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Application of response surface analysis to optimize the temperature-humidity relationship in broilers reared under commercial conditions

Optimización de la relación temperatura-humedad en pollo de engorda mediante análisis de superficie de respuesta en condiciones comerciales

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ABSTRACT

The effects of changes in house temperature and relative humidity (RH) and their relationship on broiler production indicators in a commercial system with manual control of temperature and humidity were evaluated. Four production cycles were analyzed (26 000 birds/cycle; 10 broilers/m^2). Each cycle consisted of four production phases (pre-starter, starter, grower and finisher). Feed and water were provided *ad libitum*. Six samples were taken from 120 birds per cycle in each phase, and body weight and daily weight gain were determined, as well as feed consumption and feed conversion ratio 1, phase 1 were estimated. The information was analyzed under fixed effects, principal components (PC) and response surface analysis (RSA) models. Temperatures and humidity were different (P<0.05) between cycles within each phase. Temperature and humidity affected (P<0.001) the productive indicators per cycle across phases. This was corroborated by the PC analysis (P<0.001). Meanwhile, the optimization process of the regression equations showed that the best combination of temperature and relative humidity was 29 °C/31 %, 26 °C/35 %, 25 °C/35 %, 30 °C/44 %, 14 °C/64 % y 18 °C/50 % and for weeks 1, 2, 3, 4, 5 y 6, respectively.
Keywords: broiler, response surface analysis, temperature-humidity index.

RESUMEN

Se evaluaron los efectos de los cambios de temperatura y humedad relativa dentro de la caseta (DC) y su efecto sobre los indicadores productivos en pollo de engorda criado en un sistema comercial con control manual de temperaturas y humedad. Se analizaron cuatro ciclos productivos (26,000 aves/ciclo; 10 pollos/m^2). Cada ciclo comprendió cuatro fases productivas (pre-inicio, inicio, desarrollo y finalización), el alimento y agua se proporcionaron *ad libitum*. Se tomaron seis muestras de 120 aves por ciclo en cada fase y se determinó peso corporal y ganancia de peso diaria, se estimó el consumo de alimento e índice de conversión alimenticia ciclo^{-1} fase^{-1}. La información se analizó bajo modelos de efectos fijos, componentes principales (CP) y, análisis de superficie de respuesta (ASR). Las temperaturas y humedales fueron diferentes (P<0.05) entre los ciclos y fases. La temperatura y la humedad afectaron (P<0.001) los indicadores productivos por ciclo en cada fase. Aspecto que se corroboró con el análisis de CP (P<0.001).

Mientras que, el ASR determinó, que, en los sistemas con control manual de temperatura y humedad, el proceso de optimización de las ecuaciones de regresión para el desarrollo de las aves con la mejor combinación de temperaturas y humedad relativa fueron: 29°C/31%, 26°C/35%, 25°C/35%, 30°C/44%, 14°C/64% y 18°C/50% para las semanas 1, 2, 3, 4, 5 y 6, respectivamente.
Palabras clave: pollo de engorda, análisis de superficie de respuesta, índice temperatura-humedad.

INTRODUCTION

Currently, advances in genetics, nutrition, health, and infrastructure have enabled rapid growth and productivity in the poultry industry (Hassan *et al.*, 2022; Nilipour, 2012), which are linked to the development of new genetic lines. Under experimental conditions, broilers can reach 3.5 kg of live weight within 42 days post-hatching. This rapid growth of broilers in such a short cycle implies a total feed intake of 4.6 kg/bird and a feed conversion ratio of 1.58 kg/kg of feed consumed (Cobb-Vantress, 2022; Aviagen, 2022). However, under commercial farm conditions, new broiler genetic lines face several factors that limit this genetic potential, including environmental factors such as temperature and internal humidity in the poultry house *(*Arantes de Sousa *et al*., 2016*)* Due to the high metabolic activity of broilers during their development, they are more sensitive to environmental changes in commercial farms (Quintana, 2020)*.*
The main physiological changes observed in birds under heat stress are primarily appetite modification (Hai *et al.,* 2000; Song *et al.,* 2012), changes in intestinal morphology, and nutrient absorption *(*Arantes de Sousa *et al*., 2016*),* which consequently limit broiler body development. The Temperature-Humidity Index (THI) has been established as a way to evaluate the effects of thermal conditions on the physiological state and productive performance of farm animals. This indicator has been developed as a linear combination of dry-bulb temperature (T_{db}) and wet-bulb temperature (T_{wb}) for different species (Tao & Xin, 2003). THI is one of the most widely used thermal comfort indices, incorporating both temperature and relative humidity with specific weights to quantify the degree of heat stress in farm animals (DeShazer *et al.*, 2009). THI equations describe the relative importance of T_{db} and T_{wb} in different species based on physiological parameters, heat generation, or productive performance. For this purpose, different specific weights have been proposed for various species and climatic environments (Omomowo & Falayi, 2021). However, few studies evaluate optimal conditions under commercial settings, and additionally, these indices do not indicate how the measures that compose the index contribute to the response variable. Response Surface Methodology (RSM) is a method aimed at optimizing such response and understanding the response topography, including local maximum, local minimum, and boundary lines, which together allow finding the region where the best response can occur (Pishgar-Komleh *et al.*, 2012; Aydar, 2017). RSM examines whether the degree of congruence of two independent variables is related to a response variable through a polynomial equation (Taheri *et al.*, 2011; Khuri, 2017;

Williams *et al*., 2019). The objective of the present study was to record temperature and humidity changes in the internal environment of broiler houses and to determine their effect on productive indicators, with the purpose of applying response surface analysis to identify optimal temperature and humidity values that allow optimizing productive performance.

MATERIAL AND METHODS

The study was conducted in a commercial broiler production system in the state of Michoacán, Mexico, located at 19°45' north latitude and 101°03' west longitude, at an altitude of 1 900 meters above sea level, with a warm subhumid climate where temperatures vary between 4.5 and 36.4 °C throughout the year. Four production cycles were evaluated during the months of January to October. The farm has an installed capacity to house a total of 26 000 birds per cycle (50 % males and 50 % females) at a density of 10 birds/m² under a semi-controlled environment. Radiant gas brooders (heaters) were used as a heat source, manually programmed. Both internal temperature (TIC) and internal humidity (HIC) of the houses were manually controlled to adjust TIC and HIC according to bird age (Cobb-Vantress, 2022; Aviagen, 2022). Four production phases were considered: pre-starter (1 to 7 days of age), starter (8 to 21 days of age), grower (22 to 35 days of age), and finisher (36 to 42 days of age).
Commercial feed and water were provided *ad libitum*, according to the specific requirements for the genotype of the birds acquired by the system (Cobb 500®). In each house and production cycle, internal house temperature (°C) (TIC) and internal house humidity (%) (HIC) were recorded daily. TIC was recorded both with a laser thermometer (GB Model-TN438L0, accuracy ±0.1 °C) and with a digital thermo-hygrometer (Thermo-hygro GB Model-TM-977H). A total of 120 birds (40 birds per cycle) were randomly selected for monitoring. Thus, at the end of each production cycle, 720 birds per house were used. Each bird was weighed using a digital scale (Bch-5,000/Metrology) with a capacity of 5.0 ± 0.001 kg to obtain weekly body weight (kg) (BW) and daily weight gain (kg) (DWG). Feed intake by phase and daily mortality were also recorded. Data were analyzed using Pearson correlations, linear and nonlinear regression coefficients, and ANOVA, under the fixed-effects model methodology (Littell *et al.,* 2006), using the following model: $Y_{ijkl} = \mu + C_i + FS_j + SM_k + SX_l + (CFSSX)_{ijl} + (CSMSX)_{ijk} + \varepsilon_{ijkl}$. Where: Y_{ijklm} = response variable: internal house temperature (TIC) and humidity (HIC), body weight (BW), daily weight gain (DWG), feed intake (FI), feed conversion ratio (FCR), and daily mortality (DM); μ = overall mean; C_i = fixed effect of the *i-th* cycle (i = 1st, 2nd, 3rd, and 4th); FS_j = fixed effect of the *j-th* phase (j = pre-starter, starter, grower, finisher); SM_k = fixed effect of the *k-th* week (k = 1, 2, 3, 4, 5, and 6); SX_l = fixed effect of the *l-th* sex (l = male and female); $(CFSSX)_{ijl}$ = interaction effect of cycle × phase × sex; $(C*SM*SX)_{ijk}$ =

interaction effect of cycle × week × sex; ε_{ijkl} = random error associated with each observation (~NID=0, σ^2_e).

Differences between sexes or cycles were tested using least squares means at α = 0.05 (Littell *et al.,* 2002). The collected data were analyzed using principal component analysis (PCA) based on the correlation matrix of the indicators, according to the selection criterion of components with eigenvalues greater than or equal to unity (λ ≥ 1) (Montanero, 2008; Torres *et al.*, 2008) using SPSS®. For response surface analysis (Montgomery, 2002), a Box-Behnken type model with 2 factors was used; TIC and HIC were selected as process variables on the response variable BW using MINITAB-14®. Optimization of TIC and HIC values to obtain the highest body weights was performed using the SOLVER add-in of Excel®, where the objective function was the equation obtained by surface analysis, and the decision variables were TIC and HIC. Given the nature of the analyzed variables, the GRG Nonlinear algorithm was used to find a local optimal solution (Muzzammil *et al.*, 2015).

RESULTS

Table 1 presents the least squares means for body weight (BW), daily weight gain (DWG), feed intake (FI), feed conversion ratio (FCR), internal house humidity (HIC), and internal house temperature (TIC), according to sex, phase, and production cycle. In general, differences among production cycles can be observed, where cycle 4 showed higher BW and DWG values compared to the other production cycles. Likewise, performance differences between females and males were also observed.

Regarding BW, it can be observed that, except for cycle 4, the other cycles showed no significant differences from the pre-starter phase through the starter phase. From the grower phase onward, differences in body weight among the four evaluated cycles were significant ($P < 0.05$), with cycle 4 showing the highest values; similar results were observed for both males and females.

Concerning DWG, similarly to BW, the pre-starter and starter phases in cycles 1 to 3 showed no significant differences, except for cycle 4. In the grower and finisher phases, cycles 2 and 3 showed the highest values; both cycles were similar, but different from cycles 1 and 4. This behavior was similar for both females and males.

Overall, differences in feed conversion were observed both by phase and among cycles. Likewise, differences were seen between females and males. The highest efficiency was observed in males during cycle 4. Overall, the cycle with the lowest efficiency was cycle 1.

The response of these productive indicators appears to be related to both HIC and TIC, as differences between cycles were observed for both males and females. In Table 1, it can be observed that cycles 1 and 2 generally showed lower values compared to cycles 3 and 4. The highest HIC values were observed in the grower and finisher phases of cycle 4, for both females and males.

Average TIC was found to differ ($P < 0.05$) in each phase and production week across the analyzed cycles. Regarding this, TIC during the pre-starter phase in cycle 4 was 29.9 ± 0.15 °C under a HIC of 33.5 ± 0.58 %; these values were higher ($P < 0.05$) than those recorded in cycle 1: 24.9 ± 0.15 °C/21.3 ± 0.58 % HIC (Table 1). Table 2 shows that the variability in bird BW during the pre-starter phase was explained by only two components (77.3 %): the first component (temperature-feed) explained 43 % of the total variation and was composed of TIC and DWG (both positive) and FI (negative). The second component (humidity-month) explained 34.4 % of the total variation, composed only of HIC and month, both with positive contributions. The correlation values between TIC and HIC ($r = 0.47$) in the pre-starter phase suggest that as TIC increases, HIC also increases (Table 3). However, both TIC and HIC were negatively associated with FI: $r = -0.95$ for maximum temperature (Tmax)-FI, and $r = -0.23$ for HIC-FI. The association between Tmax-DWG was high and positive ($r = 0.85$), but the association between DWG-FI was negative ($r = -0.88$).

In the starter phase, principal component analysis determined that three components explained 86 % of the variability in bird BW (Table 2). Humidity (maximum, average, and minimum) was the first component, accounting for 34.1 % of the total variation. The second component explained 32.3 % of the total variability and consisted of temperature (maximum, average, and minimum), which together with the first component (humidity) explained 66.4 % of the total variation in bird BW. The third component was composed only of DWG (negative, -0.99) and bird sex (positive, 0.97); however, this component explained only 19.7 % of the total variation. Regarding the associations among the variables analyzed for the starter phase (Table 3), temperature and humidity had a 20 % association ($r = 0.20$). However, the association between TIC-DWG was high and negative ($r = -0.59$); in contrast, HIC and DWG showed a low and positive association ($r = 0.14$). The correlation between DWG and Sex was high and negative ($r = -0.77$).

In the grower phase, two components were identified that explained 75 % of the variation (Table 2); the first, positively composed of humidity (Hmin, HIC, and Hmax) and month (negative), as well as Tmax and FI (negative), explained 37.9 % of the total variation in bird BW. The second component, composed of temperature and DWG, explained 37.6 % of the total variation.

Unlike the previous phase, both increases and decreases in humidity were directly correlated with temperature: r = 0.99 (Tmin-Hmax) and r = -0.87 (Tmax-Hmax) (Table 3). Similarly, high correlations were found between HIC-FI (r = -0.83), Tmax-FI (r = 0.72), and Tmin-FI (r = -0.83). The association between humidity and DWG showed a positive and high correlation (r = 0.53); while the associations between temperatures and DWG were: r = -0.37 (Tmax-DWG) and r = 0.56 (Tmin-DWG).

In the finisher phase, according to principal component analysis, the variables grouped into two components. Unlike the previous phases, the first component explained more than half (55.1 %) of the total variation. This component was positively composed of humidity (minimum, average, and maximum) and evaluation period (month), and negatively by FI, Tmax, and average temperature (Table 2). The second component consisted of Tmin and DWG, both positive; it explained 18.4 % of the total variation. Among the variables mentioned in the first component, the correlations between HIC-TIC (r = -0.86), FI-Tmax (r = 0.94), and FI-Hmax (r = -0.99) stood out, as well as correlations between Tmin-DWG (r = 0.62) and, finally, the correlation between Hmax-DWG (r = -0.16), which was negative and low (Table 3).

The optimization of TIC and HIC values according to the equations obtained by response surface analysis, solved by the GRG algorithm that maximized weekly body weight, is shown in Table 5. The change in the relationship between TIC and HIC values in each week of age can be observed, indicating that from the fourth week of age onward, the temperature demand decreases; however, the HIC value has a correspondence, where temperatures between 25 and 29.6 °C require HIC between 31 and 44 %. In the fifth week, with temperatures between 14 °C and 18 °C, HIC between 50 and 64 % is required, suggesting optimal BW values of 0.160, 0.395, 0.773, 1.263, 2.016, and 2.552 kg for weeks 1, 2, 3, 4, 5, and 6, respectively.

Table 1. Least squares means for productive indicators, internal house temperature (TIC), and internal house humidity (HIC) according to production cycle and phase

Evaluation cycle	Males				Females			
	Weekly production phase				Weekly production phase			
	Pre-starter 1$^{(D7)}$	*Starter* 3$^{(D21)}$	*Grower* 5$^{(D35)}$	*Finisher* 6$^{(D42)}$	*Pre-starter* 1$^{(D7)}$	*Starter* 3$^{(D21)}$	*Grower* 5$^{(D35)}$	*Finisher* 6$^{(D42)}$
				Body weight (kg)				
C.1	0.137^{a}	0.781^{a}	1.768^{a}	2.371^{a}	0.137^{a}	0.710^{a}	1.597^{a}	2.013^{a}
C.2	0.134^{a}	0.763^{a}	1.857^{b}	2.539^{b}	0.131^{a}	0.724^{a}	1.751^{b}	2.405^{b}
C.3	0.130^{a}	0.775^{a}	1.953^{c}	2.657^{d}	0.140^{b}	0.729^{a}	1.804^{c}	2.481^{c}
C.4	0.167^{b}	0.809^{b}	1.950^{d}	2.629^{d}	0.149^{c}	0.727^{a}	1.752^{b}	2.326^{d}
S.E.	0.021	0.012	0.011	0.009	0.021	0.012	0.011	0.009
				Daily weight gain (g)				
C.1	14^{a}	60^{a}	85^{a}	86^{a}	14^{a}	49^{a}	78^{a}	60^{a}
C.2	14^{a}	56^{a}	93^{b}	97^{b}	13^{a}	54^{b}	84^{b}	93^{b}
C.3	13^{a}	58^{a}	95^{b}	100^{b}	14^{a}	53^{b}	84^{b}	97^{b}
C.4	18^{b}	53^{b}	88^{a}	87^{c}	15^{a}	51^{a}	79^{a}	82^{c}
S.E.	0.003	0.002	0.001	0.001	0.003	0.002	0.001	0.001
				Feed conversion ratio (kg/kg)				
C.1	1.680^{a}	1.597^{a}	1.597^{a}	2.019^{a}	1.146^{a}	1.410^{a}	1.865^{a}	2.348^{a}
C.2	1.568^{b}	1.503^{a}	1.503^{b}	1.815^{b}	1.077^{b}	1.334^{b}	1.675^{b}	1.916^{b}
C.3	1.772^{c}	1.500^{a}	1.500^{b}	1.755^{c}	1.100^{b}	1.389^{b}	1.679^{b}	1.883^{c}
C.4	1.190^{d}	1.375^{b}	1.375^{c}	1.663^{c}	0.933^{c}	1.328^{b}	1.621^{b}	1.885^{c}
S.E.	0.087	0.050	0.039	0.036	0.087	0.050	0.039	0.036
				Feed intake (kg)				
C.1	0.157	1.194	3.199	4.931	0.157	1.130	2.978	4.484
C.2	0.152	1.077	3.151	4.839	0.141	1.039	2.933	4.389
C.3	0.156	1.102	3.253	4.996	0.154	1.016	3.028	4.355
C.4	0.148	1.044	3.050	4.688	0.139	0.965	2.939	4.087
S.E.	-	-	-	-	-	-	-	-
				Internal house humidity (%)				
C.1	21.3^{a}	25.4^{a}	31.6^{a}	38.1^{a}	25.2^{a}	34.7^{a}	35.9^{a}	42.1^{a}
C.2	21.4^{a}	24.8^{a}	41.2^{b}	42.2^{b}	25.5^{a}	35.5^{a}	43.5^{b}	44.6^{b}
C.3	42.9^{b}	46.7^{b}	44.9^{b}	47.0^{c}	43.1^{b}	46.6^{b}	44.7^{c}	44.6^{b}
C.4	31.6^{c}	36.4^{c}	61.9^{c}	58.9^{d}	33.5^{c}	40.0^{c}	62.0^{d}	58.5^{c}
S.E.	0.58	0.33	0.26	0.24	0.58	0.33	0.26	0.24
				Internal house temperature (TIC, °C)				
C.1	24.4^{a}	23.0^{a}	23.0^{a}	22.2^{a}	24.9^{a}	24.1^{a}	22.6^{a}	22.2^{a}
C.2	26.9^{b}	26.6^{b}	24.3^{b}	23.5^{b}	29.2^{b}	28.0^{b}	24.7^{b}	23.4^{b}
C.3	26.6^{c}	25.5^{c}	23.9^{c}	21.9^{a}	26.5^{c}	26.3^{c}	24.2^{c}	21.8^{c}
C.4	29.4^{d}	25.4^{c}	23.4^{d}	20.9c	29.8^{d}	25.6^{d}	23.8^{d}	21.4^{d}
S.E.	0.07	0.06	0.03	0.05	0.10	0.08	0.05	0.06

$^{a, b, c, d}$ = differ significantly (P < 0.05) within column by sex; S.E. = Standard error; * = Approximate value obtained from total feed consumption of 26 000 broilers (50% males, 50% females) per house and production phase

Table 2. Variables comprising each of the principal components in the pre-starter, starter, grower, and finisher phases

Pre-starter

Component	Variables	Contribution value	% Variation	Total variance (%)
I	Average TIC	0.93	43.0	77.3
	Maximum temperature	0.92		
	Feed intake	-0.91		
	Minimum temperature	0.89		
	Daily weight gain	0.84		
II	Average HIC	0.99	34.4	
	Minimum humidity	0.99		
	Maximum humidity	0.99		
	Month (period)	0.76		

Starter

Component	Variables	Contribution value	% Variation	Total variance (%)
I	Maximum temperature	0.96	34.1	86.1
	Average HIC	0.96		
	Minimum humidity	0.93		
	Months	0.84		
II	Average TIC	0.98	32.3	
	Maximum temperature	0.97		
	Minimum temperature	0.91		
III	Daily weight gain	-0.99	19.7	
	Sex	0.97		

Grower

Component	Variables	Contribution value	% Variation	Total variance (%)
I	Maximum temperature	-0.89	37.9	75.5
	Maximum humidity	0.87		
	Mean humidity	0.84		
	Minimum temperature	0.80		
	Months	0.71		
	Feed intake	-0.71		
II	Maximum temperature	0.92	37.6	
	Minimum temperature	0.90		
	Daily weight gain	0.86		
	Daily mortality	-0.73		

Finisher

Component	Variables	Contribution value	% Variation	Total variance (%)
I	Feed intake	-0.98	55.1	73.5
	Maximum temperature	-0.95		
	Mean humidity	0.94		
	Months	0.92		
	Minimum temperature	0.88		
	Mean temperature	-0.88		
	Maximum humidity	0.87		
II	Minimum temperature	0.97	18.4	

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Table 3. Correlations of transformed variables within principal components in the pre-starter, starter, grower, and finisher phases

Pre-starter

	Month	DWG	maxT	minT	TIC	maxH	minH	HIC	FI
Month	1								
DWG	0.90	1							
maxT	0.96	0.85	1						
minT	0.81	0.65	0.93	1					
TIC	0.81	0.65	0.93	1.00	1				
maxH	0.39	0.25	0.46	0.47	0.47	1			
minH	0.39	0.25	0.46	0.47	0.47	1.00	1		
HIC	0.39	0.25	0.46	0.47	0.47	1.00	1.00	1	
FI	-0.95	-0.88	-0.95	-0.84	-0.84	-0.23	-0.23	-0.23	1

Starter

	Months	Sex	DWG	maxT	minT	TIC	maxH	minH	HIC
Month	1								
Sex	0	1							
DWG	-0.15	0.78	1						
maxT	0.97	0.11	-0.29	1					
minT	0.89	0.26	-0.40	0.91	1				
TIC	0.87	0.41	-0.59	0.92	0.96	1			
maxH	0.38	0.08	0.16	0.29	0.24	0.20	1		
minH	0.33	0.01	0.15	0.25	0.21	0.17	0.99	1	
HIC	0.36	0.03	0.14	0.28	0.24	0.20	0.99	0.99	1

Grower

	Month	DWG	maxT	minT	TIC	maxH	minH	HIC	Md	FI
Month	1									
DWG	0.53	1								
maxT	-0.85	-0.37	1							
minT	1.00	0.56	-0.82	1						
TIC	0.32	0.86	-0.01	0.36	1					
maxH	0.98	0.39	-0.87	0.99	0.16	1				
minH	1.00	0.53	-0.85	0.95	0.32	0.98	1			
HIC	0.97	0.32	-0.79	0.96	0.16	0.99	0.97	1		
Md	-0.85	-0.51	0.68	-0.84	-0.30	-0.84	-0.85	.-0.85	1	
FI	-0.83	-0.26	0.72	-0.83	-0.13	-0.85	-0.83	-0.83	0.45	1

Finisher

	Month	DWG	maxT	minT	TIC	maxH	Hmin	HIC	FI
Month	1								
DWG	-0.14	1							
maxT	-0.94	-0.10	1						
minT	-0.44	0.62	0.34	1					
TIC	-0.84	0.04	0.87	0.58	1				
maxH	0.99	-0.16	-0.95	-0.44	-0.85	1			
minH	1.00	-0.17	-0.93	-0.43	-0.81	0.99	1		
HIC	0.98	-0.09	-0.97	-0.41	-0.86	1.00	0.99	1	
FI	-1.00	0.14	0.94	0.44	0.84	-0.99	-0.96	-0.98	1

The results of the response surface analysis (Table 4) determined that the variables most affecting broiler development were TIC ($P < 0.001$) and, with a tendency, HIC ($P = 0.06$). Likewise, it was observed that the first three weeks of age had a negative effect on broiler development, which could be related to a slow growth phase, followed by an accelerated growth phase from week 4 of age onward. When considering the interaction of TIC with week, it was observed that this relationship was positive from weeks 1 to 4, and subsequently negative. However, in the case of the interaction of HIC with week, an inverted pattern was observed, negative during the first three weeks of age.

DISCUSSION

The optimal body weight values in broilers identified by the polynomial equations obtained from the response surface analysis, estimated for each stage of broiler development, evidenced quadratic surfaces during the first four weeks. Sánchez-Chiprés *et al.* (2021) indicate that the ideal temperature for broilers is in the range of 18 to 21 °C for optimal weight gain; however, they also emphasize that the thermal comfort temperature of birds changes as they grow, depending on the development of their thermoregulatory system.

Table 4. Coefficients of the factors considered for the response surface design

Term	Effect	Coef	SE Coef.	T-Value	P-Value	VIF
Constante		1.13304	0.00413	274.45	0.000	
TIC	-0.0838	-0.0419	0.0118	-3.56	0.000	5.00
HIC	-0.0192	-0.0096	0.00510	-1.88	0.060	1.82
Week						
1	-2.00083	-1.00041	0.00775	-129.02	0.000	6.44
2	-1.49180	-0.74590	0.00712	-104.71	0.000	5.44
3	-0.73946	-0.36973	0.00614	-60.20	0.000	4.04
4	0.21773	0.10886	0.00575	18.94	0.000	3.54
5	1.35619	0.67809	0.00739	91.78	0.000	5.85
6	2.6582	1.3291	0.0112	118.94	0.000	*
TIC*TIC	-0.1862	-0.0931	0.0393	-2.37	0.018	13.57
HIC*HIC	-0.1667	-0.0833	0.0138	-6.02	0.000	5.24
TIC*HIC	-0.1408	-0.0704	0.0335	-2.10	0.036	8.57
TIC*Week						
1	0.1996	0.0998	0.0370	2.70	0.007	25.48
2	0.0843	0.0422	0.0293	1.44	0.151	11.78
3	0.0256	0.0128	0.0247	0.52	0.604	7.90
4	0.3225	0.1613	0.0315	5.12	0.000	11.85
5	-0.3696	-0.1848	0.0358	-5.17	0.000	19.30
6	-0.2624	-0.1312	0.0467	-2.81	0.005	*
HIC*Week						
1	-0.0763	-0.0381	0.0175	-2.18	0.029	7.41
2	-0.0685	-0.0342	0.0142	-2.41	0.016	4.03
3	-0.0933	-0.0467	0.0134	-3.49	0.000	3.18
4	0.1347	0.0673	0.0116	5.78	0.000	2.38
5	0.1170	0.0585	0.0160	3.66	0.000	6.99
6	-0.0136	-0.0068	0.0207	-0.33	0.743	*

Therefore, in the first days, birds require an environmental temperature between 30–33 °C; later, in the fifth week, the optimal temperature is 22 °C, and in the sixth week, the optimal temperature ranges between 18–20 °C. In the case of the present study, the temperatures reached in the houses were 1–2 °C above the values already indicated as optimal; however, the humidity ranges in our study were within the limits (minimum and maximum) indicated by these authors, between 55 and 70 %, respectively. Cassuce *et al.* (2013) conducted a study with 600 COBB birds, which were distributed in five growth chambers maintained at different temperatures during the first three weeks of age. Using linear regression models, they concluded that the highest weight gains for broiler growth occurred at 31.3, 25.5, and 21.8 °C for the first, second, and third weeks of age, respectively. Likewise, these authors indicate that for temperate climates, various temperature ranges are considered optimal; however, for countries with tropical and subtropical climates, such as Brazil, the optimal ranges are considered 33–32 °C for the first week, 32–28 °C for the second, 28–26 °C for the third, 26–24 °C for the fourth, 18–24 °C for the fifth, and 18–24 °C for the sixth week of age, values that differ from those determined as optimal in our study (Table 5).

Table 5. Optimum TIC and HIC values for maximum BW using the regression equations generated by response surface analysis for each week of broiler age

Week	TIC (°C)*	HIC (%)*	BW (kg)*	Regression equation in uncoded units by week of age
1	28.82	31.28	**0.160**	-1.977 + 0.1228 TIC + 0.02348 HIC - 0.001886 TIC*TIC - 0.000168 HIC*HIC - 0.000450 TIC*HIC
2	26.16	35.38	**0.395**	-1.523 + 0.1146 TIC + 0.02366 HIC - 0.001886 TIC*TIC - 0.000168 HIC*HIC - 0.000450 TIC*HIC
3	25.07	35.17	**0.773**	-1.017 + 0.1104 TIC + 0.02310 HIC - 0.001886 TIC*TIC - 0.000168 HIC*HIC - 0.000450 TIC*HIC
4	29.60	44.35	**1.283**	-1.290 + 0.1316 TIC + 0.02822 HIC - 0.001886 TIC*TIC - 0.000168 HIC*HIC - 0.000450 TIC*HIC
5	14.21	63.80	**2.016**	0.544 + 0.0823 TIC + 0.02783 HIC - 0.001886 TIC*TIC - 0.000168 HIC*HIC - 0.000450 TIC*HIC
6	17.85	50.17	**2.552**	1.125 0.0899 TIC + 0.02489 HIC - 0.001886 TIC*TIC - 0.000168 HIC*HIC- 0.000450 TIC*HIC

*Values obtained by optimization of the response surface regression equations using the GRG algorithm of Solver®

Ogunlowo *et al.* (2024) indicate that the optimal relative humidity range for broilers after rearing is between 50 and 70 %. In this regard, Jongbo (2024) highlights that values above 75 % can induce heat stress in birds. The values reported as optimal are higher than those observed in the present study, as well as those identified as optimal. In the results obtained in the present study, the highest body weights were recorded in cycle 4, where HIC increased as bird age advanced: from 31 % (pre-starter phase) to 62 % (grower phase), and then remained at 58 % (finisher phase). However, the highest daily weight gain was found in cycle 3, in which HIC remained almost constant throughout the different production phases (between 42 and 46 % humidity).

CONCLUSIONS

The results demonstrate a significant and non-linear interaction between temperature and relative humidity, describing a quadratic relationship that allowed the identification of optimal values to maximize broiler body weight, depending on bird age. Response surface analysis enabled the estimation of specific combinations of both environmental variables under real commercial conditions. It is confirmed that their joint adjustment explains a substantial part of the productive variability and constitutes an applicable tool for optimizing environmental management and productive performance in commercial systems.

REFERENCES

ARANTES DE SOUSA LF, Pegoraro EL, Alves de Almeida E, Lunedo R, Furlan RL, Macari M. 2016. How heat stress (continuous or cyclical) interferes with nutrient digestibility, energy and nitrogen balances and performance in Broilers. *Livestock Science*. 192:39-43. https://doi.org/10.1016/j.livsci.2016.0814.0

AVIAGEN. 2022. Pollo de engorda ROSS 308 AP: objetivos de rendimiento. *Aviagen* EUA. https://aviagen.com/assets/Tech_Center/BB_Foreign_Language_Docs/Spanish_TechDocs-v2/RossxRoss308_BroilerPerformanceObjectives2022_ES.pdf

AYDAR AY. 2017. Utilization of response surface methodology in optimization of extraction of plant materials. In (Ed.), Statistical Approaches With Emphasis on Design of Experiments Applied to Chemical Processes. *IntechOpen*. https://doi.org/10.5772/intechopen.73690

CASSUCE D, Tinôco I, Baêta F, Zolnier S, Cecon P, Vieira MF. 2013. Thermal comfort temperature update for broiler chickens up to 21 days of age. *Engenharia Agrícola*. 33:28-36. https://doi.org/10.1590/S0100-69162013000100004

COBB-VANTRESS, INC. 2022. Cobb500TM Pollo de Engorde: Suplemento informativo de rendimiento y nutrición. https://www.cobbgenetics.com/assets/Cobb-Files/2022-Cobb500-Broiler-Performance-Nutrition-Supplement.pdf

DESHAZER JA, Hahn GL, Xin H. 2009. Chapter 1: Basic Principles of the Thermal Environment and Livestock Energetics. In J.A. DeShazer (Ed.), *Livestock Energetics and Thermal Environmental Management.* 1-22. St. Joseph, Mich.: ASABE. ASABE # 801M0309. ISBN: 1-892769-74-3. https://doi.org/10.13031/2013.28294

HAI L, Rong D, Zhang ZY. 2000. The Effect of environment on the digestion of Broilers. *Journal of Animal Physiology and Animal Nutrition*. 83:57-64. https://doi.org/10.1046/j.1439-0396.2000.00223.x

HASSAN FU, Alagawany M, Jha R. 2022. Editorial: Interplay of nutrition and genomics: Potential for improving performance and health of poultry. *Frontiers in Physiology*. 13:e1030995. https://doi.org/10.3389/fphys.2022.1030995

JONGBO AO. 2024. Effects of sidewall opening areas on the performance of broiler chickens and the indoor climatic conditions of backyard poultry building. *Acta Scientiarum: Animal Sciences*. 46:1-8. https://doi.org/10.4025/actascianimsci.v46i1.66396

KHURI A. 2017. Response surface methodology and its applications in agricultural and food sciences. *Biometrics & Biostatistics International Journal*. 5(5):155-163. https://doi.org/10.15406/bbij.2017.05.00141

LITTELL CR, Milliken AG, Stroup WW, Wolfinger DR, Schabenberger O. 2006. SAS® for Mixed Models. 2da edición. Cary, NC: SAS Institute Inc. Pp. 733-735. https://es.scribd.com/document/916775419/SAS-for-Mixed-Models-2nd-ed-Edition-Ramon-C-Littell-instant-access-2025

LITTELL CR, Stroup WW, Freund JR. 2002. SAS® for Linear Models. Cuarta edición. Cary, NC: SAS Institute Inc. Pp. 191-194. https://typeset.io/pdf/sas-for-linear-models-4xf4c34car.pdf

MONTANERO FJ. 2008. Análisis multivariante. Universidad de Extremadura, Servicio de Publicaciones. ISBN: 978-84-691-6343-6.
https://dehesa.unex.es/entities/publication/5a590025-a7f4-4dd7-a986-b55874d4c071

MONTGOMERY D. 2002. Diseño y análisis de experimentos. 2da edición. México: Editorial Limusa. ISBN: 968-18-6156-6.
https://www.researchgate.net/publication/362079778_Design_and_Analysis_of_Experiments_9th_Edition

MUZZAMMIL M, Javed A, Zakwan M. 2015. An optimization technique for estimation of rating curve parameters. Indian Association of Hydrologists (IAH), Roorkee. Symposium on Hydrology, 22-23 diciembre 2015, Nueva Delhi, India. Pp. 234–240. https://www.researchgate.net/publication/305767208_AN_OPTIMIZATION_TECHNIQUE_FOR_ESTIMATION_OF_RATING_CURVE_PARAMETERS

NILIPOUR A. 2012. Pollo moderno- cómo obtener el máximo rendimiento- Desafío, oportunidades y metas. http://www.engormix.com/MA-avicultura/manejo/articulos/pollo-moderno-como-obtener-t4082/124-p0.htm

OGUNLOWO QO, Adedayo AA, Wook HN, Anis R, Misbaudeen AA, Ezatullah Z, John AA, Bukola OA, Kosemani BS, Ilori TA, Lee HW. 2024. Analysis of microclimate temperature and relative humidity distribution of local poultry house in a subtropical area of Nigeria. *Journal of Agricultural Engineering*. 55(2):e1561.
https://doi.org/10.4081/jae.2024.1561

OMOMOWO O, Falayi F. 2021. Temperature-humidity index and thermal comfort of broilers in humid tropics. *Agricultural Engineering International: The CIGR e-journal*. 23:101-110. https://cigrjournal.org/index.php/Ejounral/article/view/6425/3677

PISHGAR-KOMLEH S, Keyhani A, Mostofi-Sarkari M, Jafari A. 2012. Application of response surface methodology for optimization of picker-husker harvesting losses in corn seed. *Iranica Journal of Energy & Environment*. 3(2):e64390. https://www.ijee.net/article_64390.html

QUINTANA LJA. 2020. Manejo del pollo de engorda durante su primera semana de vida. *Avicultores y su Entorno.* BM Editores. Año 20, n.° 122. https://bmeditores.mx/avicultura/manejo-del-pollo-de-engorda-durante-su-primera-semana-de-vida/

SÁNCHEZ-CHIPRÉS DR, Valera-Rojas M, Casasola-Torres RA, Gutiérrez-Borroto O, Mireles-Flores S. 2021. Atenuación del estrés calórico en pollos con la suplementación de un producto de cromo orgánico. *Revista Colombiana de Ciencia Animal - RECIA*. 13(1):e792. https://doi.org/10.24188/recia.v13.n1.2021.792

SONG Z, Liu L, Sheikhahmadi A, Jiao H, Lin H. 2012. Effect of heat exposure on gene expression of feed intake regulatory peptides in laying hens. *Journal of Biomedicine and Biotechnology*. 2012, e484869. https://doi.org/10.1155/2012/484869

TAHERI A, Kenari AA, Motamedzadegan A, Habibi-Rezaei M. 2011. Poultry by-products and enzymatic hydrolysis: optimization by response surface methodology using alcalase® 2.4L. *International Journal of Food Engineering*. 7(5):e1969. https://doi.org/10.2202/1556-3758.1969

TAO X, Xin H. 2003. Acute synergistic effects of air temperature, humidity, and velocity on homeostasis of market-size broilers. *Transactions of the ASAE*. 46:e12971. https://doi.org/10.13031/2013.12971

TORRES V, Ramos N, Lizazo D, Monteagudo F, Noda A. 2001. Modelo estadístico para la medición del impacto de la innovación o transferencia tecnológica en la rama agropecuaria. *Revista Cubana de Ciencia Agrícola.* 42(2):133-139. https://www.redalyc.org/articulo.oa?id=193015494003

WILLIAMS Y, Basitereb M, Ntwampea SKO, Ngonganga M, Njoyaa M, Kaskotea E. 2019. Application of response surface methodology to optimize the COD removal efficiency of an EGSB reactor treating poultry slaughterhouse wastewater. *Water Practice and Technology*. 14(3):507-514. https://doi.org/10.2166/wpt.2019.032