gain and the feed conversion rations. Further research can also include the development of novel algorithm to detect diseases or other physiological conditions from real time behavioural and non-behavioural indices from the poultry birds

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