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Housing and Cooling Strategies to Mitigate Heat Stress and Enhance Broiler Performance in Humid Tropical Climates: A Systematic Review

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Abstract. *Heat stress is a major constraint in broiler production systems located in humid tropical climates, where high ambient temperature and relative humidity impair growth performance, feed efficiency, and animal welfare. This systematic review synthesizes peer-reviewed studies published between January 2015 and December 2025 evaluating environmental housing designs and cooling strategies for mitigating heat stress in broiler chickens. This systematic review followed the PRISMA 2020 guidelines and synthesized peer-reviewed studies retrieved from Scopus, Web of Science, and ScienceDirect, published between January 2015 and December 2025. From 500 records initially identified, 26 studies fulfilled the predefined eligibility criteria and were included in the qualitative synthesis. The findings demonstrate that evaporative cooling systems, tunnel ventilation, and automated climate control technologies consistently reduced indoor temperature (2–6°C) and improved body weight gain, feed conversion ratio (FCR), and mortality rates under hot-humid conditions. However, cooling efficiency was strongly influenced by ambient humidity, necessitating integrated and adaptive environmental control approaches. Smart sensor-based systems further enhanced microclimate stability and thermal uniformity within broiler houses. Beyond performance improvements, optimized environmental management reduced physiological stress indicators, including heterophil-to-lymphocyte ratios and corticosterone levels. Overall, integrated, humidity-adaptive, and energy-efficient cooling strategies are essential to sustain productivity, welfare, and climate resilience in tropical broiler production systems.*

Keyword: *Broiler chickens, Cooling systems, Environmental control, Heat stress, Humid tropical climate*

INTRODUCTION

The poultry sector remains a cornerstone of global food systems, contributing substantially to the supply of high-quality animal protein while supporting livelihoods worldwide. Broiler chicken meat production represents a major component of the global

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meat industry, owing to its efficiency in converting feed into lean tissue and its relative affordability compared with other livestock products. However, poultry physiology renders chickens particularly susceptible to environmental stressors, especially thermal stress, which can compromise both performance and welfare under high ambient temperatures (Liu et al., 2020; Brugaletta et al., 2022).

Heat stress has become a major constraint in broiler production, particularly in tropical and subtropical regions characterized by high ambient temperature and humidity. Under elevated thermal conditions, broilers reduce feed intake and increase panting behavior to minimize metabolic heat load (Brugaletta et al., 2022; Lara & Rostagno, 2013). These adaptive responses, although protective, negatively affect growth performance and production efficiency.

Prolonged exposure to high temperature leads to reduced body weight gain (BWG), impaired feed conversion ratio (FCR), and increased mortality rates (Liu et al., 2020; Santos et al., 2021). At the physiological level, heat stress induces oxidative stress through excessive reactive oxygen species (ROS) production, disrupts intestinal integrity, impairs nutrient absorption, and suppresses immune function (Ferreira et al., 2024; Brugaletta et al., 2022). Humidity further exacerbates thermal load by limiting evaporative heat loss, making humid tropical environments particularly challenging for broiler production (Apalowo et al., 2024; Kim et al., 2025). Although various mitigation strategies have been investigated, evidence regarding environmental housing and cooling interventions under humid tropical conditions remains fragmented. Therefore, a comprehensive synthesis is required to evaluate the effectiveness of housing designs and cooling technologies in improving productivity and physiological resilience in broiler chickens raised in heat-prone climates.

LITERATURE REVIEW

Heat stress in broiler chickens is defined as a condition in which ambient temperature exceeds the birds' thermo-neutral zone, resulting in physiological and metabolic imbalance. Birds respond to elevated temperature primarily through behavioral and physiological adjustments, including reduced feed intake, increased respiratory rate, and altered blood biochemical parameters (Brugaletta et al., 2022; Lara & Rostagno, 2013). These responses aim to reduce internal heat production but consequently impair growth and feed efficiency.

Heat stress exerts profound negative effects on broiler productivity through multiple physiological pathways. One of the earliest responses to elevated ambient temperature is a reduction in voluntary feed intake, which subsequently decreases body weight gain (BWG) and overall growth performance. Prolonged exposure to high thermal load deteriorates feed conversion ratio (FCR) and significantly increases mortality rates (Liu et al., 2020; Santos et al., 2021). At the cellular level, heat stress induces oxidative stress through excessive production of reactive oxygen species (ROS), leading to lipid peroxidation, mitochondrial dysfunction, and cellular damage. Oxidative imbalance compromises intestinal epithelial integrity and nutrient absorption efficiency, while chronic thermal stress suppresses immune function by altering lymphoid organ activity and immune cell responses (Ferreira et al., 2024; Brugaletta et al., 2022). These physiological disruptions ultimately reduce production efficiency and farm profitability, especially under humid tropical conditions.

Humidity exacerbates thermal load by reducing the capacity for evaporative heat loss, making conditions in humid tropical climates particularly detrimental to broiler welfare and productivity. Under elevated temperature–humidity index (THI) conditions, birds often experience physiological and biochemical alterations, including altered blood traits and compromised nutrient metabolism (Apalowo et al., 2024; Kim et al., 2025). Consequently, conventional open-sided housing systems often prove inadequate for maintaining optimal microclimate parameters, underscoring the need for environmental control strategies that target both temperature and humidity.

Environmental housing designs and cooling technologies play crucial roles in mitigating heat stress by regulating internal microclimate variables such as air temperature, relative humidity, and air velocity. Cooling systems such as evaporative cooling pads, fogging systems, and precision ventilation have been extensively evaluated for their potential to stabilize thermal conditions within poultry houses (Liu et al., 2020; Elwakeel, 2025). Recent advances also integrate sensor-based controllers and automation technologies to adjust ventilation and cooling dynamically, aiming to achieve uniform thermal environments across production units. However, the effectiveness of these interventions is context-dependent and varies according to housing design, climatic conditions, and operational practices.

Despite the growing body of literature on heat stress mitigation in poultry, existing review articles have primarily focused on nutritional interventions, physiological responses, genetic adaptations, or general management strategies rather than environmental control systems. For example, previous reviews have emphasized nutritional manipulation to alleviate heat stress, the physiological mechanisms underlying thermal stress, and broad production challenges in tropical environments, while providing limited synthesis of environmental housing design and cooling technologies specifically for broiler chickens under humid tropical conditions (Brugaletta et al., 2022; Mangan & Siwek, 2024). Furthermore, recent advances in automated climate control, sensor-based environmental monitoring, precision ventilation, and humidity-adaptive cooling systems have not been systematically evaluated within a single evidence-based framework.

Therefore, a comprehensive systematic review is needed to synthesize current evidence on environmental housing designs and cooling strategies and to identify knowledge gaps regarding their effectiveness under humid tropical conditions. Unlike previous reviews, the present study specifically focuses on environmental housing and cooling interventions and evaluates their effects on growth performance, feed efficiency, physiological responses, mortality, and welfare in broiler chickens using a systematic review approach based on the PRISMA 2020 guidelines. By integrating empirical findings from peer-reviewed studies, this review provides evidence-based recommendations for developing sustainable and climate-resilient broiler production systems in humid tropical regions.

RESEARCH METHODS

1. Study Design and Reporting Framework

This study was conducted as a systematic review following the principles of the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020) statement to ensure transparency, methodological rigor, and reproducibility of the review process. The PRISMA 2020 framework provides structured guidance for reporting systematic reviews, particularly in terms of literature identification, screening, eligibility assessment, and study inclusion. By adhering to this framework, the present review aimed to minimize selection bias, enhance traceability of the decision-making process, and provide a clear documentation of how relevant studies were identified and synthesized.

The objective of this systematic review was to evaluate environmental housing designs and cooling strategies implemented to mitigate heat stress and improve growth performance in broiler chickens reared under humid tropical climatic conditions. The review focused specifically on empirical evidence derived from experimental, field-based, and engineering-oriented studies that examined environmental control interventions within poultry housing systems. The methodological workflow followed four sequential phases in accordance with PRISMA 2020: identification of records, screening of titles and abstracts, full-text eligibility assessment, and final inclusion for qualitative synthesis.

2. Information Sources

A comprehensive literature search was conducted to identify relevant peer-reviewed studies examining environmental housing systems and cooling strategies for broiler chickens under humid tropical conditions. The primary search interface used was Publish or Perish, which retrieves indexed publications predominantly from Google Scholar. Google Scholar was selected due to its broad coverage of multidisciplinary scientific literature, including engineering, animal science, agricultural technology, and environmental management journals relevant to poultry housing research.

The search covered articles published between January 2015 and December 2025 to ensure the inclusion of contemporary technological developments, particularly in automated climate control systems, evaporative cooling optimization, and precision livestock farming applications. Only full-text articles published in peer-reviewed international journals were considered eligible. Conference proceedings, theses, dissertations, non-indexed reports, book chapters, and non-English publications were excluded to maintain consistency in scientific quality and reporting standards.

3. Search Strategy

The search strategy was developed systematically to capture empirical studies addressing environmental housing modifications and cooling technologies aimed at mitigating heat stress in broiler chickens raised under humid tropical conditions. A structured combination of keywords and Boolean operators (AND, OR) was applied to ensure both sensitivity and specificity in retrieving relevant literature. The primary search string included combinations of the following terms: “broiler chicken” OR “broiler production”, AND “heat stress” OR “thermal stress”, AND “housing system” OR “poultry house design” OR “ventilation system”, AND “cooling system” OR “evaporative cooling” OR “fogging system” OR “tunnel ventilation”, AND “tropical climate” OR “humid tropics”.

Keyword variations and synonyms were incorporated to broaden the scope of retrieval while maintaining thematic alignment with the study objective. Truncation and phrase searching were applied where appropriate to capture indexed and non-indexed variations of relevant terms. The search was restricted to titles, abstracts, and keywords to improve thematic relevance and minimize retrieval of unrelated studies.

The initial search yielded a total of 500 records. After removing 50 duplicate entries, 450 records remained for title and abstract screening. Studies that did not meet the predefined scope—such as those focusing exclusively on nutritional interventions, genetic selection, or non-tropical environments—were excluded at this stage. The remaining articles underwent full-text eligibility assessment prior to final inclusion in the qualitative synthesis, following the structured flow outlined in the PRISMA 2020 framework.

4. Eligibility Criteria

The eligibility criteria were established a priori to ensure methodological consistency and alignment with the research objective. Inclusion and exclusion criteria were defined using a structured approach adapted from systematic review standards to minimize selection bias and enhance reproducibility.

Studies were considered eligible if they met the following inclusion criteria: (1) original research articles published in peer-reviewed international journals between January 2015 and December 2025; (2) studies involving broiler chickens as the primary experimental subject; (3) research conducted under tropical or humid tropical climatic conditions; and (4) studies evaluating environmental housing design, ventilation systems, cooling technologies, or climate control interventions aimed at mitigating heat stress or improving growth performance and physiological responses. Both experimental and field-based studies were included, provided that measurable environmental or production parameters were reported.

Studies were excluded if they: (1) focused solely on nutritional, genetic, or pharmaceutical interventions without evaluating housing or environmental modifications; (2) were review papers, conference proceedings, theses, book chapters, or non-peer-reviewed reports; (3) did not provide sufficient methodological detail or quantitative data; or (4) were conducted in temperate or subtropical regions without clear relevance to humid tropical conditions. Full-text eligibility assessment was conducted after title and abstract screening. Articles meeting all predefined criteria were included in the qualitative synthesis. This structured selection process ensured that the final dataset accurately reflected technological and engineering-based mitigation strategies applicable to broiler production systems in humid tropical environments.

5. Study Selection Process

The study selection process followed a structured multi-stage screening procedure in accordance with the PRISMA 2020 framework to ensure transparency and reproducibility. The initial database search identified 500 records. After removing 50 duplicate entries, a total of 450 unique records remained for further screening. During the title and abstract screening stage, 372 records were excluded because they did not meet the predefined eligibility criteria. The primary reasons for exclusion included studies focusing exclusively on nutritional supplementation, genetic improvement, or non-tropical environmental conditions, as well as articles unrelated to housing design or cooling system interventions. Following this screening stage, 78 articles were deemed potentially relevant and proceeded to full-text assessment.

All 78 full-text articles were successfully retrieved and evaluated for eligibility. After applying the inclusion and exclusion criteria in detail, studies that lacked sufficient environmental parameters, did not report measurable production outcomes, or did not clearly describe the housing intervention were excluded. The remaining eligible studies were included in the qualitative synthesis. The overall selection process is summarized in the PRISMA flow diagram, which outlines the number of records identified, screened, excluded, and included at each stage of the review.

6. Quality Assessment

To enhance the methodological rigor of this systematic review, the quality of the included studies was critically appraised using criteria adapted from the Joanna Briggs Institute (JBI) Critical Appraisal Checklist for Quasi-Experimental Studies. The assessment focused on key methodological aspects relevant to environmental intervention studies, including: (1) clarity of the research objectives; (2) appropriateness of the study design; (3) adequate description of housing or cooling interventions; (4) reliability of environmental and production outcome measurements; (5) appropriateness of statistical analyses; and (6) completeness of reported results.

Each included study was independently evaluated against these criteria to determine its overall methodological quality. Rather than serving as a basis for excluding studies, the quality assessment was used to support the interpretation of the evidence and to identify potential methodological limitations across the included literature. Any uncertainties identified during the appraisal process were resolved through re-examination of the original full-text articles to ensure consistency and accuracy in the qualitative synthesis.

7. Data Extraction and Synthesis

Data extraction was conducted systematically to ensure consistency and accuracy in capturing relevant information from each included study. A standardized data extraction form was developed in Microsoft Excel prior to full-text review. The extracted variables included: (1) author(s) and year of publication; (2) country and climatic classification; (3) type of housing system evaluated (e.g., open-sided house, tunnel-ventilated house, environmentally controlled house); (4) cooling or ventilation technology applied (e.g., evaporative cooling pads, fogging systems, tunnel ventilation, hybrid systems); (5) experimental design and sample size; (6) environmental parameters measured (temperature, relative humidity, temperature-humidity index); and (7) performance and physiological outcomes (body weight gain, feed conversion ratio, mortality rate, rectal temperature, respiratory rate).

The extraction process was performed independently and cross-checked to reduce the risk of transcription errors and selective reporting. Any discrepancies identified during data compilation were resolved through re-evaluation of the original full-text article to ensure accuracy. Given the heterogeneity in experimental designs, climatic conditions, housing configurations, and outcome measurements across studies, a quantitative meta-analysis was not conducted. Instead, a qualitative synthesis approach was applied. The findings were categorized according to the type of environmental intervention and summarized narratively to identify patterns, technological trends, and performance outcomes associated with specific cooling strategies in humid tropical environments. This approach allowed for a comprehensive interpretation of engineering-based mitigation strategies while accounting for contextual variability among studies.

RESULTS AND DISCUSSION

1. Study Selection and Characteristics of Included Studies

The study identification and selection process was conducted following the PRISMA 2020 guidelines to ensure systematic, transparent, and reproducible documentation of the literature screening procedure. The PRISMA framework provides a structured methodology for reporting the number of records identified, screened, assessed for eligibility, and ultimately included in qualitative synthesis, thereby reducing selection bias and improving reporting clarity in systematic reviews (Page et al., 2021; Haddaway et al., 2022). The complete screening pathway and exclusion stages are presented in Figure 1.

Following the multi-stage screening and full-text eligibility assessment, a total of 26 studies met the predefined inclusion criteria and were incorporated into the qualitative synthesis. The selected studies were published between January 2015 and December 2025 and were conducted predominantly in tropical and humid subtropical regions across Asia, Africa, and Latin America. This geographical distribution reflects the increasing research emphasis on thermal stress mitigation in broiler production systems exposed to persistent high ambient temperature and relative humidity. Such climatic conditions are widely recognized as major constraints to broiler growth performance, immune stability, and survivability (Nawab et al., 2018; Mancinelli et al., 2023).

The predominance of studies conducted in Asia, Africa, and Latin America reflects the high vulnerability of broiler production systems in these regions to heat stress and the increasing adoption of environmental mitigation technologies under humid tropical conditions. However, this geographical concentration may limit the broader generalizability of the findings because climatic conditions, housing systems, management practices, and production intensities differ substantially across regions. Environmental control strategies that are effective under hot-humid tropical conditions may not exhibit the same level of effectiveness in temperate or arid climates, where ambient temperature profiles, ventilation requirements, and housing designs differ considerably (Rojas-Downing et al., 2017; Mancinelli et al., 2023). Therefore, the conclusions of this review should primarily be interpreted within the context of humid tropical broiler production systems. Future studies involving a wider range of climatic zones are warranted to strengthen the external validity and global applicability of environmental housing and cooling strategies. The temporal trend observed over the last decade also aligns with intensified global attention toward climate variability and its implications for livestock productivity (Rojas-Downing et al., 2017).

Overall, the included studies were considered to be of moderate to high methodological quality. Most studies clearly described the housing interventions, environmental measurements, and production outcomes, although several lacked detailed information regarding randomization procedures or blinding. These methodological limitations were considered during the interpretation of the findings.

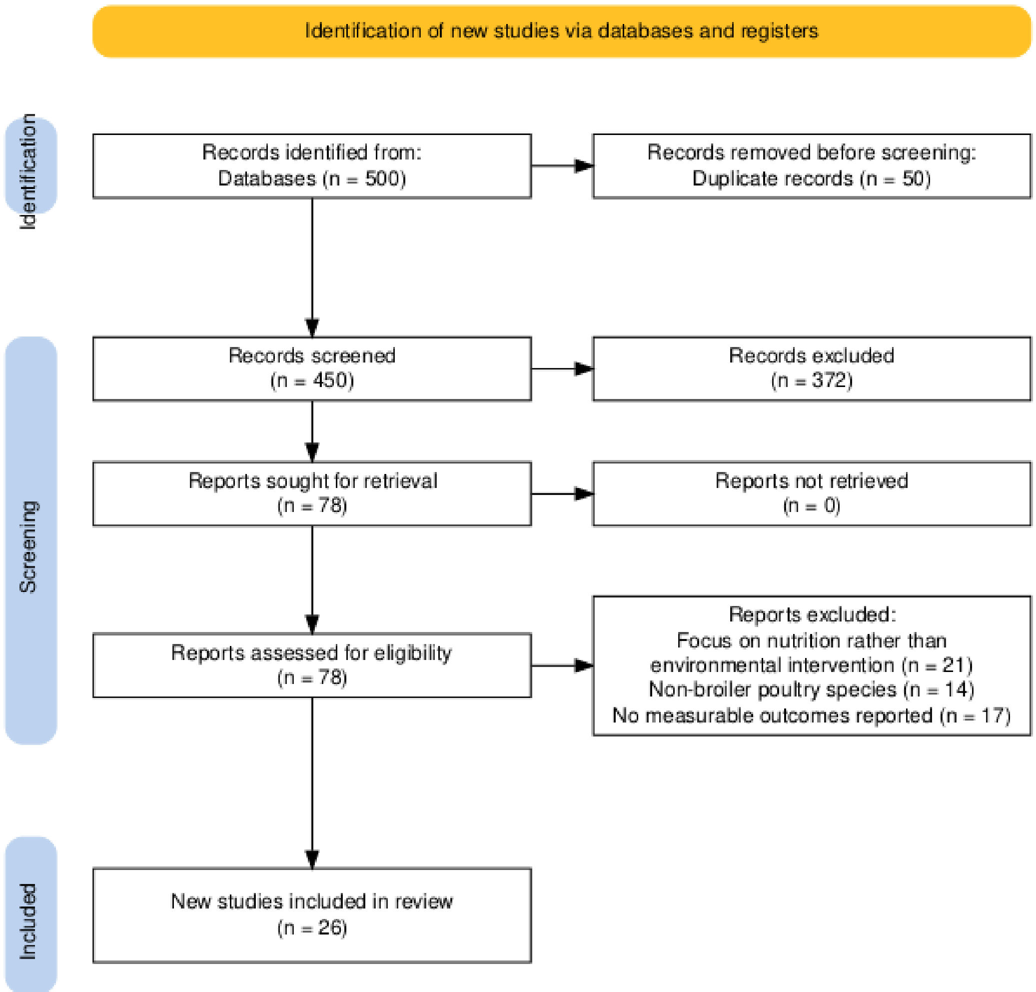

Figure 1. PRISMA Flow Diagram

In terms of research design, the majority of included studies employed controlled experimental or quasi-experimental approaches conducted in commercial broiler houses, research facilities, or pilot-scale environmentally controlled systems. Sample sizes varied considerably depending on experimental objectives, ranging from small climate-controlled chamber trials to large-scale commercial evaluations involving thousands of birds per production cycle. Production performance indicators most frequently reported included final body weight, feed conversion ratio (FCR), feed intake, and mortality rate. Additionally, a substantial proportion of studies incorporated physiological indicators of thermal stress, such as rectal temperature, respiratory rate, corticosterone levels, and heterophil-to-lymphocyte ratio. These parameters are widely accepted as reliable markers for assessing heat stress severity and production efficiency in broiler chickens (He et al., 2019; Liu et al., 2020).

Regarding housing configurations, the reviewed literature examined three primary system categories: open-sided naturally ventilated houses, mechanically ventilated tunnel systems, and fully environmentally controlled closed-house facilities. Cooling strategies commonly evaluated included evaporative cooling pads, fogging and misting systems, negative-pressure ventilation, and hybrid ventilation-cooling combinations. Environmental variables such as ambient temperature, relative humidity, air velocity, temperature–humidity index (THI), and ammonia concentration were consistently monitored across studies. Previous evidence has demonstrated that optimized environmental control significantly reduces thermal load and improves feed efficiency and growth performance under tropical production conditions (Pawar et al., 2016). Collectively, the included studies indicate a strong and consistent research focus on engineering-based climate control interventions aimed at enhancing broiler productivity and resilience under hot-humid environments.

2. General Characteristics of the Reviewed Studies

The included studies demonstrated substantial diversity in methodological approach, yet several consistent patterns emerged. The majority of investigations were conducted using controlled experimental or quasi-experimental designs, either in commercial broiler facilities or research-based climate-controlled housing units. A smaller but increasingly relevant proportion of studies employed engineering-based simulations, including computational fluid dynamics (CFD) modeling and airflow

distribution analysis, to evaluate ventilation performance and thermal mapping within poultry houses. The growing integration of engineering simulation and real-time monitoring reflects the multidisciplinary nature of modern poultry housing research, combining animal science with environmental engineering and precision livestock farming technologies (Elwakeel, 2025; Gad et al., 2020).

Across the reviewed literature, environmental monitoring formed the core of experimental evaluation. The most frequently reported parameters were ambient temperature (°C), relative humidity (%), temperature–humidity index (THI), and air velocity (m/s). Several studies also included ammonia (NH_3) concentration and carbon dioxide (CO_2) levels to assess air quality and ventilation efficiency. The consistent use of THI as an integrative thermal stress indicator highlights its widespread acceptance as a practical tool for evaluating heat load severity in broiler production systems under tropical conditions (Pawar et al., 2016; Nawab et al., 2018). Notably, studies incorporating spatial thermal mapping revealed that microclimate variability within the same housing unit can be as influential as average temperature levels, emphasizing the importance of airflow distribution efficiency.

Table 1. Comparative Analysis of Climate Control Strategies and Broiler Performance

No	Author (Year)	Country	Study Design	Sample Size	Experimental Duration	Housing Type	Cooling Strategy	Environmental Parameters Measured	Performance Indicators	Key Findings
1	Çaylı et al. (2021)	Turkey	Comparative experimental field study	Two commercial broiler houses	June–September (summer season)	Closed house	Two evaporative cooling systems	Temp, RH	–	Spray efficiency up to 92.2% in Mediterranean climate
2	Kamal & Ahmed (2024)	Egypt	Randomized experimental trial	1,920 Ross-308 broilers (5 treatments × 384 birds)	One production cycle	Closed house	Fogging system	Temp, RH	BW, FCR, Mortality, Physiology	Improved BW & FCR; reduced heat stress indicators
3	Abdi et al. (2025)	Indonesia	NR	NR	NR	Closed house	IoT automated control	Temp, RH	–	Stable environment under unstable power supply
4	Çaylı (2025)	Turkey	Observational field study	One commercial broiler house	Summer season	Tunnel-ventilated	Ventilation uniformity assessment	Temp, RH	–	Thermal non-uniformity near exhaust fans
5	Lillahulhaq et al. (2025)	Indonesia	NR	NR	NR	Negative pressure closed house	Cooling pad thickness optimization	Temp, RH, Air velocity	–	100 mm pad thickness optimal
6	Trentin et al. (2025)	Brazil	NR	NR	NR	Fully automated	Integrated climate automation	Temp, Cost	FCR	Improved economic & technical efficiency
7	Nurhidayah et al. (2025)	Indonesia	Experimental study	NR	NR	Climate-controlled	Temperature treatment	Temp, RH	BWG, FCR	Heat stress reduced growth performance
8	Ramadhan et al. (2025)	Indonesia	Experimental field study	NR	NR	Closed house	Thermal stabilization	Temp, RH, THI	BW	93.8% comfort zone maintained
9	Ferreira et al. (2024)	Brazil	Experimental environmental monitoring	NR	NR	Climate-controlled	Environmental dynamics analysis	Temp, RH, BGHI	Feed efficiency	Spatial heat variation detected
10	Daniel et al. (2024)	South Korea	Experimental study	NR	NR	Mechanical ventilation	Advanced ventilation algorithm	Temp, Airflow	Mortality	Mortality reduced 16.5%
11	Trokhaniak et al. (2024)	Ukraine	Experimental engineering study (heat exchanger evaluation)	Prototype heat-exchanger system	Laboratory experiment	Side ventilation	Heat exchanger cooling	Temp, Air velocity	–	Cooling achieved without increasing RH
12	Zakaria et al. (2024)	Indonesia	Field observational study	52,500 Cobb CP707 broilers	32 days	Closed house	Stocking density variation	Temp, RH, CO_2, NH_3	–	Density ≤18 birds/m² optimal
13	Tyris et al. (2023)	Greece	Engineering simulation	NR	NR	Closed house	Heat pump model	Temp, RH	–	SCOP >3 efficiency
14	Munonye et al. (2023)	Nigeria	Experimental field study	NR	One production cycle	Closed house	Thermal comfort assessment	Temp, RH	Mortality, FCR	Mortality increased at 32–34°C
15	Hamiyanti et al. (2023)	Indonesia	Comparative field study	NR	NR	Open, Semi, Closed	Housing comparison	Temp, RH, NH_3	BW	Closed house more stable & productive
16	Elghardouf et al. (2023)	Morocco	CFD simulation	Numerical model	Simulation	Mechanical ventilation	Pressure & airflow modeling	Pressure, Velocity	–	Prediction error <1%
17	Cho et al. (2022)	South Korea	Engineering development study	NR	NR	Mechanical ventilation	Heat stress forecasting	Temp, RH, THI	–	Web-based forecasting system effective
18	Jaradat et al. (2022)	Jordan	Experimental engineering study	Prototype cooling system	Laboratory evaluation	Closed house	Liquid desiccant cooling	Temp, RH	–	Effective RH control in humid climate

19	Santos et al. (2021)	Brazil	Comparative experimental study	NR	One production cycle	Closed house	CPC, SPK, FOG comparison	Temp, RH	–	CPC efficiency 81.6%
20	Shahzad et al. (2021)	Pakistan	Comparative thermodynamic analysis	Simulation	Simulation	Poultry house	DEC, IEC, MEC systems	Temp, RH, THVI	–	MEC most thermodynamically efficient
21	Gad et al. (2020)	Egypt	Experimental field study	NR	One production cycle	Semi-closed	Solar + ventilation system	Temp, RH, NH_3	BW, FCR, Mortality	BW 2.29 kg; FCR 1.45
22	Samadpour et al. (2018)	Iran	Multi-criteria decision analysis (AHP)	NR	NR	Broiler breeding house	Ventilation & insulation (AHP)	Vent rate	FCR	Ventilation influence 66%
23	Elkaoud & Hassan (2018)	Egypt	Experimental engineering study	NR	NR	Broiler house	Traditional cooling optimization	Temp, RH	–	Water saving 22 L/hr
24	Mesa et al. (2017)	Brazil	Comparative field study	NR	NR	Multiple housing types	Housing condition comparison	–	FCR, Mortality	Significant effect on performance
25	Osorio et al. (2016)	Brazil	Comparative experimental field study	Two commercial broiler houses	First 3 weeks of rearing	Tunnel vs Positive pressure	Ventilation comparison	Temp, RH, THI	–	Tunnel more thermally uniform
26	Rahmawati et al. (2024)	Indonesia	Comparative field study	NR	NR	Closed house (Z1 vs Z2)	Zoning evaluation	Temp, RH, NH_3	BW, Mortality	Zone 2 higher stress & mortality

Regarding productive responses, final body weight (BW), feed conversion ratio (FCR), feed intake, mortality rate, and performance index (PI) were the most commonly reported indicators. In addition to production metrics, several studies incorporated physiological stress markers such as heterophil-to-lymphocyte ratio, corticosterone concentration, and oxidative stress indicators to establish mechanistic links between environmental conditions and biological responses. This combined assessment approach strengthens causal interpretation by connecting housing interventions not only to performance outcomes but also to underlying thermoregulatory and metabolic processes (He et al., 2019; Liu et al., 2020).

A comparative overview of the selected studies, including country, housing type, cooling strategy, environmental parameters measured, performance indicators, and key findings, is presented in Table 1. The table highlights the predominance of closed-house and mechanically ventilated systems in recent investigations, as well as the increasing adoption of intelligent and automated climate control technologies in tropical broiler production.

A comparison of the included studies reveals notable methodological differences that may influence the interpretation of the reported outcomes. Experimental studies conducted under controlled environmental conditions generally demonstrated greater consistency in temperature regulation and physiological measurements, allowing clearer attribution of observed performance improvements to specific cooling interventions. In contrast, field-based studies conducted in commercial broiler houses were subject to greater environmental variability, including fluctuations in ambient weather conditions, stocking density, and management practices, which may have influenced production responses. Engineering-based investigations employing computational fluid dynamics (CFD) and environmental simulation provided detailed insights into airflow distribution and thermal uniformity but often lacked direct biological performance measurements. Consequently, integrating evidence from experimental, commercial, and engineering studies offers a more comprehensive understanding of how housing design and cooling technologies influence broiler productivity under humid tropical conditions while acknowledging the methodological heterogeneity across the reviewed literature.

3. Environmental Housing and Cooling Strategies

Based on intervention characteristics, the included studies were categorized into six major thematic groups: (1) evaporative and direct cooling systems, (2) intelligent and automated climate control technologies, (3) thermal mapping and spatial zoning approaches, (4) alternative and advanced cooling technologies, (5) physiological and stress-response assessments, and (6) housing structure and ventilation design optimization. This thematic classification enables a structured evaluation of engineering-based environmental control strategies and their respective impacts on broiler productivity under humid tropical conditions (Mangan & Siwek, 2024; Onagbesan et al., 2023).

To facilitate comparison across intervention types, the identified themes were further synthesized according to their primary technological focus and reported performance outcomes. This integrative perspective highlights how different environmental management strategies contribute to feed efficiency, growth performance, mortality reduction, and overall production stability. The consolidated thematic patterns and their associated impacts are summarized in Table 2.

Table 2. Thematic Synthesis of Environmental Housing and Cooling Interventions

Theme	Number of Studies	Main Technology / Approach	Performance Impact	Key Findings	Practical Implications
Evaporative & Direct Cooling Systems	6	Fan-pad, spray, fogging, cooling pad thickness, dew-point cooling	BW ↑, FCR ↓, Mortality ↓	Spray cooling achieved up to 92.2% efficiency. Multi-stage evaporative cooling (MEC) showed superior thermodynamic performance. Fogging improved physiological stability and production parameters under tropical heat stress.	Suitable for commercial tropical broiler farms, but cooling efficiency decreases under RH >75–80%; combining ventilation with evaporative cooling is recommended.
Intelligent & Automated Climate Control	5	IoT automation, adaptive ventilation algorithms, dynamic heat pump models, forecasting systems	Mortality ↓, FCR improved	Automated systems enhanced microclimate stability, reduced mortality (up to 16.5%), and improved energy efficiency. Low-cost IoT demonstrated practical field application.	Recommended for medium- and large-scale operations; initial investment may limit adoption by smallholders.
Thermal Mapping & Spatial Zoning	4	THI mapping, kriging, pressure modelling, zoning comparison	BW influenced by zone, Mortality ↑ in hot zones	Tunnel ventilation improved uniformity. Zones near exhaust fans exhibited higher temperatures. Spatial heat mapping identified critical heat accumulation areas.	Useful for optimizing fan placement, cooling pad arrangement, and stocking distribution during house design.
Alternative & Advanced Cooling Technologies	3	Liquid desiccant cooling, heat exchanger systems, solar-powered climate control	BW maintained, Mortality ↓	Desiccant systems effective in high-humidity climates. Solar-assisted systems improved productivity while reducing energy dependency. Heat exchangers cooled without increasing humidity.	Promising for sustainable poultry production but require further economic feasibility studies before commercial adoption.
Thermal Stress & Physiological Response	2	Controlled temperature exposure (20°C vs 30°C), THI monitoring	BW ↓ at high temp, FCR ↑	Temperatures above 32–34°C significantly increased mortality and stress markers (H/L ratio), negatively affecting feed efficiency.	Continuous monitoring of THI and physiological indicators can support early intervention against heat stress.
Housing Structure & Ventilation Contribution	6	Closed vs open housing, ventilation-insulation AHP analysis, big-data farm evaluation	FCR improved in optimized housing	Closed housing provided more stable microclimate. Ventilation contributed approximately 66% to performance variability. Density and structural configuration affected heat distribution.	Improving ventilation design and housing structure should be prioritized before investing in advanced cooling technologies.

3.1. Evaporative and Direct Cooling Systems

Evaporative cooling systems, including fan-pad systems, fogging, and misting technologies, were among the most extensively evaluated interventions. These systems function by promoting latent heat loss through water evaporation, thereby reducing indoor air temperature during periods of elevated ambient heat. Across multiple studies conducted in tropical environments, evaporative cooling reduced indoor temperature by approximately 2–6°C compared to non-cooled control houses, resulting in improved feed intake, body weight gain, and feed conversion ratio (FCR) (Nawab et al., 2018). Recent field trials in tropical broiler houses have confirmed that multi-stage evaporative cooling (MEC) improves thermo-neutral zones more effectively than single-stage systems (Lillahulhaq et al., 2025).

However, cooling efficiency was strongly influenced by ambient relative humidity. In humid tropical regions, high atmospheric moisture reduces evaporative potential, thereby limiting cooling performance. Several studies reported diminished temperature reduction efficiency when relative humidity exceeded 75–80%, indicating that evaporative systems alone may not sufficiently mitigate heat load under extreme humidity conditions (Pawar et al., 2016; Gad et al., 2020). These findings suggest that airflow velocity enhancement and hybrid cooling integration are critical for maximizing effectiveness in hot-humid climates.

Importantly, field-based performance evaluations conducted in humid tropical East Kalimantan demonstrated that improved environmental regulation in controlled housing systems was associated with lower feed conversion ratios and more stable growth performance compared to open-house systems (Rizkuna et al., 2025). A strong positive correlation between feed intake and FCR ($r = 0.961$; $p < 0.05$) further suggests that environmental stress may impair nutrient utilization efficiency. Although the study did not isolate specific cooling technologies, the findings reinforce the broader evidence that effective microclimatic control whether through evaporative cooling, ventilation optimization, or integrated systems plays a critical role in maintaining production efficiency under tropical heat stress conditions.

Similarly, a regression-based study conducted in semi-closed housing systems in Samarinda reported that feed intake positively influenced productivity, whereas FCR exerted a significant negative effect on growth performance (Aldiyanti et al., 2025). The authors emphasized that semi-closed housing contributed to improved microclimate stability, reduced heat stress exposure, and enhanced overall feed efficiency. Although these studies did not exclusively isolate evaporative cooling technologies, their findings collectively reinforce broader evidence that environmental stabilization whether achieved through cooling systems, ventilation management, or semi-controlled housing plays a decisive role in optimizing feed utilization and productivity in humid tropical broiler production systems.

Overall, evaporative and direct cooling systems remain among the most practical and widely adopted approaches for mitigating heat stress in broiler production due to their relatively simple operation and proven effectiveness in reducing indoor temperature. Nevertheless, their performance is highly dependent on ambient humidity and water availability, making them less effective during periods of persistently high relative humidity that commonly occur in humid tropical regions. Furthermore, continuous operation may increase water consumption and energy demand, potentially limiting economic feasibility for small-scale producers. Consequently, integrating evaporative cooling with optimized ventilation, intelligent environmental control, or adaptive management practices is likely to provide more stable thermal regulation and improve the long-term sustainability of broiler production under humid tropical climatic conditions.

3.2. Intelligent and Automated Climate Control Systems

Recent studies increasingly investigated automated environmental control systems integrating temperature and humidity sensors, programmable logic controllers, and adaptive ventilation algorithms. These intelligent systems dynamically regulate fan speed, cooling intensity, and air distribution in response to real-time environmental fluctuations. Compared to conventional manually adjusted systems, automated climate control demonstrated improved microclimate stability, reduced daily thermal variation, and more uniform temperature distribution across housing zones (Elwakeel, 2025; Daniel et al., 2024).

Performance outcomes associated with automated systems included reduced mortality rates, improved FCR, and enhanced flock uniformity. Some studies reported mortality reductions of up to 16% when predictive ventilation control algorithms were implemented. The integration of Internet of Things (IoT)-based monitoring platforms further enhanced decision-making efficiency and reduced labor dependency. Nevertheless, economic feasibility and accessibility remain key constraints for small- and medium-scale producers in developing tropical regions (Nalendra & Waspada, 2025; Lashari et al., 2018).

Overall, intelligent and automated climate control systems represent a promising advancement toward precision poultry farming by enabling continuous environmental monitoring and adaptive decision-making. Nevertheless, their successful implementation depends on reliable electricity supply, sensor accuracy, routine maintenance, and operator competency. Consequently, while these technologies are highly suitable for large-scale commercial operations, wider adoption among smallholder producers in developing tropical countries will require affordable system designs, user-friendly interfaces, and adequate technical support.

3.3. Thermal Mapping and Spatial Zoning Approaches

Computational fluid dynamics (CFD), thermal imaging, and spatial temperature mapping have been employed to analyze airflow distribution and heat accumulation within broiler houses (Gad et al., 2020; Ferreira et al., 2024). These approaches revealed significant microclimate variability even within the same housing unit, with hot spots often occurring near exhaust areas or in poorly ventilated corners.

Thermal mapping and computational fluid dynamics (CFD) studies demonstrate that spatial microclimate variability within broiler houses can substantially influence bird comfort and production performance. Rather than focusing solely on reducing mean ambient temperature, ensuring uniform airflow distribution and minimizing thermal heterogeneity across the house are equally critical for maintaining flock homogeneity. CFD simulations have identified the presence of stagnant air zones, uneven air velocity patterns, and localized temperature gradients that may exacerbate thermal stress when not properly managed (Küçüktopcu et al., 2022; Ferreira et al., 2024). Optimized thermal zoning designs that improve airflow redistribution and reduce spatial variability contribute to more stable physiological responses, decreased stress-related behaviors, and more consistent metabolic activity among birds. Consequently, microclimate uniformity should be considered a key performance determinant alongside absolute temperature reduction in environmentally controlled broiler production systems.

3.4. Alternative and Advanced Cooling Technologies

Emerging cooling technologies extend beyond conventional evaporative systems, including desiccant-based dehumidification systems, earth-to-air heat exchangers, radiant cooling panels, and solar-assisted ventilation solutions. Desiccant systems, in particular, showed effectiveness in high humidity environments by lowering moisture content prior to sensible cooling, thus enhancing overall cooling performance (Jaradat et al., 2022; Aleem et al., 2022).

Advanced environmental control approaches that integrate renewable energy sources, including solar-assisted ventilation and hybrid renewable energy systems—have shown potential not only for thermal management but also for reducing overall energy consumption and environmental impact in poultry and livestock environments. Several studies demonstrate that solar energy systems combined with climate control technologies (e.g., photovoltaic panels with ventilation support) can significantly enhance energy efficiency by supplementing or replacing conventional electrical inputs in poultry houses, thereby lowering dependency on grid power and reducing operational costs and emissions. Integrating hybrid solar and renewable components into ventilation and climate control systems has been associated with notable reductions in energy demand and can contribute to more sustainable production practices. Nonetheless, these integrated renewable systems require comprehensive performance validation in real-world broiler housing conditions and detailed economic and cost-benefit analyses to confirm feasibility for widespread commercial adoption (Gad et al., 2020; Jalali et al., 2023).

Although these advanced cooling technologies offer considerable potential to improve thermal regulation and energy efficiency, their commercial implementation remains constrained by high installation costs, technical complexity, and limited field validation under diverse tropical production systems. Therefore, future research should emphasize long-term on-farm performance, economic feasibility, and scalability to facilitate broader adoption within commercial broiler enterprises.

3.5. Physiological and Stress-Response Indicators

Physiological data from multiple studies indicate that improved environmental control substantially reduces markers of physiological stress such as heterophil-to-lymphocyte (H/L) ratio, corticosterone, and oxidative stress indicators (He et al., 2019; Liu et al., 2020). Birds reared in controlled environments exhibited better intestinal integrity, lower panting scores, and enhanced immune responses compared to birds in inadequately ventilated or high heat load conditions (Meyer et al., 2018; Oke et al., 2017).

Conversely, exposure to chronic heat stress (>32 °C) was associated with suppressed immune function, increased mortality, and reduced feed efficiency, highlighting the welfare and productivity costs of inadequate thermal management (Kim et al., 2025; Nawab et al., 2018).

Collectively, these physiological indicators provide objective evidence that environmental interventions influence broiler performance not only through improvements in production parameters but also by enhancing animal welfare and biological resilience. Incorporating physiological biomarkers alongside production indicators therefore offers a more comprehensive assessment of the effectiveness of environmental housing and cooling strategies in mitigating heat stress.

3.6. Housing Structure and Ventilation Design Contribution

Structural housing characteristics significantly influenced thermal load and microclimate dynamics. Closed-house systems with tunnel ventilation consistently outperformed open-sided houses in terms of thermal stability, uniformity of air distribution, and overall environmental control (Osorio et al., 2016; Samadpour et al., 2018). Roof insulation quality, house orientation, pad thickness, and stocking density emerged as key factors affecting heat retention and airflow efficiency (Hamiyanti et al., 2023; Rahmawati et al., 2024). However, closed systems generally require higher capital investment and increased reliance on electrical power, raising concerns about cost-efficiency and sustainability in resource-limited settings. An integrated design approach that balances structural optimization with energy-efficient cooling solutions may provide a pragmatic pathway for improving broiler performance in tropical climates.

Despite their superior environmental control, closed-house production systems require substantially higher capital investment, continuous electricity supply, and regular maintenance, which may limit their adoption among small- and medium-scale producers in developing countries. Consequently, selecting an appropriate housing design should balance biological performance, economic feasibility, local climatic conditions, and available farm resources. Integrating structural optimization with energy-efficient ventilation and cooling technologies may provide the most practical and sustainable strategy for improving broiler productivity under humid tropical conditions.

4. Mini-Synthesis of Environmental Mitigation Strategies

The synthesis of the reviewed studies demonstrates that environmental control interventions in broiler housing under humid tropical conditions consistently improve productive performance, although the magnitude of response varies depending on system design, climatic severity, and management precision. Across studies published between 2015 and 2025, evaporative cooling pads combined with tunnel ventilation systems were the most frequently evaluated and demonstrated significant reductions in indoor temperature (2–6°C), leading to improved feed intake, body weight gain, and feed conversion ratio (FCR) under high heat load conditions (Gad et al., 2020). These findings reinforce the critical role of airflow velocity and evaporative efficiency in mitigating heat stress in broiler production systems located in hot-humid climates.

However, the effectiveness of evaporative systems was found to be strongly influenced by ambient relative humidity. In environments where relative humidity exceeds 75–80%, the cooling efficiency of pad-based systems declines due to reduced evaporation potential, thereby limiting temperature reduction capacity (Pawar et al., 2016; Nawab et al., 2018). This limitation explains the increasing shift toward integrated and hybrid approaches combining ventilation optimization, fogging, and intelligent environmental control systems to achieve more stable microclimate conditions throughout the production cycle.

Smart and automated climate control technologies emerged as a growing trend in recent years. Studies incorporating sensor-based monitoring, real-time temperature-humidity indexing, and automated fan-speed regulation reported improved thermal uniformity and reduced spatial temperature gradients within broiler houses (Elwakeel, 2025; Gad et al., 2020). The integration of precision livestock farming (PLF) tools not only enhanced environmental consistency but also improved welfare indicators by minimizing acute heat stress episodes. This transition toward automation reflects broader global efforts to improve production efficiency while adapting to climate variability and increasing energy costs.

Beyond temperature mitigation, several studies highlighted the importance of air quality management. Elevated ammonia (NH_3) concentration under inadequate ventilation exacerbates respiratory stress and negatively affects growth performance, even when temperature is partially controlled (He et al., 2019; Liu et al., 2020). Therefore, ventilation system performance must be evaluated not solely based on temperature reduction but also on its ability to maintain optimal air exchange rates and gas concentration thresholds.

Collectively, the evidence suggests that no single cooling strategy can universally optimize broiler performance under all tropical conditions. Instead, system effectiveness depends on contextual adaptation, including housing design, stocking density, climatic intensity, and energy availability. Future technological development should prioritize energy-efficient, humidity-adaptive, and sensor-integrated systems capable of dynamically responding to fluctuating environmental conditions. Such integrated mitigation strategies are essential for sustaining productivity, improving animal welfare, and enhancing environmental resilience in tropical broiler production systems facing accelerating climate change pressures.

Despite the generally positive effects of environmental mitigation strategies, the reviewed studies reported considerable variation in the magnitude of their outcomes. While several investigations demonstrated substantial improvements in growth performance, feed conversion ratio (FCR), and mortality following the implementation of evaporative cooling or automated climate control systems, others reported only modest or inconsistent responses (Gad et al., 2020; Elwakeel, 2025). These discrepancies are likely attributable to differences in climatic conditions, particularly ambient relative humidity and heat load severity, as well as variations in housing design, stocking density, ventilation capacity, bird genotype, flock age, and management practices (Pawar et al., 2016; Nawab et al., 2018; Onagbesan et al., 2023). Moreover, methodological differences among studies, including experimental duration, environmental monitoring protocols, and performance indicators, may also have contributed to the observed heterogeneity. Therefore, comparisons among studies should be interpreted with caution, and future research should adopt more standardized experimental protocols and reporting frameworks to facilitate stronger cross-study comparisons and more robust evidence synthesis (Page et al., 2021; Haddaway et al., 2022).

5. Physiological and Welfare Implications

Beyond production performance, the reviewed literature consistently demonstrates that improved environmental control strategies exert significant physiological and welfare benefits in broiler chickens raised under humid tropical conditions. Studies reporting reduced indoor temperature and improved airflow distribution were frequently associated with lower heterophil-to-lymphocyte (H/L) ratios and decreased plasma corticosterone concentrations, both of which are widely recognized biomarkers of chronic heat stress in poultry (He et al., 2019; Nawab et al., 2018). These physiological responses indicate that optimized housing systems effectively mitigate systemic stress activation rather than merely enhancing growth performance.

Several investigations further reported reductions in oxidative stress markers, including malondialdehyde (MDA), alongside improvements in antioxidant enzyme activity such as superoxide dismutase (SOD) and glutathione peroxidase (GPx) under controlled thermal environments (Liu et al., 2020; Mancinelli et al., 2023). Improved thermal comfort was also associated with enhanced intestinal morphology, including increased villus height and villus height-to-crypt depth ratio, suggesting better nutrient absorption capacity and gut integrity. These findings provide mechanistic support for the observed improvements in feed conversion ratio (FCR) and body weight gain under effective environmental mitigation strategies.

Importantly, welfare-related indicators such as reduced panting behavior, improved activity patterns, and lower mortality rates during peak heat periods were consistently documented in mechanically ventilated and evaporatively cooled housing systems (Elwakeel, 2025). These observations align with contemporary sustainable livestock production frameworks, which emphasize that environmental optimization should be viewed not solely as a productivity-enhancing measure but also as a welfare-based intervention. The integration of environmental engineering and welfare science therefore represents a critical component of resilient broiler production systems in tropical regions increasingly affected by climate variability.

From a commercial production perspective, these physiological improvements have important practical implications. Reduced physiological stress contributes to more consistent feed utilization, improved flock uniformity, lower mortality rates, and greater resilience during periods of environmental heat challenge. Consequently, producers may benefit from improved production efficiency, reduced economic losses associated with heat stress, and enhanced compliance with increasingly stringent animal welfare standards. Integrating effective environmental control strategies into commercial broiler housing therefore represents not only a biological intervention but also a practical management approach that supports sustainable, profitable, and welfare-oriented poultry production in humid tropical regions (He et al., 2019; Liu et al., 2020; Elwakeel, 2025).

6. Research Gaps and Future Directions

Despite substantial progress in environmental mitigation research over the past decade, several critical gaps remain. First, the majority of studies focus primarily on short-term production outcomes within a single production cycle. Longitudinal assessments evaluating cumulative stress adaptation, immune resilience, and long-term flock health under repeated heat exposure remain limited (Rojas-Downing et al., 2017; Nawab et al., 2018). Such studies are essential for understanding chronic climate-related impacts on broiler production sustainability.

Second, while engineering-based cooling strategies are well documented, comparative cost-benefit and energy-efficiency analyses remain insufficient, particularly in low- and middle-income tropical regions. As energy demand increases in mechanically ventilated systems, integrating renewable energy sources and low-energy cooling technologies represents an important research frontier. Sustainable cooling solutions must balance thermal mitigation effectiveness with environmental footprint reduction and operational feasibility.

Third, future research should prioritize integrated precision livestock farming (PLF) approaches combining real-time environmental sensing, behavioral monitoring, and predictive analytics. Artificial intelligence-assisted climate control systems have demonstrated potential for optimizing ventilation and cooling efficiency dynamically; however, large-scale validation under commercial tropical conditions remains limited (Elwakeel, 2025; Gad et al., 2020). Expanding interdisciplinary collaboration between animal scientists, engineers, and data scientists will be critical to advancing adaptive climate-resilient poultry housing systems.

Overall, the highest research priority should be the development and validation of integrated precision environmental control systems that combine energy-efficient cooling technologies, real-time environmental monitoring, and data-driven decision support under commercial humid tropical conditions. Addressing this priority would not only improve broiler productivity and animal welfare but also reduce energy consumption, production losses, and operational costs associated with heat stress. In the longer term, advances in these technologies have the potential to enhance the sustainability, resilience, and economic competitiveness of the poultry industry, particularly in tropical regions where climate change is expected to intensify thermal stress challenges.

CONCLUSION

This systematic review demonstrates that integrated environmental housing and cooling strategies are effective in mitigating heat stress and improving broiler performance under humid tropical conditions. Among the reviewed interventions, evaporative cooling, tunnel ventilation, and automated climate control consistently enhanced growth performance, feed efficiency, survival rate, and physiological welfare by reducing thermal stress and improving microclimate stability. However, the effectiveness of these technologies depends on local climatic conditions, particularly ambient humidity, emphasizing the need for adaptive and integrated environmental management rather than reliance on a single cooling strategy. Overall, the findings support the adoption of energy-efficient, humidity-adaptive, and welfare-oriented environmental control systems to improve the sustainability and resilience of tropical broiler production. Future research should prioritize long-term field validation, economic feasibility assessments, and the integration of precision livestock farming technologies to facilitate practical implementation and strengthen climate-resilient poultry production systems.

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