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ORIGINAL PAPER

Impact of high temperature-humidity index on meat quality and economic benefits in broilers

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ABSTRACT. Elevated ambient temperature has a major impact on chicken growth; however, its effects on meat quality closely related to fresh food consumption and processing costs are less frequently discussed. This study investigated the effects of two microclimate temperature–humidity index (THI) levels on breast meat quality and the economic performance of broilers. Chickens were assigned either to a high THI (THI-H) or low THI (THI-L) group, with each group consisting of 60 male and 60 female Ross 308 broilers, stratified into 6 pens based on hatched chick weight. Body weight, feed intake, and survival rate were recorded to evaluate rearing efficiency and economic outcomes. Meat samples (n = 24) from 35-day-old chickens were subjected to quality and chemical composition analyses. The results showed that the THI-H group was characterised by a significantly higher ($P < 0.05$) meat toughness, firmness, cooking loss percentage, colour lightness, and fat content, while significantly lower ($P < 0.05$) water-holding capacity, pH 24 h post-slaughter, and protein content. The THI-L group showed better performance with respect to the broiler index and total benefit, suggesting that a high-THI environment, indicating heat stress conditions for broilers, negatively affects both meat quality and profitability. The study emphasises the need to consider both quality and economic factors when developing strategies to mitigate the effects of heat stress in broilers.

Introduction

Homeothermic animals, such as ruminants, pigs, and poultry, reach optimal growth performance within a specific range of ambient temperature known as the thermoneutral zone. Within this range, energy expenditure of animals is directed primarily toward basic physiological processes rather than thermoregulation (Jiang et al., 2021). However, when environmental temperature exceeds this zone, animals experience heat stress, characterised by increased body temperature and metabolic heat production. This condition requires dissipation of additional heat through mechanisms such as sweating and panting (Kim et al., 2024). Recent approaches to determining the thermoneutral zone for animals consider not only ambient temperature but also the temperature-humidity index (THI). For animals reared outdoors, the heat load index a parameter integrating THI with heat radiation and wind speed is used to objectively evaluate the effects of various climatic factors and heat stress on animals (Bryant et al., 2023).

Poultry have skin covered with feathers and lack functional sweat glands, thus these birds exhibit high susceptibility to heat stress when reared in high temperature conditions and rely on evaporative cooling for thermoregulation. This characteristic is also observed in pigs, which have substantial subcutaneous fat and underdeveloped sweat glands, limiting their ability to dissipate heat effectively. Poultry subjected to heat stress exhibit behaviours such as reduced activity, wing spreading, and rapid breathing (Shakeri and Le, 2022). These responses negatively affect their growth, leading to reduced feed intake and weight gain, increased fat accumulation, and poor intestinal development (Kuo et al., 2021). Consequently, studies aimed at improving growth performance of chickens have focused on mitigating the effects of heat stress (Awad et al., 2020). However, efforts to alleviate heat stress should address both growth performance and meat quality preservation, considering the crucial role of the latter for meat processing industry and consumer satisfaction.

Water-holding capacity (WHC), a key indicator of meat quality, is defined as the ability of meat to retain its natural water content or absorb additional moisture during processing or storage. WHC is determined by the chemical and structural properties of the muscle. The conversion of muscle to meat involves denaturation and degradation of proteins, altering the muscle's complex structure and water-binding capacity (Bowker et al., 2014). WHC influences the appearance, tenderness, and juiciness of meat, making it an important factor in assessing meat quality. Given its impact on the weight and economic value of meat products, WHC is widely used by the meat processing industry and retailers for assessing the gain, loss, and retention of water in meat (Zhang et al., 2012). According to Barbut (2024), current methods of measuring the WHC of meat can be divided into four categories. The first one does not involve application of external force (e.g., drip loss), and measures water exudation from raw meat during storage. The second category applies external mechanical force (e.g., centrifugal force) to measure water loss in raw meat during processing. The third category uses thermal force (e.g., cooking loss) to measure water loss due to muscle contraction during heating. The last category includes non-destructive estimations (e.g., nuclear magnetic resonance) to analyse the molecular structure of muscle proteins using high-precision instruments. WHC can also be assessed through salt-induced water uptake (WUC_{salt}), which measures the ability of raw meat to absorb and retain added brine in moisture-enhanced poultry products. This property is crucial for the production of poultry products that require additional moisture and flavour during processing (Bowker and Zhuang, 2016). Together, these methods evaluate the degree of water retention at different stages of meat processing, thereby indicating meat quality. In the present study, besides the non-destructive estimations one, the other four methods were applied to estimate the WHC of meat.

Few studies have investigated the impact of heat stress on meat quality. This study aimed to evaluate how varying microclimate THI levels would affect meat quality and economic benefits in broilers.

Material and methods

The experimental procedures and protocols were reviewed and approved by the Institutional Animal Care and Use Committee (IACUC) of the Taiwan Livestock Research Institute, under approval number 110-3 and an approval date of November 12, 2020.

Experimental animals and management

The trial was conducted in two batches at the experimental poultry house of the Taiwan Livestock Research Institute, located in Xinhua District, Tainan City, Taiwan. The facility is equipped with a negative-pressure ventilation system. The study was conducted during two periods, from July to August, and from December to January, when average monthly temperatures ranged from 28.9 °C to 29.4 °C and from 17.8 °C to 19.6 °C, respectively. The Institutes standard operating procedures for cleaning and disinfection were followed to prevent interference from rodents, pests, and wild birds. Ambient temperature and humidity were monitored using an AZ 88160 AZ Temp. instrument (AZ Instrument Corp., Taichung, Taiwan) at 3-h intervals starting from 2:00 each day, resulting in 8 recorded points per day. The THI was calculated following the method described by de Moraes et al. (2008). Based on the THI values, the study groups were divided into a high THI group (THI-H) and a low THI group (THI-L).

Each group consisted of 60 male and 60 female Ross 308 broilers, stratified into 6 pens based on hatched weight. The birds had been vaccinated against Marek's disease, infectious bronchitis, and Newcastle disease at the hatchery. Each pen had an area of 3.24 m^2, resulting in a stocking density of 6.17 birds/m^2. The pen floor was covered with a 5-cm-thick coarse bran bedding. The chickens were fed according to the nutritional recommendations for Ross 308 (Aviagen, 2018), receiving a starter diet (in mash form) from days 0 to 10, a grower diet (in pellet form) from days 11 to 24, and a finisher diet in (pellet form) from days 25 to 35 (Table 1).

Table 1. Composition of the basal diet for broilers

Items	Growth stage		
	starter (days 1–10)	grower (days 11–24)	finisher (days 25–35)
Ingredients			
yellow maize, ground	52.33	55.28	58.34
soybean meal (44%)	35.50	33.00	30.00
fish meal (65%)	5.00	4.00	3.00
soybean oil	3.60	4.40	5.60
dicalcium phosphate	1.25	1.15	1.05
ground oyster shell	1.10	1.05	1.00
salt	0.30	0.30	0.30
DL-methionine	0.27	0.22	0.20
vitamin-mineral premix[1]	0.40	0.40	0.40
lysine	0.20	0.15	0.06
choline chloride (50%)	0.05	0.05	0.05
Total	100.00	100.00	100.00
Analysed value, %			
crude protein, %	22.32	20.67	18.77
metabolizable energy, MJ/kg	15.60	16.77	16.40
calcium, %	1.22	1.26	1.08
phosphorus, %	0.68	0.61	0.59

the composition of basal diet refer to Kuo et al. (2021); [1] supplied per kg of diet: IU: vit. A 16 000, vit. D_3 2 667; μg: vit. B_{12} 16; mg: vit. E 13.3, vit. K 2.7, vit. B_1 1.87, vit. B_2 6.4, vit. B_6 2.7, folic acid 0.53, calcium pantothenate 26.7, niacin 40, choline-Cl (50%) 400, Fe ($FeSO_4$) 53.3, Cu ($CuSO_4 \cdot 5H_2O$) 10.7, Mn ($MnSO_4 \cdot H_2O$) 93.3, Zn (ZnO) 106.7, I (KI) 0.53, Co ($CoSO_4$) 0.27, Se (Na_2SeO_3) 0.27

The poultry had *ad libitum* access to feed and tap water (without other additives or drugs) and were exposed to a 23 h light cycle, with a combination of natural and artificial light (Philips TL-D 36W/33-640; Signify, Eindhoven, Netherlands) throughout the 35 day rearing period (Huang et al., 2020). During this time, feed intake, body weight, survival rate, and feed conversion ratio (FCR) (Bormon et al., 2024) were recorded and calculated. From each pen, two 35-day-old chickens (selected based on mean body weight) were euthanised through cervical dislocation, followed by bleeding, to collect meat samples for quality and chemical composition analyses.

Meat yield

After euthanasia, the eviscerated chicken carcasses (n = 24) were chilled at 4 °C for 24 h. Then, the fillets and tenderloins from both sides of the breast, as well as thighs from both legs were collected and weighed. Meat yield was calculated as a percentage of live body weight at 35 days. Subsequently, the physical properties and chemical composition of the breast meat were analysed.

Physical properties of breast meat

The pH of breast meat (n = 24) was measured by inserting a metallic probe 2 cm deep into the meat near the head region. The pH was recorded using the probe electrodes of a handheld PH 400 pH meter (Spectrum Technologies, Inc., Aurora, IL, USA) applied for 30 s.

Drip loss was determined following Lu et al. (2007). In brief, each sample (n = 24) was weighed and placed at the centre of a zip-lock bag, ensuring minimal contact between the meat and the bag's interior surface. The samples were then freely suspended at 4 °C for 48 h. After eliminating surface moisture, the samples were reweighed, and the percentage of drip loss was calculated based on the weight loss relative to the initial weight of the samples.

Cooking loss was assessed following the method described by van der Wal et al. (1993). Briefly, each sample (n = 24) was weighed, sealed in a vacuum bag, and incubated in a water bath at 80 °C (BA500; Yamato Scientific Co., Ltd, Tokyo, Japan) for 40 min. Then, the samples were cooled to room temperature and reweighed. The percentage of cooking loss was calculated as the weight loss relative to the initial weight of each sample.

Meat colour was evaluated based on the CIE Lab system measuring lightness (L*), redness (a*), and yellowness (b*) using a TC-1 colour difference meter (Tokyo Denshoku Co., Ltd, Tokyo, Japan). The evaluation was performed for breast meat (n = 24) collected from the following three sites: cranial, medial, and caudal portions. The average of these three measurements was used to represent the overall meat colour.

Meat texture was analysed using breast fillets (n = 24) following the estimation of cooking losses. Each breast fillet was cut parallel to the muscle fibres into cubes measuring 3 cm × 1 cm × 1 cm. These cubes were then placed on a TA.XTplusC Texture Analyser platform (Stable Micro Systems, Godalming, UK) equipped with an HDP/90 mould and tested using an HDP/BS blade (speed: 5.0 mm/s; compression distance: 5.0 mm) for meat firmness (kg) and toughness (kg × s) in triplicate for each breast fillet.

WHC was measured following the method by Carvalho et al. (2017). Briefly, 1-cm cubes of breast meat (n = 24) were excised from the cranial portion of each sample, with cuts made parallel to the muscle fibres. Each cube was weighed, placed between two filter papers, and subjected to a 1-kg weight applied on top for 2 min. The cube was then reweighed, and WHC was calculated as the percentage change in weight relative to the initial measurement.

Measurements were performed in triplicate for each fillet. WUC_{salt} was assessed following the protocol of Bowker et al. (2014). For each breast meat sample (n = 24), a 10-g sample was excised from the cranial portion, chopped, transferred to a 50-ml centrifuge tube, and combined with 15 ml of 0.6 M sodium chloride solution (Sigma-Aldrich, St. Louis, MO, USA). The tube was shaken for 1 min and then incubated at 4 °C for 15 min. After incubation, the sample was centrifuged at 7000 *g* for 15 min at 4 °C. The supernatant was removed, and the pellet was weighed. WUC_{salt} was calculated as the percentage change in weight relative to the initial weight, with measurements performed in triplicate for each fillet.

Chemical composition

The contents of protein, ash, and fat in breast meat were determined using standard methods developed by AOAC International (2016).

European broiler index

The European production efficiency factor (EPEF) and European broiler index (EBI) were calculate following Marcu et al. (2013) as follows:

$$EPEF = BW \times S \times 100 / FCR \times D,$$
$$EBI = S \times ADWG \times FCR \times 10,$$

where: BW – live body weight of 35-day-old chickens; S – survival rate; FCR – feed conversion ratio, calculated as: feed intake / weight gain; D – duration of experiment in days; ADWG – average daily weight gain.

Economic benefits

The total benefit per group (TBG) was calculated according to Kalia et al. (2018) by assessing the economic loss due to mortality (LDM) between the THI-H and THI-L groups and male and female broilers.

$$LDM = UP \times (100 - S),$$
$$TBG_{\text{THI-L or female}} = LDM_{\text{THI-L or female}} - LDM_{\text{THI-H or male}},$$

where: UP – unit price, determined as the average daily trading price per kg of live chicken based on statistics from the Taiwan Agricultural Information and Forecasting Centre (https://www.naif.org.tw/main.aspx); S – survival rate.

Statistical analysis

All data were analysed using SAS Enterprise Guide version 7.1 (SAS Institute, Inc., 2017, Cary, NC, USA), incorporating a multifactorial model (THI × sex). Means and variances were compared using one-way ANOVA and analysed using a generalised linear model. Significance of differences between groups was determined using the least squares mean test. The level of statistical significance was set at $P < 0.05$.

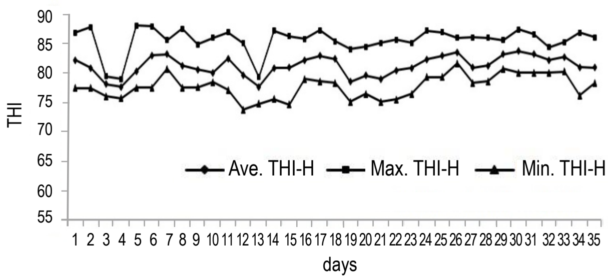
Results

THI of the rearing environment

During the 35-day rearing period, the temperature and humidity of the breeding environment were recorded every 3 h and the THI values were calculated accordingly. The daily average, maximum, and minimum THI values are shown in Figure 1.

Growth traits and meat yield

Both THI and sex significantly affected the chickens' growth traits (Table 2), specifically, body weight at Day 35 and FCR. Body weight was significantly higher in the THI-L group ($P < 0.05$), with male broilers having significantly higher body weight and feed intake ($P < 0.05$) compared to female broilers. The FCR was significantly higher in the THI-H group and female broilers. There was no interaction effect observed between the THI and sex on growth traits.



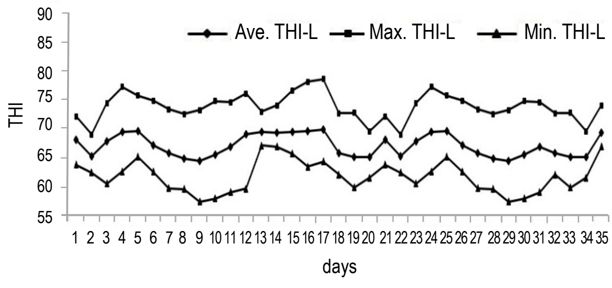


Figure 1. Daily average (Ave.), maximum (Max.), and minimum (Min.) temperature-humidity index (THI) values for the THI-H (up) and THI-L (down) groups during the rearing period

The THI also affected leg meat proportion and total meat yield, with both parameters significantly higher in the THI-H group than in the THI-L group ($P < 0.05$). However, no significant differences related to sex were noted for these parameters. Moreover, no interaction effect of the THI and sex was observed on the proportions of breast meat, leg meat,

Table 2. Effects of temperature-humidity index (THI) and sex on growth performance of broilers (n = 240)

Traits	Units	THI		Sex		SEM	Pr > F		
		H	L	M	F		THI	Sex	THI × Sex
FBW	kg	2.16[b]	2.42[a]	2.50[a]	2.09[b]	0.09	*	*	NS
ADFI	g	97.32	104.68	107.33[a]	94.67[b]	2.72	NS	*	NS
FCR	–	1.62[a]	1.55[b]	1.54[b]	1.63[a]	0.02	*	*	NS

FBW – final body weight, ADFI – average daily feed intake, FCR – feed conversion ratio, H – THI-H group, L – THI-L group, M – male broiler group, F – female broiler group, SEM – standard error of the mean, NS – not significant, * – $P < 0.05$; [ab] – means within the same row without the same superscripts are significantly different ($P < 0.05$)

or total meat yield (Table 3). Notably, while the percentage of meat yield relative to body weight varied with environmental THI and sex due to physiological responses related to thermoregulation and energy storage, total meat yield (by weight) was clearly dependent on body weight. Consequently, total meat yield was higher in the THI-L group and male broilers than in the THI-H group and female broilers.

Physical properties of breast meat

The THI influenced the physical properties of breast meat (Table 4), including toughness, firmness, cooking loss percentage, WHC, and pH 24 h post-slaughter (pH_{24}). Specifically, toughness, firmness, and cooking loss percentage were significantly higher, while pH_{24} was significantly lower in the THI-H group compared to the THI-L group ($P < 0.05$). No significant difference in drip loss was observed between the THI-H and THI-L groups. Both THI and sex affected the WHC of breast meat, with the THI-H group showing significantly lower WHC and WUC_{salt} values, indicative of reduced meat quality. Additionally, male broilers exhibited higher WHC and WUC_{salt} than female broilers, and an interaction effect between THI and sex was observed for these parameters. Apart from WHC and WUC_{salt} indices, no other physical trait varied significantly between sexes, and no interaction was noted between THI and sex.

In terms of breast meat colour, the CIE L* and a* values were affected by the environmental THI (Table 5). The THI-L group had significantly lower L* values and higher a* values ($P < 0.05$), indicating lower lightness and greater redness compared to the THI-H group. However, the b* value was not affected by the THI. It should be noted that there were no significant sex-based differences in breast meat colour, nor was any interaction effect observed between the THI and sex.

Table 3. Effects of temperature-humidity index (THI) and sex on meat yield (n = 24)

Traits	Units	THI		Sex		SEM	Pr > F		
		H	L	M	F		THI	Sex	THI × Sex
Breast meat	% BW	20.58	19.28	20.18	19.69	0.37	NS	NS	NS
Thigh meat	% BW	17.12[a]	16.31[b]	17.20	16.24	0.25	*	NS	NS
TMPR	% BW	37.71[a]	35.60[b]	37.38	35.93	0.31	*	NS	NS

TMPR – total meat production rate, % BW – (meat weight / broiler live body weight) × 100%, H – THI-H group, L – THI-L group, M – male broiler group, F – female broiler group, SEM – standard error of the mean, NS – not significant, * $P < 0.05$; [ab] – means within the same row without the same superscripts are significantly different at $P < 0.05$

Table 4. Effects of emperature-humidity index (THI) and sex on physical properties of broiler breast meat (n = 24)

Traits	Units	THI		Sex		SEM	Pr > F		
		H	L	M	F		THI	Sex	THI × Sex
Firmness	kg	4.32[a]	2.70[b]	3.32	3.37	0.26	**	NS	NS
Toughness	kg × s	7.64[a]	4.43[b]	5.71	5.72	0.46	**	NS	NS
CL	%	24.60[a]	18.54[b]	21.91	20.02	0.88	**	NS	NS
DL	%	2.11	1.40	1.54	1.83	0.04	NS	NS	NS
pH_{24}	%	5.82[b]	5.98[a]	5.92	5.90	0.19	*	NS	NS
WHC	%	80.21[b]	86.31[a]	86.63[a]	79.97[b]	1.16	**	**	**
WUC_{salt}	%	30.40[b]	48.41[a]	41.24[a]	32.08[b]	2.05	***	*	***

CL – cooking loss, DL – drip loss, WHC – water-holding capacity for pressure with 1 kg/cm^2, WUC_{salt} – water uptake capacity for salt-induced water, THI – temperature-humidity index, H – THI-H group, L – THI-L group, M – male broiler group, F – female broiler group, SEM – standard error of the mean, NS – not significant, * – $P < 0.05$, ** – $P < 0.01$, *** – $P < 0.001$; [ab] – means within the same row without the same superscripts are significantly different at $P < 0.05$

Table 5. Effects of THI and sex on the colour of broiler breast meat (n = 24)

Traits	THI		Sex		SEM	Pr > F		
	H	L	M	F		THI	Sex	THI × Sex
L*	51.88^{a}	48.88^{b}	50.49	49.88	0.62	*	NS	NS
a*	2.29^{b}	5.34^{a}	3.42	4.59	0.48	**	NS	NS
b*	8.41	8.91	8.49	8.70	0.45	NS	NS	NS

CIE L* – colour lightness, CIE a* – colour redness, CIE b* – colour yellowness, THI – temperature-humidity index, H – THI-H group, L – THI-L group, M – male broiler group, F – female broiler group, SEM – standard error of the mean, NS – not significant, * – P < 0.05, ** – P < 0.01; ^{ab} – means within the same row without the same superscripts are significantly different at P < 0.05

Chemical composition of breast meat

Both environmental THI and sex influenced the chemical composition of breast meat (Table 6). In the THI-H group, protein content was significantly reduced, while fat content was elevated (P < 0.05); however, no significant differences were observed in ash content between the THI groups. Sex-based differences showed that female broilers had significantly higher fat and ash contents than male broilers (P < 0.05). Additionally, an interaction effect between the THI and sex was recorded for both protein and fat content.

Table 6. Effects of THI and sex on chemical composition of broiler breast meat (n = 24)

Traits	Units	THI		Sex		SEM	Pr > F		
		H	L	M	F		THI	Sex	THI × Sex
Protein	%	22.06^{b}	22.95^{a}	22.19	22.95	0.20	**	NS	*
Fat	%	2.07^{a}	1.00^{b}	1.18^{b}	1.81^{a}	0.14	**	**	**
Ash	%	1.23	1.26	1.20^{b}	1.28^{a}	0.02	NS	*	NS

THI – temperature-humidity index, H – THI-H group, L – THI-L group, M – male broiler group, F – female broiler group, SEM – standard error of the mean, NS – not significant, * – P < 0.05, ** – P < 0.01; ^{ab} – means within the same row without the same superscripts are significantly different (P < 0.05)

Table 7. Rearing efficiency and economic benefits of broilers stratified by THI or sex (n = 240)

Traits	Units	THI		Sex	
		H	L	M	F
S	%	93.33	96.67	95.00	95.00
EPEF	–	356.18	430.85	439.16	347.99
EBI	–	347.92	421.92	430.02	339.91
SP_{35}	TWD	129.70	145.23	149.71	125.22
LDM	TWD	1037.61	580.90	898.24	751.31
TBG	TWD	–	456.71	–	146.93

S – total survival rate (%), EPEF – European performance efficiency factor, EBI – European broiler index, SP_{35} – sale price of broiler at 35 days of age = 60 TWD/kg live weight, LDM – loss due to mortality, TBG – total benefit per group, TWD – Taiwan dollars (0.03 USD), THI – temperature-humidity index, H – THI-H group, L – THI-L group, M – male broiler group, F – female broiler group

Rearing efficiency and economic benefits

The EBI and EPEF were utilised to assess rearing efficiency considering factors such as mortality, weight gain, and feed efficiency (Kalia et al., 2018). Results showed higher EPEF values in the THI-L group and in male broilers (Table 7). Although EBI values were slightly lower than EPEF due to age differences (days), trends were similar, reflecting overall rearing efficiency. Economic benefits were 44.02% higher for the THI-L group than for the THI-H group and 16.36% higher for female broilers than male broilers.

Discussion

In this study, the rearing environment of the THI-L group remained within the thermoneutral zone, with an average temperature ranging between 18 °C and 24 °C. Rearing environments with an average THI below 72 are considered comfortable for chickens (de Moraes et al., 2008). However, in our study, THI values exceeded 72, particularly between 8:00 and 14:00, indicating periods of heat stress. Cooling and ventilation in the rearing environment should be improved during these periods to alleviate discomfort for chickens. The average temperature of the rearing environment of the THI-H group exceeded the thermoneutral zone, leading to heat stress and insufficient thermoregulation (Kim et al., 2024). Chickens often reduce their feed intake to lower body heat production (Shakeri and Le, 2022). Although feed intake was comparable between the groups, the THI-L group outperformed the THI-H group in terms of final body weight and feed conversion ratio. These findings are in line with a previous study of Emami et al. (2021), who reported that broilers reared under varying environmental THI conditions showed variations in the proportion of leg meat to total meat yield. Due to underdeveloped sweat glands, chickens exposed to heat stress experience increased blood flow to the extremities and reduced blood flow to the breast area, causing increased heat dissipation and reduced energy storage (Emami et al., 2021). Consistent with this phenomenon, we found that the proportion of leg meat was increased in broilers reared under high-temperature conditions.

We assessed breast meat quality for its physical properties and chemical composition. Samples from chickens reared under high-temperature conditions were characterised by poor quality reflected by increased toughness, firmness, shear force, elasticity, adhesiveness, chewiness, and cooking loss, as well as lower pH values (Zhang et al., 2012). Furthermore, severe stress may also induce adverse oxidative responses, leading to protein denaturation (Liao et al., 2022). Elevated metabolic activity affects the water-binding capacity of proteins, increasing drip loss and cooking loss percentages. These findings support our results, as indicated by significantly higher cooking loss percentage in the THI-H group compared to the THI-L group.

Chicken muscles consist mainly of fast-twitch fibres and rely on anaerobic glycolysis for energy production. Stress responses can affect muscle metabolism both before and after slaughter, accelerating anaerobic glycolysis and increasing lactate production from pyruvate, and thus reducing muscle pH (Lu et al., 2007). Carvalho et al. (2017) simulated conditions that lead to poor-quality, i.e., pale, soft, and exudative (PSE) meat by heating broiler breast meat at 37 °C for 200 min after slaughter. As a consequence, the pH value dropped to 5.84 and continued to decrease. In contrast, control samples chilled for 200 min post-slaughter using commercial procedures had an initial pH of 6.59, which decreased to 5.96 after 24 h. In our study, the pH values of breast meat in the THI-L group were similar to commercially chilled meat, while those from the THI-H group were lower than the heated-meat samples, already meeting the pH criteria for PSE meat quality.

Myoglobin, haemoglobin, and cytochrome C are key proteins that affect meat colour, with myoglobin being the dominant factor (Mancini and Hunt, 2005). In heat-stressed broilers, the conversion of deoxymyoglobin to metmyoglobin in the muscle alters its colour by increasing lightness and decreasing redness (AL-Sagan et al., 2020). This phenomenon is consistent with findings on the colour of summer-reared poultry meat (McCurdy et al., 1996). Correlations between WHC, pH, and L* have also been reported. Specifically, lower WHC values have been correlated with reduced WUC_{salt}, lower pH_{24}, and higher lightness (correlation coefficient 0.71–0.83) (Bowker et al., 2014). These outcomes support our results, as shown by lower WHC, WUC_{salt}, and pH values, but higher L* colour values in the THI-H group than in the THI-L group. Moreover, WHC and WUC_{salt} were higher in male than in female broilers, demonstrating an interaction effect between the THI and sex.

Heat stress induces the degradation of skeletal proteins, thereby reducing their water-binding capacity, ultimately resulting in lower WHC and brine absorption capacity, increased drip and cooking loss percentages, as well as elevated shear force and toughness after cooking. These changes are associated with characteristics typical of PSE meat (Zhang et al., 2012; Alnahhas et al., 2014). In addition to altering pH values and protein oxidation patterns, heat stress has been shown to affect the triiodothyronine-to-tetraiodothyronine ratio (T3/T4) in turkeys, thereby disrupting thyroid hormone-mediated regulation of calcium content in skeletal muscles (Chiang et al., 2008). This can be explained by increased calcium release from the sarcoplasmic reticulum or altered channel activity in this structure, which intensifies energy metabolism and muscle contraction (Strasburg and Chang, 2009), ultimately reducing WHC and increasing the proportion of PSE meat. Heat stress activates the hypothalamus-pituitary-adrenal axis, inducing cortisol production and increasing the body's available energy for stress response regulation (Kokoris et al., 2024). Elevated body temperature triggers oxidative processes, such as the citric acid cycle and fatty acid oxidation. This in turn increases the rate of cellular and tissue metabolism and enhances the activity of reactive oxygen species, which promotes metabolic oxidation in the skeletal muscles of broilers (Mujahid et al., 2007). These metabolic changes alter sarcomere length (affecting light scattering), inhibit tenderising enzyme hydrolysis, and accelerate muscle protein oxidation, ultimately leading to protein hydrolysis. Collectively, these alterations contribute to the formation of PSE-like meat (Lonergan et al., 2010). In the present study, breast meat samples from the THI-H group more resembled PSE meat compared to those from the THI-L group. Additionally, cooking loss percentages were significantly higher in the THI-H group than in the THI-L group, and this phenomenon is detrimental to meat processing, cooked meat sales, and economic returns.

Breast meat of broilers reared under high-temperature conditions tends to have elevated moisture and fat contents but reduced protein content (Zhang et al., 2012), a trend also observed in the present study. High temperatures induce mitochondrial dysfunction, which increases protein oxidation levels (Liao et al., 2022), and accelerates protein catabolism, thereby reducing muscle protein turnover and body protein content (Zhang et al., 2012). Prolonged exposure to high temperatures causes metabolic disorders, increased resting behaviour, and reduced lipase activity; these changes subsequently raise the levels of abdominal, subcutaneous, and intermuscular fat in broilers (Zhang et al., 2012; Al-Zghoul et al., 2019; Kuo et al., 2021; Teyssier et al., 2022). Elevated muscle protein and fat oxidation levels under high-temperature conditions are associated with shorter shelf life of meat products and increased concerns regarding food safety (Imik et al., 2012). Similar to our findings, Brothers et al. (2019) have observed that male broilers grow faster and have a higher metabolic rate compared to females. Under normal feeding conditions, the mitochondria of male broiler chickens are highly active, generating more free radicals. When exposed to additional stresses, such as high temperature, this leads to a significant accumulation of reactive oxygen species (ROS) and an imbalance in oxidation reactions. Branann et al. (2022) also found that the expression of the avian uncoupling protein (avUCP) protein, which is involved in mitochondrial ROS elimination, was significantly downregulated in male broilers during heat stress, which impaired their ability to adapt to oxidative stress under acute heat. Oxidative stress induced by excessive temperature may explain the findings of this study, where the THI and sex interaction affected protein and fat content, as well as WHC, which was related to the degradation of skeletal proteins. This result suggests that both the THI and sex should be considered when assessing factors affecting broiler breast meat quality.

The Ross 308 broiler is the main breed reared in the United Kingdom, and the rearing efficiency of poultry in the UK is assessed using the EPEF value. An EPEF value exceeding 400 indicated high-efficiency rearing, but this threshold has recently been increased to 420. In the current study, the EPEF value in the THI-H group was below 400, representing 82.67% of the value for the THI-L group. Regarding sex, the EPEF value of female broilers was 79.24% of that of male broilers. It should be noted that the EPEF and EBI are indicators of rearing efficiency and are intended to help farmers improve performance through management and biosecurity measures. However, these indices are not meant for economic evaluation, which must consider factors such as feed cost, labour expenses, equipment investment, and profit per unit land area, i.e., parameters that vary across locations and farms. Therefore, we assessed economic benefits solely on the basis of mortality-related losses in broilers stratified by the THI or sex.

The broiler industry often uses temperature-controlled enclosed poultry houses, minimising in this way the effects of seasonal THI alterations on EPEF values. Nevertheless, gender differences in EPEF values remain significant. Our results revealed that rearing efficiency, as measured by EPEF values, was higher for male broilers than for female broilers. However, when economic benefits were evaluated solely based on mortality-related losses, female broilers outperformed their male counterparts, as their body weight at 35 days was lower. Market demand for processed meat products of varying weights indicates that breeding both sexes is necessary to achieve a balance between productivity and profitability.

In addition to affecting nutrient absorption, heat stress can also damage the intestinal barrier by disrupting tight junctions between transmembrane protein complexes. This damage my allow macromolecules, endotoxins or pathogens to freely pass through the intestinal epithelium of animals (Kim et al., 2023). Statistics from the United States (1998–2015) showed that 84.3% of all pathogenic infections in pigs occurred in summer, and *Salmonella* sp. was the predominant pathogen (Self et al., 2017). This suggest that heat stress increases gut mucosal permeability in chickens, facilitating the adhesion of *Salmonella* sp. to intestinal epithelial tissues and entry of other pathogens (Alhenaky et al., 2017). Given the rising temperatures and prolonged summers due to climate change, researchers must recognise the negative impact of heat stress on meat quality and explore effective strategies to improve food safety and prevent infections caused by meat-borne pathogens.

Conclusions

Heat stress adversely affects meat processing quality and economic benefits. Our findings suggest that strategies to mitigating the negative effects of heat stress should focus not only on increasing growth performance, but also on enhancing meat quality and food safety. This comprehensive approach addresses the needs of both meat processors and consumers, emphasising improvements in both rearing efficiency and meat quality. Further studies are needed to provide the poultry industry with effective solutions to problems pertaining to heat stress.

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Conflict of interest

The Authors declare that there is no conflict of interest.

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