World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(REVIEW ARTICLE)

Check for updates

PRECISION BROODING OF BROILER CHICKS: A REVIEW OF THERMAL PHYSIOLOGY, SENSING, AND A FRAMEWORK FOR EMBEDDED CONTROL

Olaide Agbolade *

Department of Electrical and Electronics Engineering, Federal University of Technology, Akure, Nigeria.
* Corresponding Author

ORCID Details
Olaide Agbolade: https://orcid.org/0000-0002-8309-1459

World Journal of Advanced Research and Reviews, 2026, 32(01), 1093–1105

Publication history: Received on 06 September 2026; revised on 14 October 2026; accepted on 16 October 2026

Article DOI: https://doi.org/10.30574/wjarr.2026.32.1.2635

Copyright © 2026 Author(s) retain the copyright of this article. This article is published under the terms of the Creative Commons Attribution License 4.0

ABSTRACT

In broiler pens, temperature, humidity and air quality are all controlled by a single factor: ventilation. Yet much of the control research has focused on temperature alone. This review treats the first four weeks of broiler production as an engineering problem. It translates experimental evidence on chick responses into measurable design specifications and derives the heat, moisture and gas balances that limit what a ventilation system can achieve. It then reviews the sensing, embedded, communication and control technologies reported for poultry houses. Finally, it proposes a layered reference architecture, a constrained control formulation and a minimum set of metrics for validation studies to report. A psychrometric analysis shows that ventilation removes moisture only when the outdoor air has a lower humidity ratio than the target indoor air. For example, with a set point of 29.4 °C and 65% relative humidity (RH), outdoor air at 27 °C and 80% RH holds 1.2 g more water per kilogram of dry air than the target indoor air. In such warm, humid weather, ventilation cannot dry the litter. Studies of low-cost ammonia, particulate matter and humidity sensors report cross-sensitivity, drift and limited field validation. Most low-cost Internet of Things (IoT) nodes have been checked against reference instruments, but not against chick outcomes. Control studies for broiler houses are mostly simulations or single-site pilots. The review identifies research gaps and priorities. The proposed framework is conceptual and has not yet been tested experimentally.

Keywords: Precision Livestock Farming; Broiler Brooding; Internet Of Things; Embedded Systems; Environmental Control; Psychrometrics; Ammonia Sensing; Model Predictive Control

1 INTRODUCTION

During the first weeks of a broiler chick's life, the housing environment can be considered as one connected system, in which thermal, moisture and chemical conditions all interdependent. Air temperature, relative humidity (RH), ammonia (NH_3), carbon dioxide (CO_2) and particulate matter (PM) are controlled by ventilation. The ventilation level in the poultry housing is also dependent on multiple factors such as outdoor weather, the heat and moisture given off by the birds, and the condition of the litter. Despite this, most control research on broiler houses has focused on temperature

alone (Detsch et al., 2018; Zheng et al., 2025), and fewer studies have examined the trade-off between humidity and energy use (Baier & Meier, 2020). Yet experimental studies show that humidity, air quality and dust significantly affect chick welfare and performance (Section 2). Due to the global influence of ventilation, other dependent variables cannot be controlled independently.

The advent of precision livestock farming (PLF) provides the sensing and computing tools needed to manage this interdependence (Berckmans, 2014; Agbolade et. Al., 2026). Previous reviews of PLF in poultry have covered smart sensors, big data and the Internet of Things (IoT) (Astill et al., 2020), as well as computer vision for welfare monitoring (Okinda et al., 2020). Another study carried out by Rowe et al. (2019) investigated how PLF technology contributes to general poultry bird welfare. Aside this, there are also studies on low-cost IoT monitoring systems for poultry houses (Lashari et al., 2023; Elwakeel, 2025). However, these systems are usually assessed by how closely their readings match reference instruments, rather than by whether they help farmers make decisions that improve chick outcomes.

This article reviews the brooding environment from an engineering perspective and makes five contributions. First, it translates biological evidence into measurable design specifications (Section 2). Second, it derives the heat, moisture and gas balances of a brooding house and uses psychrometric calculations to show when ventilation can and cannot control humidity (Section 3). Third, it reviews sensing and measurement practice, including sensor placement and the reliability of low-cost sensors (Section 4). Fourth, it reviews embedded hardware, communication and power considerations (Section 5) and existing control approaches, then proposes a layered reference architecture and a constrained control formulation (Section 6). Fifth, it proposes a minimum set of metrics that validation studies should report and identifies gaps for future research (Sections 7 and 8).

2 BIOLOGICAL REQUIREMENTS AS ENGINEERING SPECIFICATIONS

Engineering design needs clear thresholds, tolerances and time scales. This section turns the experimental evidence on chick responses into such specifications (Table 1). The thresholds depend on bird age, on how long the exposure lasts and on which outcome is measured. They are therefore best treated as adjustable constraints rather than fixed values.

2.1 Temperature:

Deaton et al. (1996) tested a poultry bird temperature regimen that started at 29.4 °C in week 1 and was lowered to 26.7 °C in week 2 and 23.9 °C in week 3. This temperature profile did not reduce birds' performance at 6 weeks compared with warmer regimens. In contrast, a colder control temperature profile (26.7, 23.9 and 21.1 °C) increased both ascites-related and total mortality among chicks. Short periods of cold exposure are sufficient to cause lasting harm. Moreira et al. (2024) demonstrated this by exposing chicks to 18 °C for 8 h per day during the first week, compared to a thermoneutral control at 32 °C. The intermittently cold-exposed chicks showed reduced yolk-sac absorption and impaired feed efficiency, with a higher feed conversion ratio at 35 days. For control design, this implies that brief deviations from the set point are biologically significant. Performance should therefore be quantified by cumulative cold exposure over time, such as degree-hours below the set point, rather than by mean temperature alone.

2.2 Humidity.

The effect of RH on heat exchange varies with age and temperature. In 1-week-old broilers, higher humidity redistributed body heat, lowering rectal temperature and raising peripheral temperature. This was helpful at high ambient temperatures but harmful at low ones (Lin et al., 2005a). In 4-week-old broilers, RH above 60% hindered heat transfer from the body core to the periphery at 35 °C but helped it at 30 °C (Lin et al., 2005b). Management guidelines recommend an RH of about 60–70% during the first three days, and adjusting the temperature when RH falls outside this range (Aviagen, 2025.). Humidity also affects litter condition. In a comparison of commercial farms, litter moisture ranged from 30.9% to 56.5% in a wet-litter house and from 15.1% to 40.0% in a dry-litter house. Footpad dermatitis (FPD) appeared at 14 days on wet litter but not until 28 days on dry litter (Taira et al., 2014). Similarly, wetting the litter from day 6 increased FPD at 21 and 36 days and reduced performance from day 28 onwards (de Jong et al., 2014). Controllers should therefore use RH in two ways: as an input to the thermal load and as an indicator of litter wetness.

2.3 Gases and particulate matter.

Council Directive 2007/43/EC sets limits of 20 ppm NH_3 and 3,000 ppm CO_2, measured at the height of the chickens' heads, for holdings stocked at more than 33 kg/m^2. In modern broilers exposed from hatch to 4 weeks of age, final body weight fell by 6% at 50 ppm and by 9% at 75 ppm NH_3, and mortality was higher at 75 ppm (Miles et al., 2004). Exposure to CO_2 at 3,000–9,000 ppm during days 1–14 increased cumulative mortality up to day 42, although final body weight was unaffected (Olanrewaju et al., 2008). Studies on how ammonia causes harm, at 15–35 ppm, used birds aged 21 days or older (Zhou et al., 2020; Han et al., 2021). These studies are useful, but they cannot set limits for the brooding period. Ammonia production depends on litter moisture, pH, temperature and ventilation (Kristensen & Wathes, 2000; Naseem & King, 2018), so ammonia concentration acts as a downstream indicator of moisture conditions in the house. PM

concentrations in poultry houses have been reported at 10–100 times outdoor levels, and PM can carry ammonia and microorganisms into the birds' airways (Wang et al., 2023). The Directive sets no limit for PM.

2.4 Spatial uniformity.

Conditions at chick level vary across the pen. A computational fluid dynamics (CFD) study of a heated house on day 7 found thermoneutral conditions over most of the floor, but also areas that were warmer or cooler than the thermoneutral zone (Ferraz et al., 2022). A CFD study of a ventilated house identified hot zones in summer and stagnant pockets of hot, humid air in winter (Küçüktopcu et al., 2022). In a stacked-cage house, uneven lateral (side-to-side) temperature distribution was the main cause of poor temperature uniformity (Deng et al., 2024). Management guidelines likewise recommend placing thermometers at chick level throughout the house (Aviagen, 2025.). A single sensor therefore cannot represent conditions across the whole house.

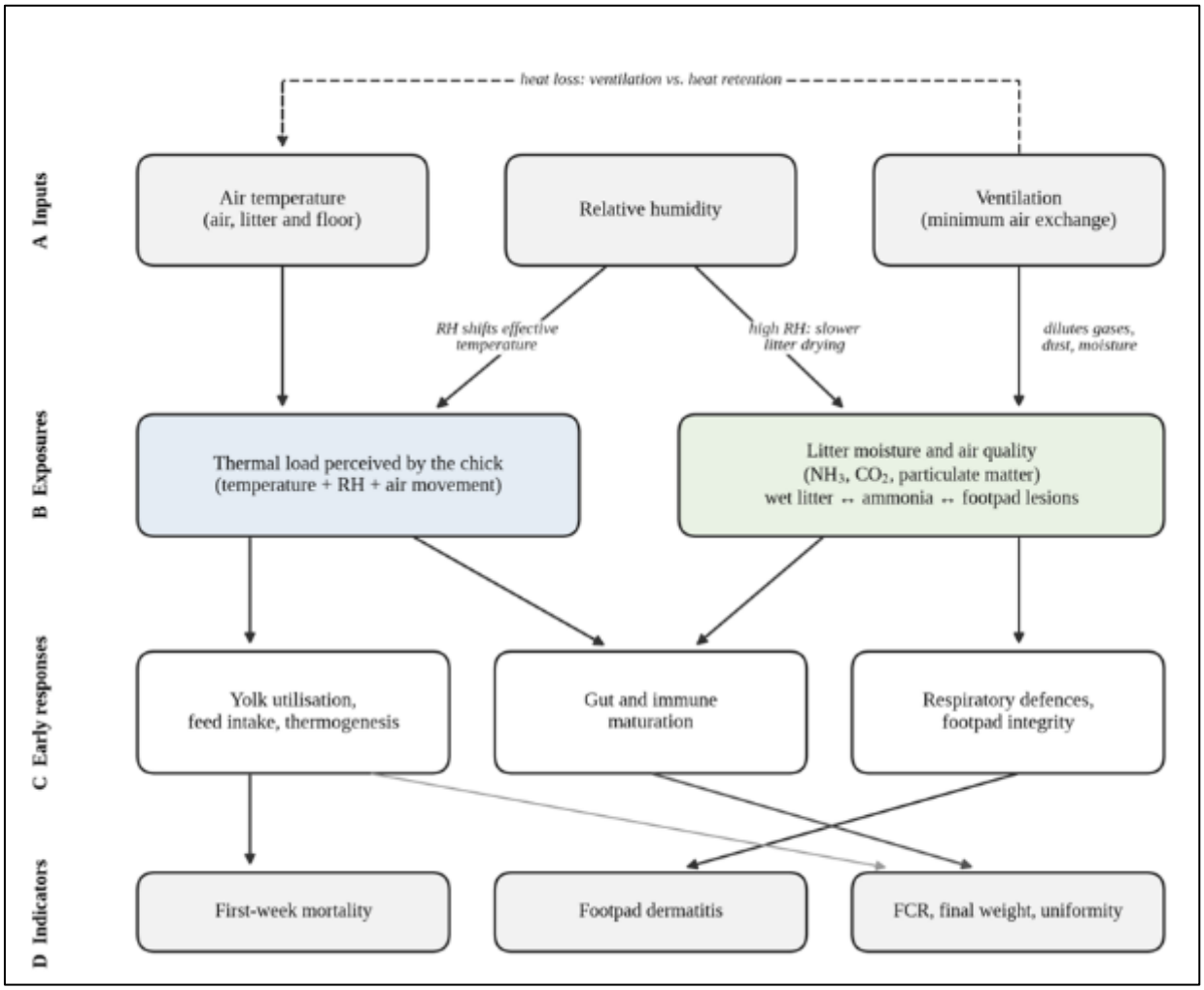

Figure 1: Causal map linking controllable inputs (A) to chick-level exposures (B), early physiological responses (C), and welfare and production indicators (D). The dashed line indicates the trade-off between ventilation and heat retention. Some links, such as thermal deficit delaying gut maturation, are hypotheses (Section 2).

Table 1: Biological evidence translated into engineering specifications for the brooding microclimate.

Variable	Evidence (source)	Implication for design
Air temperature	Starting at 29.4 °C and stepping down to 26.7 and 23.9 °C did not impair 6-week performance; a colder regimen increased ascites and mortality (Deaton et al., 1996). Exposure to 18 °C for 8 h/day in week 1 reduced yolk-sac absorption and worsened later feed conversion (Moreira et al., 2024)	Control at chick level; log cumulative exposure (for example, degree-hours below set point) as well as the mean; limit the duration of cold excursions
Relative humidity	Effect on heat exchange depends on age and temperature (Lin et al., 2005a, 2005b); guidance of 60–70% in the first three days (Aviagen, 2025); 48-h average ≤70% when outdoor temperature is <10 °C on higher-density holdings (Directive 2007/43/EC)	Measure RH at chick level; estimate effective temperature; also treat RH as a proxy for litter wetness
Litter moisture	Wet vs. dry litter: FPD from day 14 vs. day 28 (Taira et al., 2014); wetting from day 6 increased FPD and reduced performance (de Jong et al., 2014)	Estimate litter moisture from mass balances, drinker flow and RH; no robust continuous sensor is available
Ammonia	≤20 ppm at head level on higher-density holdings (Directive 2007/43/EC); final weight −6% at 50 ppm and −9% at 75 ppm, mortality higher at 75 ppm, exposure 0–4 weeks (Miles et al., 2004)	Sensor range of at least 0–75 ppm with low-ppm resolution; compensate for RH and temperature; note that ammonia generation depends on litter state
Carbon dioxide	≤3,000 ppm at head level on higher-density holdings (Directive 2007/43/EC); cumulative mortality higher at 3,000–9,000 ppm on days 1–14 (Olanrewaju et al., 2008)	NDIR sensing with a range of at least 9,000 ppm; useful as a check on ventilation consistency
Particulate matter	Concentrations of 10–100 times outdoor levels reported; PM carries ammonia and microorganisms (Wang et al., 2023); no limit set in Directive 2007/43/EC	Optical sensing with humidity correction; treat as an indicator until limits are established
Spatial uniformity	Zones outside the thermoneutral range on day 7 in a heated house (Ferraz et al., 2022); hot and stagnant zones (Küçüktopcu et al., 2022); lateral temperature distribution dominates non-uniformity in a stacked-cage house (Deng et al., 2024)	Multi-point, chick-level sensing; CFD or pilot mapping to select locations

FPD, footpad dermatitis; NDIR, non-dispersive infrared. Thresholds depend on age, exposure duration and endpoint and should be treated as tunable constraints.

3 HEAT, MOISTURE AND GAS BALANCES OF THE BROODING HOUSE

3.1 Governing balances

Ventilation and heating systems in livestock buildings are conventionally designed and operated using steady-state heat and moisture balances. Gates et al. (1996) applied this approach to modern broilers. From bird weight and number, house R-value, and indoor and outdoor temperature and RH, they calculated the ventilation needed for temperature and moisture control, the minimum ventilation rate and the supplemental heat required. Following the same approach, let q_v ($m^3\ s^{-1}$) be the ventilation flow, ρ the air density, c_p the specific heat of air, UA the overall envelope conductance ($W\ K^{-1}$), T_i and T_o the indoor and outdoor temperatures, and w_i and w_o the indoor and outdoor humidity ratios. The sensible heat balance is then

$$\Phi_{sb} + \Phi_h = (\rho\, c_p\, q_v + UA)(T_i - T_o) \quad (1)$$

where Φ_{sb} is the sensible heat from the birds (and lighting) and Φ_h is the supplemental heat input. The moisture balance gives the ventilation rate required to remove a moisture release g_w ($kg\ s^{-1}$):

$$q_w = \frac{g_w}{\rho\,(w_i - w_o)} \quad (2)$$

and the gas balance gives the ventilation rate required to maintain a gas at concentration $C_{i,k}$ given a generation rate G_k and outdoor concentration $C_{o,k}$, for k = CO_2, NH_3 (or PM):

$$q_k = \frac{G_k}{C_{i,k} - C_{o,k}} \quad (3)$$

The humidity ratio is obtained from the RH φ, the saturation vapour pressure $p_{sat}(T)$ and total pressure p:

$$w = 0.622 \frac{p_v}{p - p_v}, \quad p_v = \varphi\, p_{sat}(T) \quad (4)$$

These balances depend on input values that are uncertain and have changed over time. The heat and moisture production of broilers depends on body mass, age, activity, lighting and housing, and published design values disagree. In house-level measurements on deep litter, total heat production matched common calculation rules, but sensible heat production was about 17% lower than expected (Pedersen & Thomsen, 2000). In 20 commercial flocks of modern birds, specific total heat production at 0.4 kg body mass was up to 31% higher than earlier published values, while moisture production was lower, probably because nipple drinkers were used (Xin et al., 2001). Values for individual birds should be kept distinct from values for the whole house (Pedersen & Thomsen, 2000), and design values should come from recent data for the genotype, drinker type and litter system actually in use.

3.2 When ventilation can and cannot remove moisture

Equation 2 shows that the moisture-removal capacity of ventilation air is proportional to ($w_i - w_o$). Heating outdoor air to the indoor temperature does not change its humidity ratio. The sign and size of this difference therefore depend only on the moisture content of the outdoor air and on the indoor target. Table 2 and Figure 2 show the results for a range of outdoor conditions. The indoor set points are taken from the regimen of Deaton et al. (1996): 29.4 °C in week 1 and 23.9 °C in week 3. The target indoor RH is 65%, which lies within the recommended range of 60–70% (Aviagen, 2025).

Two consequences follow. First, as the outdoor humidity ratio approaches the indoor value, the ventilation rate needed to remove a given moisture load rises without limit. Once the outdoor value exceeds the indoor value, ventilation adds moisture to the house instead of removing it. For the week-1 set point, outdoor air at 27 °C and 80% RH has a humidity ratio 1.2 g kg^{-1} above the target, so no ventilation rate can bring the house down to 65% RH. At the week-3 set point, this limit is reached at even lower outdoor temperatures, because a cooler house holds less water vapour at 65% RH. Second, conventional minimum-ventilation logic was developed for cold, dry conditions, which are the easy case. In warm, humid weather, moisture must be controlled in other ways: by raising the indoor set point within the permitted range, by limiting moisture sources at the drinkers and in the litter, or by dehumidification. Each option carries energy and welfare costs. These conclusions assume steady, well-mixed air at sea-level pressure and ignore moisture stored in the litter. They therefore set a limit, not a prediction for any particular house.

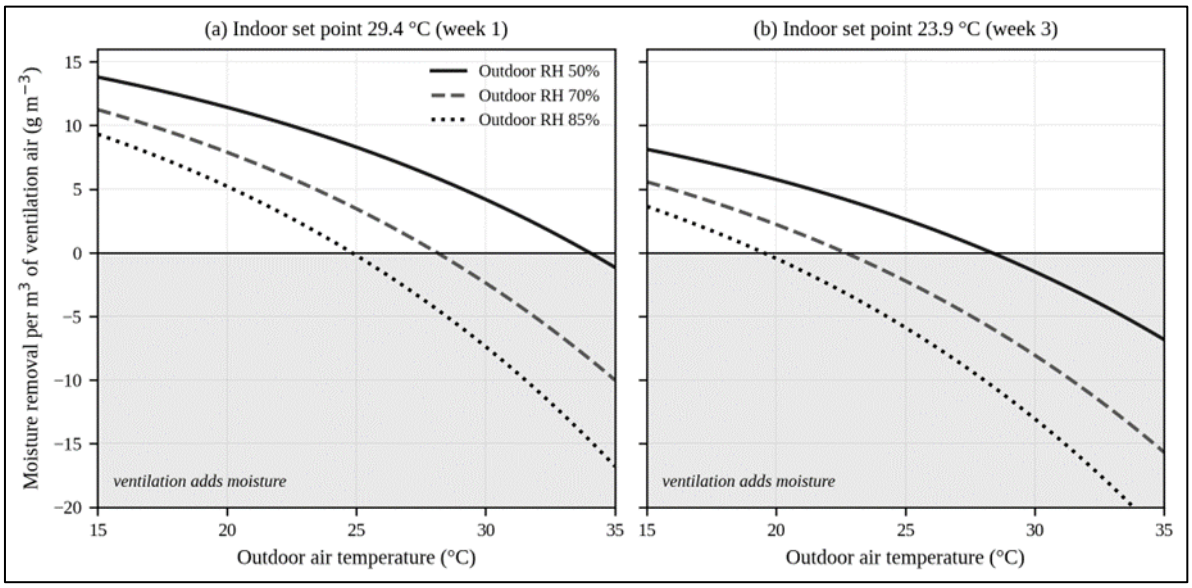

Figure 2: Moisture-removal capacity of ventilation air as a function of outdoor temperature for outdoor RH of 50%, 70% and 85% and a target indoor RH of 65%, at indoor set points of (a) 29.4 °C and (b) 23.9 °C. In the shaded region, ventilation adds moisture to the house (Equations 2 and 4).

Table 2: Moisture-removal capacity of ventilation air for a target indoor RH of 65% (psychrometric calculation at 101.325 kPa).

Indoor set point (°C)	Outdoor (°C / RH)	w_i (g kg^{-1})	w_o (g kg^{-1})	$w_i - w_o$ (g kg^{-1})	Moisture removed (g m^{-3} air)	Air per 1 g h^{-1} moisture (m^3 h^{-1})
29.4	20 / 50%	16.77	7.25	9.53	11.43	0.09
29.4	25 / 70%	16.77	13.89	2.88	3.46	0.29
29.4	27 / 80%	16.77	17.98	−1.21	−1.45	none (adds moisture)
29.4	30 / 85%	16.77	22.92	−6.15	−7.38	none (adds moisture)
23.9	20 / 50%	12.04	7.25	4.79	5.75	0.17
23.9	25 / 70%	12.04	13.89	−1.85	−2.22	none (adds moisture)
23.9	27 / 80%	12.04	17.98	−5.94	−7.13	none (adds moisture)
23.9	30 / 85%	12.04	22.92	−10.88	−13.06	none (adds moisture)

Humidity ratios were calculated from Equation 4 using the Magnus formula for saturation vapour pressure; air density was taken as 1.2 kg m^{-3}. Indoor set points are the week-1 and week-3 values of the regimen of Deaton et al. (1996); the 65% target RH lies within the recommended range of 60–70%. The final column gives the airflow required per gram per hour of moisture released into the air (Equation 2). Calculations assume quasi-steady, well-mixed air and neglect moisture storage in the litter.

3.3 Gas dilution, minimum ventilation and heating demand

The minimum ventilation rate is determined by the most demanding of the moisture and gas requirements:

$$q_{v,min} = max(q_w, q_{CO2}, q_{NH3}) \quad (5)$$

and the heating demand is the heat required to warm this airflow and offset envelope losses, minus the sensible heat produced by the birds:

$$\Phi_h = max\{0, (\rho\, c_p\, q_v + UA)(T_i - T_o) - \Phi_{sb}\} \quad (6)$$

Two features make this a coupled problem rather than a set of separate ones. First, the ammonia generation rate G_{NH3} is not constant; it rises with litter moisture, pH and temperature (Kristensen & Wathes, 2000; Naseem & King, 2018). Wet litter therefore increases the ventilation needed to control ammonia, yet in humid weather ventilation cannot dry the litter (Section 3.2). This creates a plausible positive feedback loop. We infer it from the balance equations and the cited ammonia literature; to our knowledge, it has not been demonstrated in a controlled brooding experiment. Second, because Φ_h grows with q_v, every extra unit of ventilation for air quality costs heating energy in cool weather, while in hot weather it is limited by the available cooling capacity.

The air-exchange time constant of the house,

$$\tau = \frac{V_h}{q_v} \quad (7)$$

where V_h is the house air volume, governs the dynamics of the humidity and gas states, whereas the thermal response of the litter, floor and structure is slower. Sensor sampling intervals and controller sample times should be short relative to τ at the lowest ventilation rate in use, and state estimators should account for these different time scales.

4 SENSING AND MEASUREMENT

4.1 Spatial sampling

Measurements need to be taken at chick level and at multiple points (Section 2). CFD has been used to map temperature and airflow in broiler houses, with the models checked against field measurements. Ferraz et al. (2022) validated a model of a heated house with measurements at 16 points on day 7, and Küçüktopcu et al. (2022) validated a model of a ventilated house with measurements of temperature, RH and air speed. Such models can help select representative sensor locations and test whether a smaller sensor network can still estimate conditions in the house. Pilot mapping with temporary data loggers can then confirm the choice. How many sensors are needed for control, as opposed to research, and where they should be placed, has not yet been established for brooding houses.

4.2 Sensor technologies and their limitations

Table 3 summarises sensing principles and their reported limitations. Ammonia is the hardest variable to measure. In poultry-house evaluations, Wheeler et al. (2000) found an electrochemical unit suitable for research or demonstration at reasonable cost, whereas hand-held pull tubes and passive dosimeters gave questionable accuracy in dirty, low-ammonia environments. Semiconductor and electrochemical sensors have been reported to suffer from short service life, severe baseline drift and slow response in poultry housing. By comparison, a portable tunable diode laser absorption spectroscopy (TDLAS) sensor responded in under 15 s with an accuracy of 0.2 ppm over 0–6 ppm in a house holding 36 roosters (Wang et al., 2022). At the other end of the cost range, a low-cost IoT unit for small poultry farms achieved correlations above 0.96 with certified reference devices for temperature, humidity, ammonia and methane, at about 12% of the reference cost (Elwakeel, 2025). These results do not contradict each other. A high correlation over a short test does not prove the long-term stability, selectivity and resistance to cross-sensitivity that control requires, and the TDLAS result covers only concentrations below the regulatory limit. For particulate matter, a field evaluation of an IoT system with low-cost $PM_{2.5}$ sensors in a dairy barn found it less reliable than the reference device, with performance that varied with temperature and humidity. The authors therefore proposed a parameter-based adjustment (D'Urso et al., 2025). We found no similar evaluation in brooding houses.

Table 3: Sensing technologies for the brooding microclimate and their reported or expected limitations in poultry housing.

Variable	Typical principles	Reported or expected limitations	Evidence
Temperature	Digital silicon, thermistor, RTD	Placement and radiant effects; air and floor temperatures differ; multi-point, chick-level coverage needed	Aviagen (2025); Ferraz et al. (2022)
Relative humidity	Capacitive polymer	Condensation, dust and chemical contamination can degrade accuracy (general sensor behaviour; see manufacturers' data sheets); RH is also needed to compensate gas and PM sensors	General; D'Urso et al. (2025)
Ammonia	Electrochemical, metal-oxide semiconductor, TDLAS	Short life, baseline drift, delayed response and cross-interference reported for semiconductor and electrochemical types; hand-held tubes of questionable accuracy at low concentrations in dirty houses; TDLAS accurate and fast but tested only at 0–6 ppm	Wheeler et al. (2000); Wang et al. (2022); Elwakeel (2025)
Carbon dioxide	NDIR	Generally selective; response time and temperature or pressure dependence should be checked (general sensor behaviour)	General; CO_2 is among the variables measured by Lashari et al. (2023)
Particulate matter	Optical scattering (low cost)	Lower reliability than the reference device in a livestock barn; performance dependent on temperature and humidity; adjustment proposed; no brooding-house evaluation found	D'Urso et al. (2025)

NDIR, non-dispersive infrared; RTD, resistance temperature detector; TDLAS, tunable diode laser absorption spectroscopy. “General” denotes widely documented sensor behaviour not tied to a single cited study.

4.3 Calibration, drift and data quality

Reliable control depends on reliable measurements, and the harsh conditions in poultry houses (dust, ammonia, humidity and wash-down) make sensor degradation likely. The following is our own design guidance, drawn from the literature rather than from any single study. A robust sensing layer should combine: redundant sensors with voting or disagreement alarms for safety-critical variables; correction for cross-sensitivity to temperature and RH, using equations fitted against a reference under representative conditions; scheduled zero and span checks with traceable calibration gas for ammonia and CO_2; plausibility checks based on the balance equations (for example, CO_2 should change in step with ventilation); and health indicators for each sensor that pass measurement uncertainty on to the controller. If a gas or humidity sensor is flagged as faulty, the controller should fail gracefully by switching to conservative ventilation.

4.4 Effective-temperature indices

Because RH, air speed and temperature together determine the heat load on the birds, composite indices are attractive for control. Zheng et al. (2025) used an apparent temperature (AT) index, which combines temperature, humidity and wind speed, as the target of multi-step forecasting models for broiler houses. However, as Section 2 showed, the direction and size of the humidity effect depend on age and temperature (Lin et al., 2005a, 2005b). A fixed-form index may therefore be accurate under some conditions but misleading under others. Indices used for control should be validated against the birds' physiological or behavioural responses across ages, not only against other environmental variables.

5 EMBEDDED, COMMUNICATION AND POWER CONSIDERATIONS

Platforms. Most reported monitoring systems for poultry houses use low-cost microcontrollers or single-board computers with digital sensors. Examples include IoT nodes that record temperature, RH, oxygen, CO_2, carbon monoxide and ammonia in a poultry farmhouse (Lashari et al., 2023); a GSM-based automatic monitoring and control unit (Elwakeel, 2025); and a LoRa system for a 25 × 100 m closed house (Tooprakai et al., 2022). In the LoRa system, sensor data are sent to a gateway and database and shown on a web dashboard, and fans and pumps are controlled from mobile applications. These systems show that the approach is feasible, but the studies reviewed here do not report long-term reliability, calibration maintenance or failure rates.

Communications. Low-power wide-area networks are well suited to sensor telemetry in large houses. A LoRa ad hoc network for livestock houses, using a rate-adaptive algorithm, achieved packet loss below 1% at distances of up to 604 m (Fu et al., 2022). Metal roofs, dense stocking and multiple houses all affect radio link budgets, so link margins should be measured on site. We recommend using wireless links for telemetry and supervisory commands, but keeping safety-critical actuation on deterministic wired buses (for example, RS-485) with local fail-safe behaviour. A loss of connectivity then cannot leave fans or vents in a harmful state.

Edge versus cloud. The control loop must run locally; cloud services can handle logging, analytics, alarms and remote configuration. Newer models for forecasting broiler-house temperature use hybrid deep-learning architectures. They have been evaluated at 5-, 15- and 30-min horizons against long short-term memory (LSTM), gated recurrent unit (GRU), Autoformer and Informer baselines (Zheng et al., 2025). Two engineering questions remain open: whether such models can run on microcontroller-class hardware within the time limits of a control loop, and whether their accuracy carries over to other houses and seasons.

Power and environment. Ammonia, dust and condensation damage electronics and connectors. Enclosures therefore need suitable ingress protection and protective coatings, and sensor temperature compensation and self-heating must be taken into account. Because the reliability of mains power varies by region, brooding control hardware should have a defined response to power loss. This includes a safe actuator state, battery or solar backup for sensing and communications, and non-volatile storage of the system state so that the controller can restart without sudden changes. These recommendations reflect general engineering practice rather than findings from the cited studies.

6 CONTROL APPROACHES AND A REFERENCE ARCHITECTURE

6.1 Reported control approaches

Table 4 summarises the control and decision-support approaches reported for broiler houses. Most of the evidence comes from simulations or single-site pilots. Detsch et al. (2018) developed a self-correcting, real-time model based on partial differential equations, with parameters updated from sensor data. In simulations and pilot-farm experiments, it achieved a mean bias of 0.6 °C relative to the ideal temperature, compared with 3.3 °C for the existing automatic ventilation system. Baier and Meier (2020) simulated model predictive control (MPC) for a Swiss broiler house using a validated dynamic model. They found that most of the energy savings came from letting indoor humidity drift from its usual set point to take advantage of outdoor conditions, and that lighting control and animal activity reduced these savings. This finding matters for welfare. The most energy-efficient humidity may conflict with litter and ammonia limits (Sections 2 and 3), so humidity bounds must be treated as constraints based on biological evidence, not as free variables. CFD-based design studies have also evaluated ventilation and cooling options. In one study, an evaporative cooling pad lowered air temperature by about 3 °C when the mean house temperature exceeded 25 °C, and circulation fans cleared pockets of hot, humid air from stagnant zones (Küçüktopcu et al., 2022).

6.2 Proposed reference architecture

Figure 3 shows a layered architecture that follows from the preceding sections. The perception layer takes measurements at chick level and at multiple points. The edge layer checks and corrects the signals, estimates the state

of the house (effective temperature, humidity ratio and gas mass balance, including slowly changing litter conditions) and runs the controller on local hardware. A separate safety layer, independent of the main controller, enforces hard limits and fail-safe behaviour and can override controller commands. Communication links carry telemetry and supervisory commands to a gateway and a cloud service. The cloud service stores records, raises alarms, distributes configuration and software updates, and holds the welfare and production data needed to evaluate and retune the system.

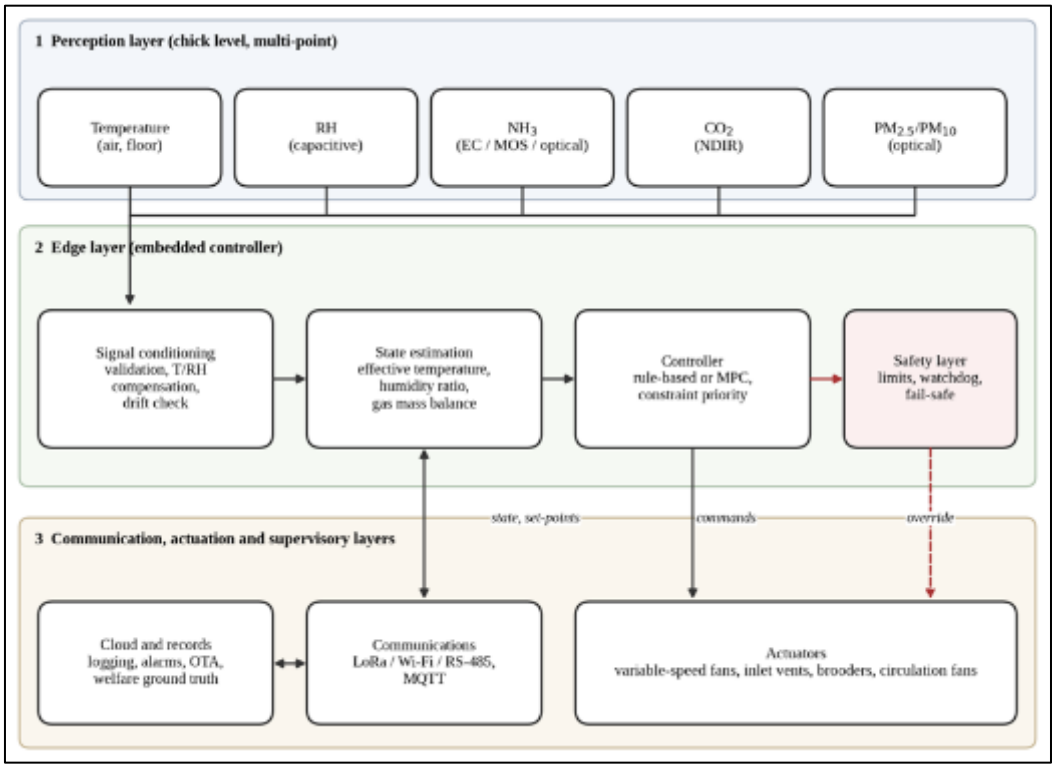

Figure 3: Proposed layered reference architecture. The safety layer is independent of the main controller and can override actuator commands. EC, electrochemical; MOS, metal-oxide semiconductor; NDIR, non-dispersive infrared; MPC, model predictive control; OTA, over-the-air.

Table 4: Control and decision-support approaches reported for broiler houses and the level of supporting evidence.

Approach	Reported result	Evidence level and limitation	Source
Self-correcting PDE-based real-time controller (fan switching)	Mean bias 0.6 °C relative to ideal temperature vs. 3.3 °C for the existing automatic ventilation system	Simulations and pilot-farm experiments; temperature only; tropical/subtropical setting	Detsch et al. (2018)
Model predictive control for humidity and energy	Energy savings achieved mainly by allowing indoor humidity to deviate from the usual set point; lighting control and animal activity reduced savings	Simulation only (validated dynamic model); welfare consequences of humidity deviation need assessment	Baier & Meier (2020)
Hybrid deep-learning forecasting of apparent temperature (SE-TCN–Transformer with Kalman filtering)	Multi-step forecasts at 5, 15 and 30 min compared with LSTM, GRU, Autoformer and Informer baselines	Trained on one commercial house; offline evaluation; embedded deployment not reported in the abstract reviewed	Zheng et al. (2025)
CFD-guided design of ventilation and cooling	Evaporative pad lowered air temperature by about 3 °C when mean house temperature exceeded	Model validated against field measurements in one house; evaluation of design options	Küçüktopcu et al. (2022)

	25 °C; circulation fans eliminated hot, humid stagnant zones		
CFD analysis of a brooding heating system	Thermoneutral conditions over most of the house on day 7; some areas above and below the zone	Steady-state model; data from a single time of day	Ferraz et al. (2022)

PDE, partial differential equation; CFD, computational fluid dynamics.

6.3 Constrained control formulation

Let u_k = (fan speed, vent opening, heater output) denote the control input at sample k, and let the plant model be the discretised balances of Section 3, extended with a slow litter-moisture state. A multi-objective formulation that treats biologically derived limits as constraints and energy as the primary objective is

$$min \ \sum_{k=0}^{N-1} c_e(P_{f,k} + P_{h,k})\Delta t + \lambda_T(T_{eff,k} - T_k^*)^2 + \lambda_w \, max(0, \varphi_k - \varphi_{max})^2 \qquad (8)$$

subject to the dynamics of Equations 1–4; the gas limits $C_{CO2} \leq 3{,}000$ ppm and $C_{NH3} \leq C_{NH3,max}$ (set from the regulatory limit and the evidence in Section 2); actuator magnitude and rate limits; and, optionally, a cap on cumulative cold exposure, $\Sigma \max(0, T_{min}(age) - T_{eff})\Delta t$, over a defined window. Here, P_f and P_h are the fan and heater power, c_e is the energy price, T^* is the age-dependent set point, φ_{max} is the upper RH bound, and λ_T, λ_w are weighting factors. When not all constraints can be met at once, which Section 3.2 shows can happen in warm, humid weather, a priority order decides which to relax. Safety limits (gas concentration and heat stress) come first, followed by thermal comfort, then RH and litter condition, and finally energy. Recording which constraint was relaxed, and for how long, shows directly how often physical limits prevent the target microclimate from being reached. With variable-speed fan drives, the fan term in Equation 8 is strongly nonlinear in airflow, because fan power rises roughly with the cube of fan speed. It is therefore usually more efficient to run several fans at moderate speed than a few fans at high speed, provided inlet and air-distribution constraints allow it. This is a general fan-law argument and should be checked for each installation.

Rule-based supervisory logic is a sensible first implementation. The same constraint hierarchy can be coded as a prioritised set of rules with hysteresis, and MPC can be reserved for houses where model quality and computing resources justify it. Whatever controller is used, three safeguards are needed: hard limits enforced independently of the optimiser; limits on how quickly ventilation can change, to avoid chilling the chicks or creating draughts; and logging of sensor health, constraint status and actuator state for later analysis.

7 VALIDATION FRAMEWORK AND MINIMUM REPORTING SET

Table 5: Proposed minimum reporting set for validation of brooding-microclimate sensing and control systems.

Level	Metrics to report	Notes
Sensor	Bias and RMSE against reference; precision; response time (t90); drift over at least several weeks; cross-sensitivity to temperature and RH; calibration procedure and interval	Test under representative dust, humidity and ammonia conditions; report mounting height and enclosure
Spatial	Number and positions of sensors; between-location variability; representativeness of a reduced network	Justify using CFD or pilot mapping
Network	Packet delivery ratio, latency, availability, energy per message, link margin in situ	Report house construction and gateway placement
Control	Set-point tracking error; time outside bands by variable; constraint relaxations by type and duration; energy per bird; actuator cycling	Report the constraint hierarchy and any manual overrides
Reliability	Uptime, sensor health flags, failures, behaviour on power or communication loss	Report maintenance interventions
Bird outcomes	First-week mortality, litter moisture, FPD score, body weight, feed conversion ratio; flock and breeder details	Collect with protocols that allow comparison with the engineering variables; replicate over flocks and seasons

RMSE, root-mean-square error; t90, time to reach 90% of a step change; FPD, footpad dermatitis.

Most studies of low-cost monitoring systems report only agreement with a reference instrument (Section 4.2). Most control studies rely on simulations or single-site pilots (Section 6.1). Few link engineering results to bird outcomes, which is the concern raised by Rowe et al. (2019). A convincing validation should therefore cover four levels. At the sensor level, bias, precision, response time, drift and cross-sensitivity to temperature and RH should be measured against a reference under representative conditions, and measured again after several weeks of use. At the network level, packet delivery, latency, availability and energy use should be reported. At the control level, the key metrics are set-point tracking, time outside target ranges, constraint violations by type, energy use per bird and actuator wear. At the bird level, first-week mortality, litter moisture, FPD scores, growth and feed conversion should be recorded using protocols that allow comparison with the engineering data. Where possible, studies should compare paired houses or rooms with and without the intervention, repeated over several flocks and seasons. Table 5 lists a minimum reporting set.

8 RESEARCH GAPS AND ROADMAP

Validated chick-level thermal indices. Composite indices already exist (Zheng et al., 2025), but experiments show that the effect of humidity depends on age and temperature (Lin et al., 2005a, 2005b). Indices used for control must be validated against physiological and behavioural responses at different ages.

Drift-aware low-cost gas and PM sensing. Most evidence on low-cost sensors in poultry and livestock housing comes from short-term comparisons with reference instruments (Elwakeel, 2025; D'Urso et al., 2025). Long-term stability, selectivity and field calibration methods for ammonia sensors in dusty, humid brooding houses have yet to be demonstrated.

Litter-moisture estimation. Litter moisture links humidity to FPD and ammonia (Taira et al., 2014; de Jong et al., 2014), yet it is rarely measured continuously. Estimating litter moisture from the moisture balance, drinker flow and RH, and checking these estimates against litter samples, would close the loop on a key welfare pathway.

Coupled control under psychrometric limits. Section 3.2 shows that ventilation alone cannot always control humidity in warm, humid weather. Controllers and design guidance for these conditions, including energy-efficient dehumidification and strategies for open-sided houses, need to be developed and tested. None of the studies reviewed here specifically addressed humidity control in warm, humid, open-sided houses.

Sensor-to-outcome studies. Studies that link detailed, spatially resolved microclimate data and controller performance to first-week mortality, litter condition, FPD and growth performance would show which sensing and control improvements actually benefit the chicks.

Edge intelligence and reliability. The studies reviewed do not report whether predictive models can run on low-power hardware, or how reliable systems remain over time when exposed to ammonia, dust and unstable power supplies. Open datasets and common reporting standards (Table 5) would make it possible to compare systems.

9 CONCLUSIONS

The brooding microclimate is a coupled system in which ventilation is the shared actuator. Biological evidence can be translated into time-resolved, chick-level specifications for temperature, humidity, ammonia, CO_2 and dust. A first-principles analysis shows that outdoor humidity, and not only outdoor temperature, limits what ventilation can achieve. In warm, humid weather, ventilation cannot dry the house, so the constraint hierarchy must decide which objectives to give up. Sensing is the weakest link for ammonia and particulate matter, where low-cost sensors still need validation against reference instruments and long-term drift data. Published control studies are promising, but most are simulations or single-site pilots, and few link engineering metrics to chick outcomes.

We propose a layered architecture with an independent safety layer; a constrained control formulation with biologically based limits and a clear priority order; and a minimum reporting set covering the sensor, network, control and bird levels. These proposals are conceptual and need to be tested in paired-house trials. For engineers working on IoT and embedded systems, the main opportunities lie in robust, drift-aware sensing at multiple points; reliable low-power networking; fail-safe edge control; and, above all, studies that link engineering performance to bird welfare and production.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Funding Source

This research was funded by the Tertiary Education Trust Fund (TETFund) Institutional-Based Research (IBR) Grant 2025/2026 (Grant No. TETF/DR&D/CE/UNI/AKURE/IBR/2026) awarded through the Centre for Research and Development, Federal University of Technology, Akure.

REFERENCES

[1] Agbolade, O. A., Udekwe, C., & Daniels, P. (2026). An IoT Architecture for Automated Microclimate Control in Smallholder Poultry Brooder Cages. *International Journal of Progressive Sciences and Technologies, 59(1), 552-564. DOI: http://dx.doi.org/10.52155/ijpsat.v59.1.8627*

[2] Astill, J., Dara, R. A., Fraser, E. D. G., Roberts, B., & Sharif, S. (2020). Smart poultry management: Smart sensors, big data, and the internet of things. *Computers and Electronics in Agriculture*, *170*, 105291. https://doi.org/10.1016/j.compag.2020.105291

[3] Aviagen. (2025). *Ross broiler management handbook*. Aviagen Group.

[4] Baier, N. U., & Meier, T. (2020). Using model predictive control to modulate the humidity in a broiler house and effect on energy consumption. *Athens Journal of Technology and Engineering*, *7*(3), 157–183. https://doi.org/10.30958/ajte.7-3-1

[5] Berckmans, D. (2014). Precision livestock farming technologies for welfare management in intensive livestock systems. *Revue Scientifique et Technique (International Office of Epizootics)*, *33*(1), 189–196.

[6] Council Directive 2007/43/EC of 28 June 2007 laying down minimum rules for the protection of chickens kept for meat production. (2007). *Official Journal of the European Union*, *L 182*, 19–28.

[7] de Jong, I. C., Gunnink, H., & van Harn, J. (2014). Wet litter not only induces footpad dermatitis but also reduces overall welfare, technical performance, and carcass yield in broiler chickens. *Journal of Applied Poultry Research*, *23*(1), 51–58.

[8] Deaton, J. W., Branton, S. L., Simmons, J. D., & Lott, B. D. (1996). The effect of brooding temperature on broiler performance. *Poultry Science*, *75*(10), 1217–1220.

[9] Deng, S., Li, Z., Wei, Y., Wang, Y., Li, B., & Zheng, W. (2024). Assessing temperature distribution inside commercial stacked cage broiler houses in winter. *Animals*, *14*(18), 2638. https://doi.org/10.3390/ani14182638

[10] Detsch, D. T., Conti, D., Diniz-Ehrhardt, M. A., & Martínez, J. M. (2018). On the controlling of temperature: A proposal for a real-time controller in broiler houses. *Scientia Agricola*, *75*(6), 445–451. https://doi.org/10.1590/1678-992x-2016-0456

[11] D'Urso, P. R., Finocchiaro, A., Cinardi, G., & Arcidiacono, C. (2025). In-field performance evaluation of an IoT monitoring system for fine particulate matter in livestock buildings. *Sensors*, *25*(16), 4987. https://doi.org/10.3390/s25164987

[12] Elwakeel, A. E. (2025). A smart automatic control and monitoring system for environmental control in poultry houses integrated with earlier warning system. *Scientific Reports*, *15*, 31630. https://doi.org/10.1038/s41598-025-17074-2

[13] Ferraz, P. F. P., de Andrade, E. T., Vilas Boas, R. B., Rezende, R. P., Yanagi Junior, T., & Barbari, M. (2022). Three-dimensional simulation of the temperature distribution in a commercial broiler house. *Animals*, *12*(10), 1278. https://doi.org/10.3390/ani12101278

[14] Fu, X., Shen, W., Yin, Y., Zhang, Y., Yan, S., Kou, S., et al. (2022). Remote monitoring system for livestock environmental information based on LoRa wireless ad hoc network technology. *International Journal of Agricultural and Biological Engineering*, *15*(4), 79–89. https://doi.org/10.25165/j.ijabe.20221504.6708

[15] Gates, R. S., Overhults, D. G., & Zhang, S. H. (1996). Minimum ventilation for modern broiler facilities. *Transactions of the ASAE*, *39*(3), 1135–1144.

[16] Han, H., Zhou, Y., Liu, Q., Wang, G., Feng, J., & Zhang, M. (2021). Effects of ammonia on gut microbiota and growth performance of broiler chickens. *Animals*, *11*(6), 1716. https://doi.org/10.3390/ani11061716

[17] Kristensen, H. H., & Wathes, C. M. (2000). Ammonia and poultry welfare: A review. *World's Poultry Science Journal*, *56*(3), 235–245.

[18] Küçüktopcu, E., Cemek, B., Simsek, H., & Ni, J.-Q. (2022). Computational fluid dynamics modeling of a broiler house microclimate in summer and winter. *Animals*, *12*(7), 867. https://doi.org/10.3390/ani12070867

[19] Lashari, M. H., Karim, S., Alhussein, M., Hoshu, A. A., Aurangzeb, K., & Anwar, M. S. (2023). Internet of Things-based sustainable environment management for large indoor facilities. *PeerJ Computer Science*, *9*, e1623. https://doi.org/10.7717/peerj-cs.1623

[20] Lin, H., Zhang, H. F., Jiao, H. C., Zhao, T., Sui, S. J., Gu, X. H., Zhang, Z. Y., Buyse, J., & Decuypere, E. (2005a). Thermoregulation responses of broiler chickens to humidity at different ambient temperatures. I. One week of age. *Poultry Science*, *84*(8), 1166–1172. https://doi.org/10.1093/ps/84.8.1166

[21] Lin, H., Zhang, H. F., Du, R., Gu, X. H., Zhang, Z. Y., Buyse, J., & Decuypere, E. (2005b). Thermoregulation responses of broiler chickens to humidity at different ambient temperatures. II. Four weeks of age. *Poultry Science*, *84*(8), 1173–1178. https://doi.org/10.1093/ps/84.8.1173

[22] Miles, D. M., Branton, S. L., & Lott, B. D. (2004). Atmospheric ammonia is detrimental to the performance of modern commercial broilers. *Poultry Science*, *83*(10), 1650–1654. https://doi.org/10.1093/ps/83.10.1650

[23] Moreira, L. M., Sousa, L. S., Guamán, C. A. G., Vieira, M. C., Santini, M. B., Cardoso, A. R., Leme, F. O. P., Lara, L. J. C., & Araújo, I. C. S. (2024). Effects of cold stress on physiologic metabolism in the initial phase and performance of broiler rearing. *Journal of Thermal Biology*, *119*, 103773.

[24] Naseem, S., & King, A. J. (2018). Ammonia production in poultry houses can affect health of humans, birds, and the environment—Techniques for its reduction during poultry production. *Environmental Science and Pollution Research*, *25*, 15269–15293. https://doi.org/10.1007/s11356-018-2018-y

[25] Okinda, C., Nyalala, I., Korohou, T., Okinda, C., Wang, J., Achieng, T., Wamalwa, P., Mang, T., & Shen, M. (2020). A review on computer vision systems in monitoring of poultry: A welfare perspective. *Artificial Intelligence in Agriculture*, *4*, 184–208.

[26] Olanrewaju, H. A., Dozier, W. A., Purswell, J. L., Branton, S. L., Miles, D. M., Lott, B. D., Pescatore, A. J., & Thaxton, J. P. (2008). Growth performance and physiological variables for broiler chickens subjected to short-term elevated carbon dioxide concentrations. *International Journal of Poultry Science*, *7*(8), 738–742.

[27] Pedersen, S., & Thomsen, M. G. (2000). Heat and moisture production of broilers kept on straw bedding. *Journal of Agricultural Engineering Research*, *75*, 177–187.

[28] Rowe, E., Dawkins, M. S., & Gebhardt-Henrich, S. G. (2019). A systematic review of precision livestock farming in the poultry sector: Is technology focussed on improving bird welfare? *Animals*, *9*(9), 614. https://doi.org/10.3390/ani9090614

[29] Taira, K., Nagai, T., Obi, T., & Takase, K. (2014). Effect of litter moisture on the development of footpad dermatitis in broiler chickens. *Journal of Veterinary Medical Science*, *76*(4), 583–586. https://doi.org/10.1292/jvms.13-0321

[30] Tooprakai, S., Krueaprasit, R., Penchalee, R., & Tulathon, W. (2022). A management system for poultry farm using LoRa communication technology. *2022 International Conference on Engineering, Applied Sciences, and Technology (ICEAST)*. https://doi.org/10.1109/iceast55249.2022.9826321

[31] Wang, K., Guo, R., Zhou, Y., Jiao, L., & Dong, D. (2022). Detection of NH_3 in poultry housing based on tunable diode laser absorption spectroscopy combined with a micro circular absorption cell. *Frontiers in Physics*, *10*, 1051719. https://doi.org/10.3389/fphy.2022.1051719

[32] Wang, K., Shen, D., Dai, P., & Li, C. (2023). Particulate matter in poultry house on poultry respiratory disease: A systematic review. *Poultry Science*, *102*(4), 102556. https://doi.org/10.1016/j.psj.2023.102556

[33] Wheeler, E. F., Weiss, R. W. J., & Weidenboerner, E. (2000). Evaluation of instrumentation for measuring aerial ammonia in poultry houses. *Journal of Applied Poultry Research*, *9*(4), 443–452.

[34] Xin, H., Berry, I. L., Tabler, G. T., & Costello, T. A. (2001). Heat and moisture production of poultry and their housing systems: Broilers. *Transactions of the ASAE*, *44*(6), 1851–1857.

[35] Zheng, P., Zhang, W., Gao, B., Ma, Y., & Chen, C. (2025). Multi-step apparent temperature prediction in broiler houses using a hybrid SE-TCN–Transformer model with Kalman filtering. *Sensors*, *25*(19), 6124. https://doi.org/10.3390/s25196124

[36] Zhou, Y., Liu, Q. X., Li, X. M., Ma, D. D., Xing, S., Feng, J. H., & Zhang, M. H. (2020). Effects of ammonia exposure on growth performance and cytokines in the serum, trachea, and ileum of broilers. *Poultry Science*, *99*(5), 2485–2493. https://doi.org/10.1016/j.psj.2019.12.063