Research Article

Heat Stress Impacts on Broiler Performance and Mortality in Non-Cooled Equatorial Housing

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Abstract | This study investigated how high temperature and humidity affect growth and survival of broilers raised in open-sided houses in equatorial Indonesia. We monitored 180 Cobb 500 broilers across dry and rainy seasons, recording temperature, humidity, body weight, feed intake, and daily mortality. Midday temperatures averaged 32.4°C with 56.6% humidity, well above the thermoneutral zone for broilers. Cumulative weekly heat exposure explained 61% of variation in body weight (P<0.01) and 54.5% of variation in feed intake (P<0.001). Mortality risk increased when late-afternoon (4:00 PM) temperatures exceeded 32.5°C or when the temperature-humidity index passed 35.80, though the humidity index showed poor ability to distinguish safe from dangerous days (only 9% specificity). Birds ate less and grew slower during dry season compared to wet season. Heat-stressed broilers had a significant growth deficit, with an average relative live weight (RLW) of -552g at day 35. This is roughly 22% below the Cobb 500 target weight, highlighting the negative impact of heat stress on performance. We conclude that prolonged afternoon heat, not just midday peaks, drives mortality in open-sided tropical houses. Farmers should focus cooling efforts on late afternoon hours when birds struggle to shed accumulated heat before nightfall.

Keywords | Broiler, Equatorial climate, Growth performance, Heat stress, Mortality, Temperature-humidity index

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INTRODUCTION

Domestic birds are now extensively reared as a primary source of animal-based food. Over the years, breeders have selected birds for enhanced meat and egg production, leading to the development of high performance commercial flocks. In these systems, birds were maintained under optimal thermal, nutritional, and housing conditions in accordance with established commercial broiler management guidelines (Olanrewaju *et al*., 2018). Among these, broilers are specifically bred for rapid growth and high meat yield. However, achieving their genetic potential depends heavily on stable environmental conditions. Recent regional climate studies have recorded increases in mean daily maximum temperatures in Central Java between 2010 and 2023, indicating a gradual escalation in heat exposure risk for open-sided broiler production systems in this location.

Fluctuations in environmental temperatures, whether too low or excessively high can significantly impair broiler productivity, often resulting in inconsistent growth among individuals within the same flock (Nawab *et al*., 2018). The degree to which animals are affected by heat stress is influenced by multiple variables, including their species, stage of growth, and the type of management system in place (Huang *et al*., 2015). In the poultry sector, heat induced stress contributes to notable economic setbacks, with industry wide losses estimated to range from $128 million to $165 million annually (Huang *et al*., 2015).

Modern broiler strains are genetically selected for fast growth, typically achieving a body weight of 2 kilograms or more in less than eight weeks (Tallentire *et al*., 2016). However, this level of growth is attainable only when environmental temperatures remain within the thermoneutral range of 18 to 24 °C (Charles, 2002; Kim *et al*., 2025). Exceeding these thresholds can overwhelm the birds' thermoregulatory abilities, resulting in elevated internal body temperatures. This thermal imbalance adversely affects physiological functions, causing reductions in growth rate, feed utilization efficiency, and overall product quality (Kim *et al*., 2025).

Poultry, like mammals, are classified as homeothermic animals, meaning they regulate their internal body temperature within a narrow, stable range despite variations in ambient conditions. In adult broilers, normal body temperature typically falls between 41–42 °C. To cope with changes in external temperatures, they lose heat through evaporation, radiation, conduction, and convection (Khan *et al*., 2023). When the surrounding temperature exceeds the broiler's body temperature, conduction and convection may actually lead to heat gain, prompting the body to depend more heavily on evaporative cooling to release excess heat. Since poultry lack sweat glands, thermal stress is often assessed using Temperature-Humidity Index (THI).

Poultry routinely face multiple sources of stress, both environmental and physiological. While brief exposures to high temperatures commonly referred to as acute heat stress, may cause only minor disruptions, sustained or repeated exposure can significantly impair productivity and compromise welfare (Virden and Kidd, 2009). The impact of heat stress varies according to its duration. For instance, a six-hour exposure to 36 °C may cause immediate but short-lived physiological changes, while continuous exposure over three weeks may result in chronic stress symptoms. Acute stress is frequently linked to sudden increases in mortality (Rasheed, 2016). Whereas chronic stress leads to long-term consequences such as reduced growth and impaired performance. Studies have shown that ongoing or recurring heat exposure can reduce broiler growth rates by 36% and 21%, respectively (Pareja *et al*., 2018).

Heat stress in climate-controlled houses has been extensively studied; but less is known about broilers raised in small-scale, open-sided systems that are common in equatorial regions. Smallholder farmers frequently use these production strategies, which expose broilers to changing environmental circumstances. As a result, yet less known regarding the environmental stressors and how they affect broiler performance in these environments. The necessity for study on broilers raised in tropical climates in open-sided housing is highlighted by this knowledge gap. Although heat stress's effects on the world economy have been extensively documented, practical mitigation techniques for small-scale, open-sided systems remain underexplored.

This study aims to guide affordable and practical heat stress management strategies for broilers raised in tropical regions, where advanced climate-control technology is typically unavailable. Therefore, this study was conducted to investigate the effect on fattening performance and mortality in broilers raised in tropical climate with high ambient temperatures and humidity conditions throughout the year under conditions of limited environmental control.

MATERIALS AND METHODS

Study location and housing system

We conducted this study in a privately owned broiler house constructed from bamboo, located in Nglipar, Gunungkidul, Yogyakarta, Indonesia under collaboration project supported by Faculty of Veterinary Medicine Universitas Gadjah Mada. The structure featured an open-sided design, elevated above the ground and supported by wooden pillars. Within the facility, five individual enclosures measuring 1 meter by 1 meter were prepared. Each pen was lined with a 5 cm layer of rice husk as bedding material, and each enclosure contained 12 birds (12 birds/m^2). We acknowledge this represents relatively high stocking density. However, this reflects common smallholder practice in open-sided tropical housing systems. Tube feeders were used for feed distribution and bell-type automatic drinkers were used for water supply installed in every enclosure to ensure adequate access to feed and water.

A two phases feeding program was implemented throughout the trial. Broilers were provided with starter rations up to 21 days of age, after which they received finisher diets until the study concluded. The starting diet (24% crude protein; 3,075 kcal/kg metabolizable energy) and finisher diet (20% crude protein; 3,200 kcal/kg metabolizable energy) were developed in accordance with the nutritional recommendations for Cobb 500 broilers under tropical production circumstances (Cobb-Vantress, 2022). Environmental factors were continually monitored from October 16, 2023 to February 2, 2024, to capture climatic fluctuation during both the dry and rainy seasons. However, each broiler production cycle lasted 35 days, and performance data were collected over these specified grow-out periods.

Experimental design and sampling

The study was carried out between October 16, 2023, and February 2, 2024, during natural environmental variation included periods commonly associated with dry and rainy seasons. However, the study was not designed as a controlled seasonal comparison. Instead, the objective was to evaluate broiler performance under naturally occurring thermal conditions in an open-sided tropical housing system.

Based on logistical capacity, pen availability, and compatibility with similar environmental stress studies carried out under small-scale production systems, the sample size of 180 broilers was established. Before the experiment, no formal a priori power analysis was carried out. Nevertheless, pen-level weighted regression modeling and repeated weekly measurements were included in the study design, which improved statistical sensitivity.

The key outcome variable (Residual Live Weight, RLW) showed a significant impact size (R^2= 0.61) according to post hoc analysis, indicating that the sample size was adequate to identify significant relationships between cumulative heat load (∑HL) and growth performance. One of the study's stated limitations is the lack of a formal power calculation. A further limitation of this study is the absence of a formal a priori power analysis; although the observed effect size suggests adequate sensitivity, future studies should incorporate prospective power calculations to strengthen experimental design rigor.

When a bird died, we replaced it with a same-age bird from a reserve flock to maintain consistency within treatment groups. However, the need to replace dead broilers during the trial could increase unpredictability and be a potential restriction of the study. To assess the potential influence of replacement birds, studies were conducted with and without these individuals. Because no significant changes were found in the key outcome variables, replacement birds were included in the final dataset. To reduce disruption to flock dynamics, replacement broilers were carefully matched by age, health state, and initial body weight category.

Individual-level mortality and growth data were collected, and studies concentrated on residual feed parameters and RLW, which take pen variability into consideration. Broilers in open-sided tropical systems are especially susceptible to environmental stressors is supported by the fact that overall trends in performance and mortality stayed constant. This underscores the significance of low-cost, practical heat stress mitigation strategies for smallholder producers.

Birds and management

A total of 180 broilers were involved at the outset of the trial, and they provided pen-level performance data throughout the production cycle. To investigate development variance, a representative subsample of 60 birds had their individual body weights measured on day 14, 21, 28 and 35. The following performance measures, such as body weight increase, feed intake, and feed conversion ratio, were determined at the pen level using aggregated data.

When birds died, they were replaced with animals of comparable age and body weight from a reserve flock to provide a continuous stocking density. Sensitivity analysis revealed that include replacement birds had no significant effect on the results; therefore, all birds were retained in the final dataset. All statistical analyses were conducted using the pen as the experimental unit. Pen-level weighted regression modeling was used to assess the correlation between ∑HL and performance factors. In addition, repeated weekly assessments were used to account for temporal fluctuation and increase statistical sensitivity. Although no a priori power analysis was undertaken, a post-hoc evaluation of effect size was employed to determine the appropriateness of sample size (Figure 1).

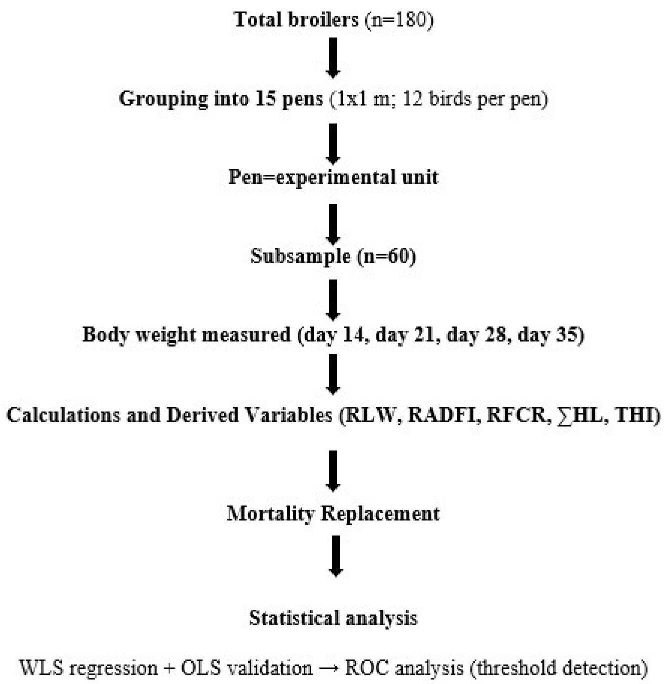

Figure 1: Flowchart of broiler sample size and measurement design.

A total of 180 broilers were divided into 15 pens (1 x 1 m; 12 birds per pen), with each pen serving as an experimental unit. A representative subsample of 60 birds was utilized to determine individual body weight on days 14, 21, 28, and 35. The study collected environmental data (temperature and humidity), feed consumption, body weight, and mortality. Data were analyzed using pen-level weighted regression and repeated weekly measurements to assess the correlation between ΣHL and performance results. Replacement birds were used to maintain stocking density, with no significant impact on results.

Environmental monitoring

Ambient temperature and relative humidity were recorded three times daily at 07:00, 11:00, and 16:00, we used these measurements to calculate THI. In open-sided tropical housing systems, early morning circumstances, late-morning temperature rise, and late-afternoon peak thermal exposure are usually the most crucial heat stress periods. These time points were chosen to capture these situations. Since there was no continuous 24-hour monitoring, the dynamics of thermal recovery at night were not directly evaluated. Instead of being isolated peak values, the 16:00 data were thought to represent the cumulative midday heat burden.

The equation suggested by Renaudeau *et al.* (2012) was used to compute the THI, a composite measure of environmental heat load that takes into account both relative humidity and ambient temperature. This formulation was first created for mammals and does not accurately represent the thermoregulatory physiology of birds, who mostly rely on respiratory evaporation rather than sweating, despite the fact that it has been extensively used in investigations of heat stress in tropical environments. The predictive utility of this approach for evaluating heat stress in broilers has been validated by numerous research on tropical poultry. This formulation is physiologically useful for broilers that predominantly rely on respiratory evaporation for thermoregulation because it integrates dry-bulb temperature and relative humidity in a way appropriate for humid conditions. The goal of this study was to apply a proven and widely used heat-stress indicator suitable for tropical, open-sided housing systems rather than to compare indices, despite the existence of various alternative poultry-specific THI equations.

$$THI = t - [(0.31 - 0.31 \times (RH/100)) \times (t - 14.4)]$$

t, dry bulb temperature in degrees celsius; RH, Percentage relative humidity.

Data collection (growth, feed intake, mortality)

We weighed individual birds on days 14, 21, 28, and 35 of the experiment. These target weights correspond to Cobb 500 mixed-sex performance standards under commercial management conditions (Coob-Vantress, 2022). To calculate weekly weight gain, the live weight recorded at the start of the week was subtracted from that at the end, and the difference was then divided by the number of days in the interval. Feed intake per week was determined by deducting the leftover feed from the total quantity provided in each pen. Average daily feed consumption was subsequently obtained by dividing the weekly intake by the number of days and the total number of broiler. Feed conversion ratio (FCR) was calculated as the ratio between feed consumed and body weight gained over the corresponding period. Mortality events were noted on a daily basis throughout the study.

Calculations and derived variables (RLW, RADFI, RFCR, ΣHL, THI)

The standard live weights for days 14, 21, 28, and 35 were set at 570 g, 1116 g, 1783 g, and 2510 g, respectively, based on growth benchmarks for mixed-sex broilers as specified in the Cobb 500 performance guide. During the experiment, actual individual body weights were compared against these reference values. The difference between the observed and standard weights was calculated to determine the RLW, which served as a performance indicator relative to the expected norm.

Reference values for weekly feed intake in mixed-sex Cobb 500 broilers were determined by averaging the daily feed consumption provided by the breeding company for each respective week of the experiment. Accordingly, feed intake from days 15–21, 22–28, and 29–35 was recorded as 104.57 g, 148.43 g, and 182.29 g, respectively. The corresponding weekly feed conversion ratios (FCR) for these intervals were reported as 1.34, 1.56, and 1.73 grams of feed per gram of weight gain.

The residual average daily feed intake (RADFI) and residual feed conversion ratio (RFCR) were computed as deviations from age-specific Cobb 500 mixed-sex performance requirements. RADFI was specifically defined as follows:

RADFI= Observed ADFI – Expected ADFI (Coob-Vantress, 2022).

The RFCR was defined as:
RFCR = Observed FCR - Expected FCR (Coob-Vantress, 2022).

Expected values were calculated using Cobb 500 performance targets at the same age under commercial management conditions (Coob-Vantress, 2022). Positive or negative residual values imply over- or under-performance in relation to breed requirements. The weekly heat load (ΣHL) for Cobb 500 broilers was estimated by

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adding the daily positive deviations between the recorded ambient temperature and the age-specific recommended thermoneutral temperature. The recommended temperatures for each production week (as shown in Table 1) were specifically used as reference values in the calculation. Only temperatures over the specified upper thermoneutral limit contributed to ΣHL, measuring the cumulative heat burden above ideal conditions.

Table 1: Temperature and relative humidity guidelines for Cobb 500 broilers

Days	Relative humidity (%)	Temperature (°C)
14	40-60	27
21	50-70	24
28	50-70	21
35	50-70	19

In order to account for variations in relative humidity, ΣHL was further modified. Sensitivity analysis, however, showed that taking uncorrected temperatures into account did not significantly change the direction or intensity of relationships between ΣHL and performance. The documented measurement uncertainty of low-cost digital temperature sensors used in field conditions was reflected by a correction factor of ±2 °C (Abdinoor *et al*., 2025). This correction allows for instrument tolerance rather than arbitrary alteration of recorded data.

Statistical analysis

Before starting regression analysis, the distributions of residual performance variables (RLW, RADFI, and RFCR) were assessed. Normality was determined using Shapiro-Wilk tests and visual examination of Q-Q plots and histograms, whereas homoscedasticity was investigated using residual-versus-fitted plots. When heteroscedasticity was identified, Weighted Least Squares (WLS) regression was used to increase variance stability. These diagnostic tests verified that the model assumptions were reasonably satisfied.

To assess the influence of environmental conditions on broiler performance, the effects of ambient temperature, relative humidity, and THI (as independent variables) on the residuals of live weight, daily feed intake, and feed conversion ratio (as dependent variables) were analyzed using Weighted Least Squares Regression. A forward selection process was used as an exploratory approach to discover the most influential environmental predictors while reducing overfitting due to the small sample size. Recognizing the acknowledged limitations of automated selection approaches, candidate variables were originally selected based on biological plausibility and prior research, with final model inclusion influenced by both statistical contribution and theoretical significance. This method ensured that model creation was not simply based on statistical criteria.

Although mixed-effects models are suited for hierarchical data (e.g., birds nested within pens), this study's analyses were undertaken at the pen level because both environmental and performance factors were aggregated by enclosure. Thus, the pen acted as the experimental unit, limiting the significance of within-pen nesting effects. To address the heteroscedasticity discovered during residual diagnostics, where outcome variance increased with age, we used Weighted Least Squares (WLS) regression with an inverse-variance weighting scheme. Unweighted ordinary least squares (OLS) models were also fitted for robustness, and they showed similar coefficient directions and statistical significance, demonstrating that the major conclusions were not affected by the weighting method.

A Receiver Operating Characteristic (ROC) curve analysis was used to evaluate the discriminative ability of temperature and THI thresholds in predicting mortality risk. The diagnostic accuracy of each factor was evaluated based on the area under the ROC curve (AUC), and the two most influential parameters were selected. The optimal cut-off points were determined using the positive likelihood ratio, calculated as the ratio of sensitivity/1-specificity, to maximize the predictive power of each climatic indicator. Exposure to chronic heat stress resulted in a significant loss in broiler growth, with RLW at day 35 average -552 g (≈22% below goal weight). This highlights the impact of high ambient temperatures on broiler performance and welfare.

Mortality data

Throughout the trial, mortality rates were not routinely reported. Instead, broiler mortality was estimated indirectly using environmental data in predictive modeling. ROC analysis was used to determine the relationship between temperature, relative humidity, and Temperature-Humidity Index (THI) values and the probability of death. As a result, the findings concentrate on the prediction ability of these climatic factors rather than absolute death rates.

RESULTS AND DISCUSSION

Descriptive statistics summarizing broiler performance and climatic parameters recorded during the experimental period are presented in Table 2. Only two of the 35 observation days during the production cycle had ambient temperatures that were within the acceptable thermoneutral range. At the onset of the study, the actual body weights at days 14, 21, 28, and 35 are shown in Supplementary Table S3, together with the matching residual live weight (RLW) values. This innovation enables direct comparison of observed weights to Cobb 500 performance requirements, ensuring increased openness in performance evaluation. Multiple linear regression showed climatic variables were modeled as predictors and residual live weight (RLW) served as the dependent variable, are presented in Table 3.

Table 2: Mean values and standard deviations of live weight, average daily weight gain, feed intake, feed conversion ratio residuals, and environmental parameters

Variable	$\bar{x}$	Sd	n
RLW (g)	-552,1	1230,2	540
RADFI (g)	-29,21	16,80	45
RFCR (g/g)	0,440	0,683	45
Heat 07:00 am (°C)	27,9	1,4	66
Heat 11:00 am (°C)	34,1	1,5	66
Heat 04:00 pm (°C)	31,3	1,8	66
RH 07:00 am (%)	90,8	2,7	66
RH 11:00 am (%)	54,2	3,5	66
RH 04:00 pm (%)	54,3	3,8	66
THI 07:00 am	31,49	3,10	66
THI 11:00 am	36,62	3,21	66
THI 04:00 pm	34,08	2,36	66
ΣHL	167,49	110,00	45
ΣTHI>27,8	128,01	31,84	45

RLW; Residual Live Weight, RADFI; Residual Average Daily Feed Intake, RFCR; Residual Feed Conversion Ratio, RH; % Relative Humidity, THI; Temperature-Humidity Index, ΣHL; The cumulative Heat Load, ΣTHI>27,8; The cumulative Stress Index. "n" denotes the number of daily observations for environmental measurements (RH and THI), and n differs among parameters due to data availability: RLW (n=40) excludes 5 birds with missing final body weight; RADFI (n=45) includes all pens; RFCR (n=45) calculated from available feed and weight data. Environmental measurements (n=66) represent 66 days of valid continuous recordings; days with instrument malfunction or missing data were excluded. RLW= Actual body weight – Cobb 500 target body weight, and negative values indicate underperformance relative to the standard.

Environmental variables accounted for 61% of RLW variation (R^2 = 0.61), with ΣHL being the most significant predictor. This confirms previous results that ambient temperature is a significant regulator on broiler development and metabolism (Altan *et al.*, 2003). Similar trends have been seen, indicating that heat stress reduces body weight, particularly after 3 weeks of age. Liu *et al.* (2020) observed that there was no significant difference in broiler body weight during the first three weeks of life when broilers were raised under constant environmental temperatures of 35°C and 24°C. However, during the 4th to 6th week, broilers reared in high-temperature environments exhibited substantially lower body weights, indicating that the detrimental effects of heat become more pronounced with age.

Supporting these findings, Liu *et al.* (2020); Olfati *et al.* (2018); and Ruff *et al.* (2020) reported that broilers subjected to temperature-induced stress did not show significant differences in body weight during the initial 21 days of rearing. Nevertheless, during the later growth period (days 21–42), those exposed to thermal stress achieved approximately 26% less final body weight compared to broiler raised under optimal thermal conditions. The current findings are similarly consistent with studies that have shown lower development under both acute and chronic heat stress situations (Habibian *et al.*, 2014).

This finding aligns with previous studies indicating that weight loss due to heat stress is less pronounced during the early growth stages of broilers. Although the THI and the cumulative stress index (ΣTHI>27.8) are composite metrics that incorporate both ambient temperature and relative humidity, they were not effective in accurately predicting weight loss in this study. Unlike other climatic parameters, which remain constant across age groups, the ΣHL is age-sensitive, reflecting the decreasing requirement for optimal environmental temperatures as broilers mature. Consequently, ΣHL values were higher in later weeks due to the widening gap between actual temperatures and age adjusted optimums. With a regression value of −3.40, ΣHL was shown to be the best predictor of growth performance, meaning that every 1°C increase in weekly heat load was associated with an average decrease of 3.4 g in broiler live weight.

Table 3: Weighted least squares regression analysis for residual live weight (RLW).

Predictor variable	B (Coefficient)	Standard Error (SE)	t-value	P-value	95% confidence interval
Intercept	12,84	4,21	3,05	0,004	4,31 to 21,37
ΣHL (°C/week)	-3,40	0,78	-4,36	<0,001	-4,99 to -1,81
Morning THI (07:00)	-0,92	0,63	-1,46	0,152	-2,20 to 0,36
Afternoon THI (16:00)	-1,08	0,71	-1,52	0,136	-2,53 to 0,37

Dependent variable: Residual Live Weight (RLW). Model: Weighted Least Squares Regression (age-weighted). Model statistics: R^2 = 0.61; Adjusted R^2 = 0.58; F = 15.42; P < 0.001. The cumulative weekly heat load (ΣHL) was identified as the most significant predictor of RLW (P < 0.001). Other climatic parameters, including morning and afternoon THI values, were not statistically significant predictors in the final model. Only predictors retained in the final model are shown. Variables tested but excluded are reported in the Supplementary Table S1. Multicollinearity diagnostics are provided in Supplementary Table S2.

We found that in open-sided tropical settings, broiler development was more affected by prolonged heat stress than by humidity. The extra energy needed for thermoregulation is represented by ΣHL, which is the departure from age-specific thermoneutral conditions. In a study investigating acclimatization to heat, Abdelqader and Al-Fataftah (2014) subjected broilers to acute heat stress (38 °C). We observed no mortality in broiler previously acclimated to high temperatures, whereas mortality reached 25% in non-acclimated groups.

Recent studies indicate that broiler mortality under heat stress shows mixed results depending on acclimation and environmental controls. For instance, investigations have shown that broilers maintained under elevated temperatures (around 35 °C) and moderate conditions (24–26 °C) sometimes exhibit no significant differences in mortality when high ventilation or cooling systems are used Liu *et al.* (2020); Sohail *et al.* (2012), and Teyssier *et al.* (2022). Heat acclimation is a critical factor: in one controlled trial, acute exposure to 38 °C resulted in 0% mortality among broilers preconditioned to heat, while mortality reached ~25% in non-acclimated birds (Ahmed *et al.*, 2021).

Other studies have observed spikes in mortality once ambient temperatures exceed the 35 °C threshold (Vecerek *et al.*, 2006). In a Cobb-strain trial, mortality rates of ~36% were reported under 34–36 °C compared to ~6% under standard (21 °C) thermal conditions (Awad *et al.*, 2020). Similarly, significant drops in survival rates from 80% at ~27 °C to 49% at ~39 °C were documented, although recovery was possible after temperatures normalized (Biswal *et al.*, 2022). Environmental stress indicators also play a role. Broiler mortality has been shown to correlate positively with elevated THI values. Furthermore, spray-cooling systems has been consistently associated with lower mortality rates than systems using only forced-air fans (Lara *et al.*, 2013; dos Santos, 2017).

In the present study, mortality was found to increase with advancing age under high-temperature conditions. This is likely related to the progressive increase in metabolic heat production as body weight increases, which in turn elevates the thermal load. Although midday ambient temperature and THI values were consistently the highest, they were not effective predictors of mortality. Instead, measurements taken at 16:00, when ambient temperature exceeded 32.5 °C and THI surpassed 35.80, were more closely associated with increased mortality. This suggests that the duration of thermal exposure, rather than peak temperature alone, may play a more significant role in heat-induced mortality.

Heat stress had a significant impact on broiler growth, resulting in an average RLW of -552g at day 35, 22% lower than the Cobb 500 goal weight. ROC analysis revealed that afternoon THI (04:00 pm) had intermediate predictive capacity (AUC = 0.709), while morning THI had low specificity (9%), resulting in false alarms on 91% of days. The calculated LR+ for the AM THI threshold was 0.599, showing weak discriminatory ability. These findings show that THI thresholds should be supplemented with behavioral and production indicators rather than utilized alone to make on-farm decisions.

The fact that environmental data were taken at predetermined daytime intervals rather than continuously throughout a 24-hour period is one of the study's limitations. As a result, temperature drops at night and possible recovery from heat stress during the day were not directly measured. Future research may increase understanding of diurnal recovery capacity and clarify mortality threshold estimates by include nighttime thermal profiles, even though late-afternoon values were substantially related with death and probably reflect cumulative heat burden.

Furthermore, birds in open-sided equatorial housing systems are chronically suited to warm climes, and minor increases in early-morning temperature may lower the energy expenditure associated with cooler nocturnal conditions. This could have a temporary impact on feed utilization dynamics while maintaining the well-established deleterious consequences of protracted or cumulative heat load. The model explains a little amount of variance (R^2= 0.21), demonstrating that RFCR is influenced by many biological and environmental factors.

Feed intake increased with age, but decreased considerably with ΣHL (R^2= 0.545, $P < 0.001$). This is consistent with previous study indicating that heat stress reduces appetite via thermoregulatory and hormonal mechanisms. Exposure to elevated ambient temperatures activates peripheral thermal receptors, which inhibit the hypothalamic appetite center, resulting in suppressed feed intake (Al-Fataftah and Abu-Dieyeh, 2007). Broiler feed intake is often lowered during heat stress due to appetite suppression and behavioral changes that limit metabolic heat output (te Pas *et al.*, 2020). Moreover, heat stress has been shown to reduce the circulating levels of metabolic hormones such as triiodothyronine (T3) and thyroxine (T4), which play key roles in regulating metabolic rate (Bartlett and Smith, 2003; Liu *et al.*, 2022). Feed intake regulation is multifactorial, including genetic and environmental interactions. Since broilers are typically fed ad libitum, feed seeking behavior is minimal, making high voluntary feed intake a desirable trait in commercial broiler production. Feed intake is influenced by a combination of genetic factors, environmental conditions, and their interactions (Özentürk and Yıldız, 2021). However, ΣHL was able to more effectively capture this relationship than THI, which is likely due to its age-sensitive structure.

The THI threshold discovered in this study should be viewed with caution and not used for real farm decision-making because its predictive accuracy was poorer than chance. This restriction implies that THI alone may not fully convey the complexities of heat stress dynamics under the settings investigated. In contrast, ΣHL showed greater and more consistent relationships with broiler performance indicators, suggesting that ΣHL may be a more robust and physiologically meaningful biomarker of heat stress in this setting.

ROC analysis revealed that afternoon (16:00) THI and ambient temperature were significant predictors of mortality, with moderate discriminative capacity (AUC = 0.70). However, low specificity and likelihood ratios suggest that the model has little predictive utility on its own. Similar results have been observed, with THI showing inconsistent relationships with mortality. Similarly, Kim *et al*. (2025) found no significant differences in mortality among broilers under thermal stress when evaluated using the THI. Broiler mortality rates during heat stress vary greatly depending on acclimation and environmental management. For example, under acute stress, heat-acclimated birds died at a rate of zero, compared to 25% in non-acclimated groups.

The findings suggest that the length of heat exposure is more important than the peak temperature. Late-afternoon circumstances were more significantly related with mortality than midday peaks, most likely due to sustained heat load that hampered recovery before nighttime. When environmental temperatures exceed the thermoneutral zone, broilers adapt their behavior to manage thermal stress. This includes a reduction in feed intake and a compensatory increase in water intake (Nawaz *et al*., 2021). In response to heat intensity, broilers spread their wings and pant characterized by open mouth breathing, as a means to increase evaporative heat loss. If thermoregulation fails to maintain internal homeostasis, hyperthermia can occur, potentially leading to mortality. Broilers are particularly susceptible to elevated ambient temperatures due to their lack of sweat glands, full feather coverage, and rapid growth rate (Nawaz *et al*., 2021). In open-sided tropical systems, incomplete nighttime cooling further exacerbates cumulative heat stress.

In the multiple linear regression model assessing the RFCR, THI recorded at 07:00 a.m. emerged as a statistically significant predictor ($P < 0.05$). The RFCR model explained 21% of the variance ($R^2 = 0.21$), demonstrating that thermal factors had only a minor impact on feed conversion variability, as summarized in Table 5. This finding shows that feed efficiency is influenced by a variety of other environmental and management parameters beyond those assessed in the current study. These results demonstrate how feed conversion in broilers raised in open-sided, tropical environments is complex.

Multiple factors influence feed conversion ratio, including ambient conditions, feed composition, and bird behavior, all of which were not fully reflected by the thermal variables assessed in this study. As a result, this finding should be taken as evidence of a partial link rather than a strong predictive relationship, emphasizing the complexities of FCR control under commercial raising circumstances.

Average daily feed intake during days 14–21 was 84.6 ± 0.86 g per bird, 120.34 ± 0.77 g during days 21–28, and 146.87 g during days 28–35 of the experimental period representing the observed intake rather than the residual average daily feed intake (RADFI) presented in Table 2. The regression analysis revealed that ΣHL was significantly associated with RADFI. Increasing ΣHL resulted in a decrease in RADFI (B = -0.113 ± 0.016, t = -7.06, $p < 0.001$). Table 4 shows detailed regression coefficients. The value indicates a statistically robust relationship, but without implying unrealistically extreme estimation precision.

Table 4: Weighted least squares regression analysis for residual average daily feed intake (RADFI).
Dependent variable: RADFI. Weighting factor: Week

Predictor	B	Std. Error	t	P-value
Constant	-10,333	2,766	-3,73	< 0.001
ΣHL	-0,113	0,016	-7,06	< 0.001

R^2= 0.545. Only predictors retained in the final model are shown. Variables tested but excluded are reported in the Supplementary Table S1. Multicollinearity diagnostics are provided in Supplementary Table S2.

Table 5: Weighted least squares regression analysis for residual feed conversion ratio (RFCR).
Dependent variable: Residual feed conversion ratio (RFCR). Weighting factor: Week

Predictor	B	Std. Error	t	P-value
Constant	3,617	0,940	3,85	< 0.001
THI 07:00 am	-0,101	0,030	-3,37	0.002

R^2= 0.210. Only the significant predictor retained in the final weighted least squares model is presented. Non-significant predictors tested in the model selection process are reported in the Supplementary Table S1. Multicollinearity diagnostics are provided in the Supplementary Table S2.

Feed conversion ratios (FCR) were determined to be

1.74±0.04g/g, 2.37±0.06g/g, and 1.90±1.3g/g for the periods spanning days 14–21, 21–28, and 28–35, respectively. Significant susceptibility to prolonged high temperatures was shown by broilers raised in the open-sided tropical housing. While daily fluctuations in humidity seemed to have less of an impact, weekly cumulative temperature deviations from the Cobb 500 suggested ΣHL were highly linked to decreased body weight increase.

ROC curve analysis demonstrated that THI and ambient temperature recorded at 04:00 p.m. were significant predictors of mortality in broilers ($P < 0.05$). The area under the curve (AUC) for THI at 04:00 p.m. was 0.709, with a 95% confidence interval of 0.537–0.882, indicating fair discriminative ability in predicting the outcome. The AUC for ambient temperature measured at 04:00 p.m. was 0.694 (95% CI: 0.529–0.858), demonstrating prediction ability comparable to that of THI measured at the same time point, implying that ambient temperature alone may provide roughly identical predictive information under the settings of this investigation.

Other climate variables measured at different times did not significantly predict mortality outcomes (P > 0.05). The ROC analysis indicated that a THI threshold of greater than 35.80. Environmental variables, such as ambient temperature, relative humidity, and THI, are represented as mean ± standard deviation values based on monitoring measurements as recorded in Table 6 was the best cutoff for predicting heat stress risk. However, because the THI equation used in this study was initially designed for sheep, this value should be considered an empirical, study-specific operational threshold rather than a verified physiological breakpoint for broiler chickens.

Supplementary Table S1 that lists mortality events by pen along with the date of occurrence and the matching bird age (days) has been shown. Using the ROC-derived cutoff, the THI threshold (>35.80) had a sensitivity of 54.5% and a specificity of 9%, for a positive likelihood ratio (LR+) = sensitivity/(1-specificity) = 0.545/(1-0.09) = 0.545/0.91 = 0.599. An LR+ score less than 1 suggests that the threshold performs worse than chance and may impair, rather than increase, the capacity to accurately detect mortality risk. These findings emphasize the limits of using non-species-specific THI models in poultry, emphasizing the importance of validated, broiler-specific thermal stress indicators.

Broilers consume a large portion of their daily feed in the cooler early hours, morning thermal conditions may have a disproportionate effect on digestive efficiency, metabolic partitioning, and subsequent feed consumption. Thus, morning THI may serve as a measure of recovery capacity rather than acute daily heat load. In contrast, afternoon THI reflects a brief peak in exposure, during which feed intake is frequently decreased and behavioral heat-avoidance behaviors take precedence. Once growth and intake variance are factored into the RFCR model, such acute stress may reduce overall intake but have no effect on residual feed efficiency. Thus, morning THI may capture modest physiological changes influencing feed conversion more consistently than afternoon peaks.

In comparison, for ambient temperature at 04:00 p.m., a threshold of >32.5 °C recorded with the same sensitivity (54.5%) but slightly higher specificity (14.8%) and a positive likelihood ratio of 3.692. These findings suggest that broiler mortality risk is more effectively anticipated using late-afternoon THI values rather than other climatic indicators, emphasizing the importance of afternoon heat stress management in open-house production systems.

Mortality patterns

This study did not disclose actual mortality numbers or percentages, hence no weekly or seasonal death distributions are offered. Instead, death trends were analyzed using predictive modeling (Table 6), and ROC analysis was utilized to investigate the diagnostic potential of environmental indicators in identifying increased mortality risk. Measurements obtained in the afternoon had a higher

Table 6: ROC analysis of climate parameters predicting broiler mortality with diagnostic metrics.

Variable	Cut-off	Sensitivity (%)	Specificity (%)	LR+	LR–	AUC	Std. Error	P value	95% CI Lower	95% CI Upper
Heat 07:00 am (°C)	28,5	55	52	1,15	0,87	0,546	0,106	0,596	0,339	0,753
Heat 11:00 am (°C)	30,2	60	58	1,43	0,69	0,599	0,077	0,258	0,447	0,750
Heat 04:00 pm (°C)	32,8	72	65	2,06	0,43	0,694	0,084	0,026	0,529	0,858
RH 07:00 am (%)	68	65	61	1,67	0,57	0,616	0,096	0,183	0,428	0,804
RH 11:00 am (%)	70	58	54	1,26	0,78	0,563	0,069	0,472	0,426	0,699
RH 04:00 pm (%)	72	63	62	1,66	0,60	0,617	0,063	0,180	0,494	0,740
THI 11:00 am	75	56	51	1,14	0,86	0,548	0,102	0,585	0,347	0,748
THI 04:00 pm	79	70	66	2,06	0,46	0,709	0,088	0,016	0,537	0,882

*Cut-offs are based on the Youden index. LR+ = Sensitivity / (1 – Specificity), LR– = (1 – Sensitivity) / Specificity.

predictive value than morning measurements, indicating that persistent heat exposure is more relevant than transient temperature conditions. However, because absolute mortality figures were not available, these findings should be seen as suggestive rather than definitive. Future research should employ substantial mortality data to confirm and enhance these predictive findings.

CONCLUSION

We found that heat stress significantly reduces feed intake in broilers, thereby limiting their ability to reach their full genetic potential for body weight gain. Broiler performance fluctuated during the production cycle due to differences in ΣHL. Periods with significantly decreased thermal burden were followed by partial gains in growth performance; however, this trend should be viewed as typical performance variation in response to changing environmental conditions, not as verified compensatory growth.

The current data show that cumulative daily heat exposure, particularly during the late afternoon hours, has a significant impact on broiler productivity and mortality risk in open-sided tropical production systems. However, this adaptive response is insufficient during heat waves, where prolonged exposure to elevated temperatures can lead to significant performance losses and increased mortality. Our findings apply to prolonged high-temperature conditions observed in the study, not acute heat waves, and caution should be applied when extrapolating.

Based on our study showed afternoon heat (approximately 2:00 PM–6:00 PM) is most detrimental, we suggest that farmers with limited resources prioritize active cooling during these critical hours rather than cooling continuously throughout the day. To mitigate these effects, the use of active cooling strategies, such as fan ventilation or evaporative cooling systems is recommended, particularly during peak afternoon temperatures, which is both resource-efficient and aligned with the observed patterns of heat stress impact. Implementing such interventions can help maintain more stable performance metrics and reduce mortality rates under chronic heat stress conditions.

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NOVELTY STATEMENT

This study examines cumulative heat load (ΣHL) and late-afternoon thermal burden as indicators of broiler performance and mortality in open-sided tropical housing systems. By combining cumulative heat indices with weighted least squares regression and ROC-based risk assessment, the study offers a realistic approach for identifying high-risk times in real-world smallholder settings. These findings provide contextually relevant insights for heat stress monitoring in humid tropical broiler farming.

AUTHOR'S CONTRIBUTION

Conceptualization: Artina Prastiwi and Najeebullah Mohammadi; Methodology and Investigation: Artina Prastiwi and Najeebullah Mohammadi; Formal analysis, Data curation, Validation: Agus Purnomo, Indira Putri Negari, and Mungky Ema Ramadhanni; Writing-Original draft: Artina Prastiwi, Najeebullah Mohammadi, Dhirgo Aji, Devita Anggraeni, and Omer Coban; Writing-ReviewandEditing, English Proof-read: Indira Putri Negari; Supervision: Artina Prastiwi. All authors have read and agreed to the published version of the manuscript.

Ethical approval

The research was ethically approved by the Atatürk University Faculty of Veterinary Medicine Unit Ethics Committee (Protocol no: 2023/30, dated 19.10.2023).

Generative AI and AI-assisted technology statement

Generative AI and AI-assisted technologies were utilized for grammar and style checking, as well as to refine author written paragraphs for improved clarity. The authors thoroughly reviewed, verified, and edited all AI-generated output to ensure the accuracy and integrity of the scientific content.

Conflict of interest

The authors have declared no conflict of interest.

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Supplementary Table S1: Variables tested but excluded from final weighted least squares models.

Variable	Dependent model tested	Reason for exclusion
Heat 07:00 am	RLW, RADFI	Not retained after model selection
Heat 11:00 am	RLW, RADFI	P > 0.05
Heat 04:00 pm	RLW, RADFI	P > 0.05
RH 07:00 am	RLW, RADFI	Not retained in final model
RH 11:00 am	RLW, RADFI	Not retained in final model
RH 04:00 pm	RLW, RADFI	P > 0.05
THI 07:00 am	RLW, RADFI	Not retained in final model
THI 11:00 am	RLW, RADFI	P > 0.05
THI 04:00 pm	RLW, RADFI	P > 0.05
∑THI > 27.8	RLW, RADFI	Not retained after model selection

Supplementary Table S2: Multicollinearity Diagnostics for Predictors Included in Final Models

Predictor	Tolerance	VIF
∑HL (RLW model)	1,000	1,000
∑HL (RADFI model)	1,000	1,000

Note: All tolerance values were > 0.1 and VIF values < 5, indicating no multicollinearity concerns.

Supplementary Table S3: Actual body weights and residual live weight (RLW) relative to Cobb 500 mixed-sex performance standards.

Age (days)	Cobb 500 standard (g)*	Observed body weight (Mean ± SD, g)	n (pens)	Residual live weight (RLW, g)**
14	570	430,3 ± 6,15	5	–139,7
21	1,116	771,6 ± 13,3	5	–344,4
28	1,783	1,127.2 ± 19,0	5	–655,8
35	2,510	1,684.2 ± 117,7	5	–825,8