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Effects of thermal control systems on body reserve mobilization and metabolic responses in sows during late gestation and lactation

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Abstract

This study evaluated the effect of thermal control systems on body reserve mobilization and metabolic responses in sows during late gestation and lactation. A total of 140 sows (Yorkshire × Landrace) were evaluated under commercial conditions with either manual (MTC) or automated thermal control (ATC) systems. Temperature–humidity index (THI), daily feed intake (DFI), and productive performance were recorded. Blood metabolites including glucose, urea, β-hydroxybutyrate (BHB), and non-esterified fatty acids (NEFA) were determined. Associations among environmental variables, DFI, and metabolic indicators were analyzed using correlation and linear regression models. During lactation, DFI was higher under ATC (5.78 vs. 4.52 kg/day; $p = 0.0011$), accompanied by reduced body weight loss (8.34 vs. 14.70 kg; $p < 0.0001$) and fat mass loss (9.22 vs. 13.17 kg; $p < 0.0001$). Concentrations of glucose (73.05 vs. 66.8 mg/dL), NEFA (0.36 vs. 0.30 mmol/L), BHB (0.59 vs. 0.48 mmol/L), and urea (33.9 vs. 23.8 mg/dL) were higher under MTC ($p < 0.05$). Under MTC conditions, THI was positively correlated with glucose ($r = 0.66$), NEFA ($r = 0.64$), and BHB ($r = 0.73$; $p < 0.0001$), whereas DFI showed negative correlations ($r = −0.78$ to $−0.63$; $p < 0.0001$). THI was a significant predictor of NEFA ($\beta = 0.18$) and BHB ($\beta = 0.23$). Furthermore, ATC increased the number of weaned piglets and weaning weight, and reduced the weaning-to-estrus interval ($p < 0.05$). These results demonstrate that ATC reduced lipolytic activation and improved productive efficiency, confirming the regulatory role of thermal load on maternal metabolism.

Keywords: Heat stress; Temperature–humidity index; Energy balance; Non-esterified fatty acids (NEFA); β-hydroxybutyrate (BHB); Metabolic adaptation.

Introduction

Heat stress represents one of the main physiological challenges in intensive swine production systems, particularly during the gestation–lactation transition, a period characterized by high energy demand, increased metabolic heat production, and activation of thermoregulatory and endocrine mechanisms (Mayorga et al., 2019; Bjerg et al., 2020). When ambient temperature exceeds the thermoneutral zone, the animal's capacity for heat dissipation is compromised, leading to a sustained increase in body temperature and respiratory rate. This phenomenon is further exacerbated during lactation due to the increased metabolic heat production associated with milk synthesis (Williams et al., 2013; Katiyar et al., 2025). Under these conditions, reduced feed intake constitutes an adaptive response aimed at decreasing diet-induced thermogenesis; however, this strategy exacerbates negative energy balance during a physiologically demanding stage characterized by high metabolic requirements (Mosnier et al., 2010; Renaudeau et al., 2012).

However, heat stress–induced alterations are not limited to changes in feed intake patterns. Exposure to elevated temperatures has been shown to modify metabolic regulation independently of feed intake, promoting a catabolic state characterized by increased mobilization of non-esterified fatty acids and alterations in hormonal signaling associated with energy balance (Prunier et al., 1997; Williams et al., 2013). This metabolic condition is of particular reproductive relevance, as energy availability and peripheral metabolic regulation influence the dynamics of the hypothalamic–pituitary–ovarian axis and may impair reproductive recovery after weaning (Ma et al., 2023). Consequently, the impact of heat stress on reproductive performance should be interpreted as the result of an integrated interaction among thermal load, energy balance, and systemic endocrine regulation.

During gestation, exposure to elevated thermal conditions can compromise embryonic viability and alter the intrauterine environment (Boni, 2019). Reduced conception rates and embryonic survival have been reported when ambient temperature exceeds critical thresholds (Wegner et al., 2014), along with potential effects on offspring metabolic programming derived from alterations in maternal endocrine status (Lucy and Safranski, 2017). Furthermore, susceptibility to heat stress is not uniform among individuals, as factors such as age, physiological status, body condition, productive level, and genetics influence the magnitude of metabolic and hormonal responses to thermal load (Ross et al., 2015, 2017). These variables can modify energy and endocrine profiles, thereby affecting the animal's adaptive capacity under adverse environmental conditions. It has been suggested that selection for high prolificacy and

74 lean efficiency may have reduced thermal tolerance margins in modern genetic lines, increasing their vulnerability
75 during periods of high metabolic demand (Johnson et al., 2023; Oster et al., 2025).

76 The magnitude of heat stress perceived by the sow depends not only on absolute ambient temperature, but
77 also on its interaction with relative humidity and the efficiency of the ventilation system (Godyń et al., 2020; Villa-
78 Mancera et al., 2024). Increases in relative humidity elevate effective temperature and reduce evaporative heat
79 dissipation capacity, thereby intensifying thermal load even when ambient temperature remains relatively constant (Ma
80 et al., 2023). In this context, systems with manual environmental control may generate greater thermal variability
81 compared to automated systems that continuously stabilize environmental conditions. This can result in measurable
82 physiological differences in feed intake, body reserve mobilization, and productive performance (Fernandes et al.,
83 2023).

84 Despite the experimental evidence on the physiological effects of heat stress under controlled conditions,
85 there remains limited information integrating, under real commercial production scenarios, the type of thermal control
86 system with maternal metabolic dynamics and productive performance during the gestation–lactation transition. Most
87 available studies have been conducted under controlled environments (Vilas et al., 2018), whereas under commercial
88 conditions the interaction among environment, genetics, and physiological status may modulate the magnitude of the
89 observed response. In this context, it was hypothesized that an automated thermal control system would reduce the
90 thermal load perceived by the sow and, consequently, decrease the mobilization of body reserves associated with
91 negative energy balance during the gestation–lactation transition. Based on this premise, the objective of the present
92 study was to comparatively evaluate two commercial swine production systems operating under manual and automated
93 thermal control schemes, determining their effects on body reserve mobilization and metabolic responses in sows
94 during late gestation and lactation.

95 **Materials and Methods**

96 ***Animal care***

97 The experimental protocol was reviewed and approved by the Scientific and Technical Committee of CENID–
98 Fisiología y Mejoramiento Animal. Animal handling procedures were conducted in accordance with the Mexican

Official Standard for the Production, Care, and Use of Laboratory Animals NOM-062 (NOM-062-ZOO, 1999), as well as with the International Guiding Principles for Biomedical Research Involving Animals (CIOMS, 2012).

Animals, diets and housing

This experiment was conducted in two commercial farrow-to-finish swine production systems belonging to the same operation, one operating under manual thermal control (MTC) and the other under automated thermal control (ATC). In both systems, a total of 140 sows (70 per system; Yorkshire × Landrace) were monitored from day 85 of gestation until weaning.

The system operating under MTC consisted of conventional facilities in which environmental regulation relied primarily on human intervention. Thermal management was achieved through manual adjustment of side curtains, intermittent use of wall-mounted axial fans, and operational decisions based on personnel perception, external climatic conditions, and the physiological stage of the sows. In contrast, the ATC system was equipped with a mechanized and electronically regulated environmental control scheme. Temperature and relative humidity were continuously monitored using environmental sensors placed at animal level, which automatically controlled the operation of fans, exhaust systems, air inlets, and, when required, evaporative cooling systems.

Both systems were evaluated under real commercial production conditions, without additional experimental modifications, in order to compare the impact of thermal control type on productive, metabolic, and physiological performance of sows during the gestation–lactation transition.

During gestation, sows were housed in individual crates (217 × 64 × 110 cm; length, width, and height, respectively). Throughout gestation, sows were fed according to their body condition score (BCS; Table 1), which was assessed visually following the guidelines of Young et al. (2004). All feeding levels described in Table 1 were provided in two daily meals at 08:00 and 16:00 h. Diets were formulated and supplemented with vitamins and minerals to meet or exceed the nutritional requirements recommended by the NRC (2012) for each physiological stage evaluated. Table 2 presents the ingredients and nutritional composition of the diets used in the experiment.

At farrowing and during lactation, sows were housed in conventional stainless steel farrowing crates equipped with plastic slatted flooring, remaining in these facilities until weaning of the litters (21 ± 1 days postpartum). Farrowing was not induced and occurred naturally at 115 ± 0.41 days of gestation. During lactation, sows were fed ad

libitum. To stimulate daily feed intake (DFI), feed was offered three times per day (08:00, 12:00, and 16:00 h). Feed refusals were collected and weighed daily in the morning prior to the provision of the corresponding ration. Reproductive and productive parameters were recorded, including total number of piglets born, born alive, stillborn, and mummified, as well as the number of piglets weaned. Additionally, individual piglet body weights were recorded at birth and weekly throughout lactation.

Environmental conditions, thermal monitoring, and temperature–humidity index

To evaluate the effect of ambient temperature according to the type of thermal control system, climatic data corresponding to the period from January to May 2025 were used, representing the seasonal conditions during the gestation and lactation phases of the sows. Both production systems were located within the same geographical region; therefore, ambient temperature and relative humidity data were obtained from common local climatic records corresponding to the study area.

Additionally, internal temperature and relative humidity within the gestation and lactation facilities were continuously recorded using HOBO MX2302® environmental sensors (Onset Computer Corporation, Bourne, MA, USA). Sensors were positioned at animal level and protected from direct radiation and water contact. These devices allowed for the characterization of the actual microclimatic conditions inside the facilities under MTC and ATC systems. Figure 1 illustrates the daily dynamics of external ambient temperature and relative humidity, as well as the internal microclimatic conditions within the facilities (temperature and relative humidity) throughout the evaluation period.

To integrate the combined effects of temperature and relative humidity on the thermal environment perceived by the sows, the temperature–humidity index (THI; Figure 1) was calculated. The THI was estimated using the following equation:

$$THI = 0.8T + RH(T - 14.4) + 46.6$$

where T corresponds to ambient temperature (°C) and RH to relative humidity (%).

Measurements

Body weight and backfat thickness of sows were determined on day 85 of gestation, at transfer to the lactation unit (≈110 to ≈112 days of gestation), and at weaning. All measurements were performed by the same operator. Backfat thickness was measured at the P2 position (Maes et al., 2004) on both sides of the spine using ultrasound (Renche Lean Affe, S.E.C. Repro Inc., Québec, Canada). The final value was calculated as the average of two measurements. Sows were weighed using a fixed electronic scale (STG-1500-T1500SL, OCONY®; 1–1500 kg). Postpartum sow body weight was estimated using the equation proposed by Mallmann et al. (2018):

$$\text{PoFBW, kg} = 13.03 + (0.93 \times \text{PrFBW, kg}) + (-1.23 \times \text{ PB, n})$$

where PoFBW is postfarrowing body weight, PrFBW is prefarrowing body weight, and PB is the number of piglets born.

Protein and fat mass of the sows at day 85 of gestation, at ≈110 to ≈112 days of gestation, and at weaning were estimated using the equations proposed by Dourmad et al. (1997):

$$PM, kg = 2.28 + 0.178 \times (\text{LBW, kg}) - 0.333 \times (\text{BFT, mm})$$

$$FM, kg = -26.40 + 0.221 \times (\text{LBW, kg}) + 1.331 \times (\text{BFT, mm})$$

where PM is protein mass, FM is fat mass, LBW is live body weight, and BFT is backfat thickness.

Piglets were weighed at birth and weekly throughout lactation using a digital scale (Dibatec®; 0.005–40 kg).

Sampling and analysis

For blood and milk composition analyses, a subgroup of 30 sows per thermal control system was selected, taking parity into account. Within each group, 10 primiparous sows, 10 second-parity sows, and 10 sows with three or more parities were included.

Blood sampling

On day 85 of gestation and on days 0, 7, and 21 of lactation, a 10 mL blood sample was collected from each sow under fasting (preprandial) conditions. On each sampling day, a snare was applied to the upper jaw of each animal to facilitate sample collection, which was performed from the jugular vein using a syringe fitted with an 18G × 200 hypodermic

needle. Samples were collected between 07:30 and 08:00 h, following approximately 16 h of fasting in gestating sows and approximately 10 h in lactating sows (feed was withdrawn at 22:00 h).

Immediately after blood collection, each sample was divided into two aliquots: 4 mL in tubes with a clot activator for glucose and urea analysis, and 4 mL in lithium heparin tubes for the determination of β-hydroxybutyrate (BHB) and non-esterified fatty acids (NEFA). Aliquots were maintained at 4 °C until centrifugation at 1,000 × g for 10 min. Serum and plasma were then stored at −20 °C until further analysis.

Serum glucose and urea concentrations were determined using enzymatic methods adapted to a Cobas c 111 analyzer (Roche, Basel, Switzerland). The reagents used were: for glucose, GLUH2 (ref. 04 657 527 190, USA; sensitivity: 2.0 mg/dL; intra- and inter-assay coefficients of variation: <1.0% and <1.9%, respectively, at 128.0 mg/dL); and for urea, UREAL (ref. 04 657 616 190, USA; sensitivity: 6.5 mmol/L; intra- and inter-assay coefficients of variation: <5.0% and <12.0%, respectively, at 40 mmol/L).

Plasma BHB concentrations were determined using an enzymatic colorimetric method based on the conversion catalyzed by β-hydroxybutyrate dehydrogenase. For this analysis, commercial Randox® β-Hydroxybutyrate kits (ref. R-BHB, RB1009) were used (minimum sensitivity ~0.02 mmol/L; working range ~0.1 to 8.0 mmol/L). NEFA concentrations were quantified using an enzymatic colorimetric assay based on sequential enzymatic reactions involving acyl-CoA synthetase and acyl-CoA oxidase. Commercial Wako NEFA-HR(2) kits (ref. 434-91995) were used for this analysis (measurement range: 0.1–2.0 mmol/L; sensitivity ~0.02–0.05 mmol/L). For both metabolites, absorbance was measured using a benchtop spectrophotometer at assay-specific wavelengths (340 nm for BHB and 550–560 nm for NEFA), according to the manufacturer's specifications.

Milk sampling

For milk composition analysis, 10 mL milk samples were collected from each sow on days 1, 7, and 21 of lactation. Prior to sample collection, sows received an intramuscular injection of 2 mL of oxytocin (Oxitopisa®, Pisa Agropecuaria, Mexico) to stimulate milk letdown. Approximately five minutes after oxytocin administration, the udder was manually massaged to facilitate milk ejection, followed by manual extraction (milking) directly from functional teats.

Milk samples were collected in sterile containers, avoiding external contamination, and maintained at 4 °C immediately after milking. Milk composition analysis was performed within the first hour after collection using an automatic milk analyzer (Lactoscan®), which allowed determination of lactose, protein, and fat content, following the manufacturer's recommended procedures and calibration guidelines.

Statistical analysis

All statistical analyses were performed using SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA). Prior to analysis, normality and homogeneity of variances were assessed using PROC UNIVARIATE. Normality was evaluated using the Kolmogorov–Smirnov test ($p < 0.05$), and homogeneity of variances was assessed using Bartlett's test. Data were analyzed using analysis of variance (ANOVA) with repeated measures through PROC MIXED (Littell et al., 1998). The experimental unit was the sow. Sows nested within group (MTC or ATC) were considered as a random effect. The effects of group, parity, time (day or week of evaluation), and their interactions were evaluated for daily feed intake (DFI), metabolic indicators, and the corresponding productive variables. The model used was:

$$Y_{ijklm} = \mu + G_i + S(G)_{j(i)} + P_k + D_l + G \times P_{ik} + G \times D_{il} + G \times P \times D_{ikl} + e_{ijklm}$$

where Y_{ijklm} is the response variable; μ is the overall population mean; G_i represents the fixed effect of the ^{i}th group (i = MTC, ATC); $S(G)_{j(i)}$ is the random effect of the ^{j}th sow nested within the ^{i}th group; P_k is the fixed effect of the ^{k}th parity (k = 1, 2, and ≥3 parities); D_l is the fixed effect of the ^{l}th day of evaluation (l = 85, 86, …, 115 for gestation and 0, 1, …, 21 for lactation); $(G \times P)_{ik}$ is the fixed effect of the interaction between the ^{i}th group and the ^{k}th parity; $(G \times D)_{il}$ is the fixed effect of the interaction between the ^{i}th group and the ^{l}th day of evaluation; $(G \times P \times D)_{ikl}$ is the fixed effect of the three-way interaction among group, parity, and day of evaluation; and e_{ijklm} is the random residual error associated with each observation, assumed to be normally and independently distributed with mean zero and variance $\sigma_e^2 \sim \text{NID}(0, \sigma_e^2)$.

To evaluate associations between environmental variables and metabolic indicators in lactating sows under MTC and ATC systems, Pearson correlation coefficients were estimated using PROC CORR. Ambient temperature and THI were considered as environmental variables, while DFI during lactation and serum concentrations of glucose, NEFA, BHB, and urea were included as metabolic variables. Correlations were estimated independently for each thermal control system.

To determine whether the associations between environmental variables and metabolic biomarkers were maintained independently of DFI or thermal load, partial Pearson correlations were performed using the PARTIAL option in PROC CORR. Based on a priori physiological hypotheses, associations between THI and glucose, NEFA, and BHB were evaluated adjusting for DFI, as well as associations between DFI and metabolic biomarkers adjusting for THI. Additionally, multiple linear regression models were fitted using PROC MIXED to quantify the effects of THI, DFI, and thermal control system on serum concentrations of glucose, NEFA, and BHB during lactation. In these models, the system (MTC vs. ATC) was included as a fixed effect, along with the THI × system interaction, while sow was included as a random effect to account for within-animal dependency.

Differences between means were determined using the least squares means (LSMeans) method, with a significance level of $\alpha \leq 0.05$. Results are presented as least squares means ± standard error of the mean (SEM). In the Results section, only the main effects and the most relevant interactions describing the biological phenomenon are reported.

Results

Effect of thermal control system and parity during late gestation

DFI between day 85 and day 115 of gestation was not affected by the thermal control system ($p = 0.1260$) or parity ($p = 0.1142$), and no thermal control system × parity interaction was detected ($p = 0.5762$) (Table 3).

Body weight at day 85 of gestation and at farrowing was influenced by parity ($p = 0.0018$), but not by the thermal control system ($p = 0.2280$). In both systems, multiparous sows (≥3 parities) exhibited higher body weight compared with primiparous sows (Table 3). No significant thermal control system × parity interaction was observed for this variable. Backfat thickness at day 85 of gestation and at farrowing did not show significant differences associated with either the thermal control system or parity ($p > 0.05$), and no significant interactions were detected (Table 3).

Estimated protein mass at day 85 of gestation was affected by parity ($p = 0.0194$), with higher values observed in multiparous sows compared with primiparous sows (Table 3). This parity effect was also maintained at farrowing ($p = 0.0289$). The thermal control system did not significantly influence this variable ($p > 0.05$), and no thermal control system × parity interaction was detected (Table 3). Similarly, estimated fat mass at day 85 of gestation and at farrowing

was affected by parity ($p = 0.0195$), with greater reserves in sows with higher parity (Table 3). No significant effects of the thermal control system ($p > 0.05$) or thermal control system × parity interaction were observed (Table 3).

Effect of thermal control system and parity during lactation

As shown in Table 4, DFI during lactation was higher ($p < 0.05$) under ATC compared with MTC across all evaluated periods. During days 1–7, DFI was 4.45 kg in the automated system versus 3.70 kg in the manual system ($p = 0.0003$). Between days 8–14, DFI reached 6.35 kg under ATC and 4.91 kg under MCT ($P < 0.0001$), whereas during days 15–21 it was 6.54 kg and 4.94 kg, respectively ($p < 0.0001$). Over the entire lactation period, sows under ATC consumed 5.78 kg/day compared with 4.52 kg/day under MTC ($p = 0.0011$). Parity affected DFI during days 1–7 ($p = 0.0058$), days 8–14 ($p = 0.0027$), and days 15–21 ($p < 0.0001$) (Table 4). Additionally, a significant effect of week ($p = 0.0001$) and a thermal control system × week interaction were detected for cumulative feed intake ($p = 0.0019$), indicating a progressive increase in DFI as lactation advanced (Table 4).

Body weight at weaning was higher in the ATC system (234.72 kg) compared with the MTC system (223.61 kg), with effects of thermal control system ($p = 0.0008$) and parity ($p < 0.0001$) (Table 4). A significant thermal control system × parity interaction was also detected ($p = 0.0010$) (Table 4). Estimated maternal body weight loss was lower under ATC (8.34 kg) compared with MTC (14.70 kg; $p < 0.0001$). Similarly, total body weight loss was reduced in the ATC system (28.50 kg) relative to MTC (34.50 kg; $p = 0.0002$). In both cases, parity effects were observed ($p < 0.05$; Table 4), along with significant thermal control system × parity interactions ($p < 0.05$; Table 4).

Backfat thickness at weaning was higher under ATC (16.15 mm) compared with MTC (14.59 mm; $p = 0.0438$). Backfat loss during lactation was lower in the ATC system (2.20 mm) than in MTC (4.17 mm; $p < 0.0001$), with additional effects of parity ($p = 0.0006$) and a significant thermal control system × parity interaction ($p < 0.0001$) (Table 4). Estimated fat mass at weaning was greater under ATC (46.97 kg) compared with MTC (42.45 kg; $P = 0.0014$). Likewise, fat mass loss was lower in the ATC system (9.22 kg) than in MTC (13.17 kg; $p < 0.0001$), with a significant effect of parity ($p = 0.0109$) and a thermal control system × parity interaction ($p = 0.0027$) (Table 4). In contrast, estimated protein mass at weaning was not affected by the thermal control system (38.68 vs. 37.22 kg; $P = 0.1257$), although a parity effect was observed ($p < 0.05$; Table 4). Protein mass loss was not affected by thermal control ($p = 0.2012$) or parity ($p = 0.1198$) (Table 4).

Effect of thermal control system and parity on milk composition and litter performance

Milk fat concentration was affected by the thermal control system and day of lactation (Table 5). On day 7, sows under ATC exhibited higher fat content (8.02%) compared with those under MTC (7.58%; P = 0.0256). A significant effect of day was observed ($p < 0.0001$), with a progressive increase toward day 21 (Table 5).Significant thermal control system × parity ($p = 0.0309$) and thermal control system × parity × day interactions ($p = 0.0285$) were also detected (Table 5).

Milk protein content was not affected by the thermal control system ($p = 0.6064$) or parity ($p = 0.6585$), but it was influenced by day of lactation ($p < 0.0001$), showing a decrease from day 1 to day 21 (Table 5). A similar pattern was observed for milk lactose concentration, which was also not affected by the thermal control system ($p = 0.9849$) or parity ($p = 0.6155$), but was influenced by day of lactation ($p < 0.0001$), with a progressive increase toward the end of lactation (Table 5).

Regarding litter development, the total number of piglets born was not affected by the thermal control system ($p = 0.0873$) or parity ($p = 0.0616$) (Table 5). The number of piglets born alive was influenced by parity ($p = 0.0378$), but not by the thermal control system ($p = 0.1197$) (Table 5). The number of piglets weaned was higher under ATC (11.9 piglets) compared with MTC (11.2 piglets; $p = 0.0429$). A significant effect of parity ($p = 0.0189$) and a thermal control system × parity interaction ($p = 0.0439$) were also observed (Table 5).

Piglet body weight did not differ at birth ($p > 0.40$). However, at day 7, it was higher under ATC (2.44 kg) compared with MTC (2.26 kg; $p = 0.0061$). This difference was maintained at day 14 (4.16 vs. 3.84 kg; $p = 0.0061$) and at weaning (6.23 vs. 5.85 kg; $p = 0.0061$). A significant effect of parity was also observed ($p = 0.0412$) (Table 5). The weaning-to-estrus interval was reduced under ATC (5.0 vs. 6.1 days in MTC; $p = 0.0218$). Parity did not show a significant effect ($p = 0.1834$), although the thermal control system × parity interaction was significant ($p = 0.0244$) (Table 5).

Influence of thermal control system and parity on metabolic response during the gestation–lactation transition

As shown in Table 6, serum glucose concentrations were affected by the thermal control system ($p = 0.0041$), parity ($p = 0.0109$), and day of evaluation ($p < 0.0001$), with a significant thermal control system × parity × day interaction ($p = 0.0008$) (Table 6). Mean glucose concentration was higher in the MTC system (73.05 mg/dL) compared with ATC (66.8 mg/dL). Glucose concentrations reached their peak at farrowing (95.28 mg/dL in primiparous sows under MTC), followed by a decline during lactation, particularly on days 7 and 21 (Table 6).

NEFA concentrations were also affected by the thermal control system ($p = 0.0010$), parity ($p = 0.0409$), and day of evaluation ($p < 0.0001$), with a significant thermal control system × parity × day interaction ($p = 0.0300$) (Table 6). The overall mean was higher in the MTC system (0.36 mmol/L) compared with ATC (0.30 mmol/L). Under MTC conditions, peak concentrations were observed at farrowing (≈0.47 mmol/L). Although values declined during lactation, they remained consistently higher than those observed under ATC (Table 6).

For BHB, a significant effect of the thermal control system was detected ($p = 0.004$), along with a marginal effect of parity ($p = 0.0517$) and a significant effect of day of evaluation ($p < 0.0001$), as well as a thermal control system × parity × day interaction ($p = 0.0465$) (Table 6). Mean concentrations were higher under MTC (0.59 mmol/L) compared with ATC (0.48 mmol/L). BHB levels peaked at farrowing (up to 0.80 mmol/L in second-parity sows under MTC) and declined toward day 21 of lactation, particularly under ATC (0.36 mmol/L).

Regarding serum urea, significant effects of the thermal control system ($p = 0.0076$), parity ($p = 0.0095$), and day of evaluation ($p < 0.0001$) were observed, along with a significant thermal control system × parity × day interaction ($p = 0.0081$) (Table 6). The overall mean was higher in the MTC system (33.9 mg/dL) compared with ATC (23.8 mg/dL). The highest concentrations were recorded toward day 21 of lactation under MTC (up to 40.41 mg/dL), whereas under ATC values remained considerably lower (≈22 mg/dL) (Table 6).

Correlations between environmental variables and metabolic biomarkers in lactating sows

As shown in Table 7, under MTC conditions, temperature and THI were positively and significantly correlated ($p < 0.0001$) with glucose ($r = 0.80$ and 0.66), NEFA ($r = 0.65$ and 0.64), and BHB ($r = 0.67$ and 0.73), indicating a strong association between thermal load and metabolic mobilization. DFI showed strong negative correlations ($p < 0.0001$) with glucose ($r = −0.78$), NEFA ($r = −0.63$), and BHB ($r = −0.70$).

Under ATC conditions, these associations remained significant but were of lower magnitude (e.g., THI–BHB $r = 0.53$; THI–NEFA $r = 0.45$; $p < 0.0001$). Negative correlations between DFI and metabolites also persisted, although attenuated (NEFA $r = −0.40$; BHB $r = −0.44$).

Regarding partial correlation analysis to determine whether the relationship between thermal load and metabolic biomarkers was maintained independently of DFI or THI (Table 8), under MTC conditions, after adjusting for DFI, the associations between temperature and glucose ($r = 0.73$), NEFA ($r = 0.55$), and BHB ($r = 0.57$) remained

highly significant ($p < 0.0001$). Similarly, correlations between THI and glucose ($r = 0.56$), NEFA ($r = 0.56$), and BHB ($r = 0.68$) remained significant after adjustment, indicating that the relationship between thermal load and metabolic activation was not exclusively mediated by reduced DFI.

In the ATC system, these associations also persisted after adjustment for DFI, although with lower magnitude (temperature–glucose $r = 0.71$; temperature–NEFA $r = 0.39$; temperature–BHB $r = 0.42$; THI–BHB $r = 0.46$; $p < 0.05$), suggesting an attenuation of the thermal effect on metabolic response. When correlations were adjusted for THI, DFI showed significant negative associations with glucose, NEFA, and BHB in both systems (Table 8).

Under MTC, correlations were stronger (DFI–glucose $r = -0.73$; DFI–NEFA $r = -0.56$; DFI–BHB $r = -0.62$; $p < 0.0001$), whereas under ATC, associations were of lower magnitude (Table 8).

Following the correlation analyses (Tables 7 and 8), mixed linear regression models were fitted to simultaneously evaluate the effects of THI, feed intake, and thermal control system on metabolic biomarkers (Table 9).

For glucose, both THI ($\beta = -0.27$; $p < 0.001$) and DFI ($\beta = -0.57$; $p < 0.001$) were significant predictors (Table 9). The effect of the thermal control system was not significant ($p = 0.5421$), nor was the THI × system interaction ($p = 0.6835$). The model explained 75% of the observed variability ($R^2 = 0.75$). For NEFA, THI showed a positive effect ($\beta = 0.18$; $p = 0.0309$), whereas DFI had a stronger negative effect ($\beta = -0.43$; $p < 0.0001$). The thermal control system was not significant ($p = 0.4208$), and the THI × system interaction showed a trend ($p = 0.0815$). The model explained 48% of the variability ($R^2 = 0.48$). For BHB, both THI ($\beta = 0.23$; $p = 0.0001$) and DFI ($\beta = -0.46$; $p < 0.0001$) were significant predictors (Table 9). No independent effect of the thermal control system ($p = 0.3365$) or significant interaction ($p = 0.1018$) was observed. The model explained 53% of the variability ($R^2 = 0.53$). Finally, when DFI was considered as the dependent variable, THI showed a significant negative effect ($\beta = -0.30$; $p < 0.0001$), whereas the thermal control system ($p = 0.6542$) and its interaction with THI ($p = 0.8638$) were not significant.

Discussion

Heat stress represents one of the major physiological challenges in intensive swine production systems, particularly in regions with high thermal variability and environmental humidity. Beyond its productive implications, environmental thermal load acts as a systemic modulator integrating thermoregulatory, metabolic, and endocrine responses, thereby

affecting maternal energy partitioning and reproductive efficiency. Previous studies have demonstrated that the gestation–lactation transition constitutes a period of heightened vulnerability, during which metabolic heat production, body reserve mobilization, and neuroendocrine activation interact in a complex manner in response to increases in ambient temperature (Renaudeau et al., 2012; Williams et al., 2013). In this context, the ability of housing systems to modulate effective thermal load may play a decisive role in maintaining metabolic stability in the sow.

The present results confirm that heat stress should not be interpreted solely as an external environmental factor, but rather as a central modulator of the sow's energetic and reproductive physiology (Ross et al., 2017). The consistent association between higher values and variability of THI under the MTC system and the increase in markers of lipid mobilization suggests that even small variations in effective thermal load are sufficient to disrupt metabolic homeostasis during the gestation–lactation transition. Previous reports have established that the upper critical temperature in sows is around 25 °C, while also emphasizing that relative humidity increases effective temperature (Ma et al., 2023); thus, an increase in relative humidity from 50% to 70% may correspond to nearly a 1 °C increase in thermal load. This phenomenon is particularly relevant in manually ventilated systems, where evaporative heat dissipation may be less efficient and more variable.

In the present study, the greater mobilization of NEFA under higher THI confirms that sows respond to heat stress by intensifying negative energy balance. It has been demonstrated that during lactation, heat stress increases rectal temperature and respiratory rate more markedly than during gestation, indicating that lactation represents the period of greatest thermal vulnerability due to the elevated metabolic heat production associated with milk synthesis (Williams et al., 2013; Xiong et al., 2022). This increased internal thermal load promotes a reduction in DFI as a compensatory mechanism, a phenomenon widely reported in the literature (Renaudeau et al., 2012; Cabezón et al., 2017; Bjerg et al., 2020). However, the present results suggest that the reduction in DFI alone does not fully explain the magnitude of the increase in NEFA and BHB, reinforcing the hypothesis of direct effects of heat stress on endocrine signaling.

There is evidence indicating that the impact of heat stress on reproductive function is not limited to reduced feed intake, but also involves direct physiological effects (Prunier et al., 1997). From a metabolic perspective, hyperthermia has been proposed to alter peripheral insulin sensitivity and modify endocrine signaling associated with energy balance. Several studies have reported lower serum concentrations of insulin and IGF-1 in sows exposed to

heat stress during lactation, accompanied by increased lipid mobilization (Williams et al., 2013). Although these hormones were not evaluated in the present study, the greater mobilization of NEFA observed under higher thermal load is consistent with a catabolic metabolic environment similar to that described in previous reports. Reduced IGF-1 levels have been associated with impaired follicular growth and delayed return to estrus (Lucy et al., 2001), suggesting a potential endocrine mechanism that may contribute to the reproductive differences observed under varying levels of thermal load.

In addition to the above, the concomitant increase in BHB suggests that lipid mobilization is not merely transient but metabolically significant, activating hepatic ketogenesis pathways (Theil et al., 2013). This pattern resembles that observed under conditions of severe energy restriction, although in this case it is induced by heat stress. Hyperthermia may impair hepatic and muscle mitochondrial function, promoting incomplete fatty acid oxidation and increased ketone body production (He et al., 2024). Furthermore, sympathetic activation associated with heat stress increases catecholamine release, thereby promoting lipolysis through activation of hormone-sensitive lipase (Gonzalez et al., 2020). Increased levels of adrenaline and noradrenaline during the peripartum period under stress conditions have been reported, highlighting that neuroendocrine activation is a key component of the physiological response to environmental stressors (Oster et al., 2025).

The interaction between heat stress and the hypothalamic–pituitary–ovarian axis is particularly relevant. It has been established that temperatures above 23 °C reduce estrus expression and impair the secretion of FSH and LH, effects attributed to alterations in hypothalamic function (Ma et al., 2023). This suggests that prolonged exposure to heat reduces the pulsatile release of gonadotropins, possibly due to sustained increases in cortisol (Flowers and Day, 1990). Elevated cortisol, beyond its classical glucocorticoid role, inhibits GnRH secretion and alters pituitary sensitivity. Thus, the catabolic state induced by heat stress not only reflects increased energy mobilization but also a physiological prioritization that shifts resource allocation away from reproductive investment.

During early gestation, exposure to temperatures ranging from 30 to 38 °C has been reported to reduce embryonic viability (Wright, 2012). The proposed mechanism involves oxidative stress and mitochondrial dysfunction in oocytes (Li et al., 2015). Although the critical phase evaluated in the present study was the gestation–lactation transition, the greater energy mobilization observed under higher THI may alter the uterine microenvironment and

potentially compromise fetal programming. It has been suggested that gestational heat stress may modify the metabolic programming of the offspring, affecting their future thermoregulatory capacity (Lucy and Safranski, 2017).

The lower litter performance observed under MTC should not be interpreted solely as a consequence of greater maternal lipid mobilization, but also as the result of a potential redistribution of nutrients that may compromise mammary function. Although milk composition followed the typical physiological pattern of lactation (Hansen et al., 2012), the higher fat content observed under ATC suggests a more efficient partitioning of energy toward the mammary gland under lower thermal load conditions. In contrast, the greater lipolytic activation observed under higher THI conditions may reflect a metabolic trade-off between maintaining thermal homeostasis and supporting milk synthesis, favoring the systemic utilization of circulating fatty acids at the expense of their efficient incorporation into milk.

Hyperthermia has been associated with alterations in peripheral perfusion and mammary metabolism that may impair secretory efficiency independently of feed intake (Farmer et al., 2008). In this context, the greater NEFA mobilization observed under MTC may not necessarily translate into increased lipid supply to milk, but rather into a metabolic utilization aimed at compensating for maternal energy deficits. In contrast, under ATC conditions, the energetic competition associated with thermoregulation is likely reduced, allowing greater nutrient allocation toward the mammary gland. This is reflected in improved litter growth and an earlier return to estrus (Silanikove et al., 2009).

In line with the above, the metabolic and reproductive outcomes, together with the correlation and regression analyses, confirm that thermal load acts as a systemic modulator capable of reorganizing maternal energy partitioning during the gestation–lactation transition. In this context, the observed correlations should not be interpreted as isolated associations, but rather as the statistical expression of an integrated physiological process: increased thermal load → reduced DFI and increased thermoregulatory expenditure → negative energy balance → activation of lipid mobilization → altered metabolic signaling → modification of reproductive performance. This sequence confirms that the thermal control system not only modulates environmental comfort but also directly influences metabolic stability and the overall biological efficiency of the sow.

Partial correlations provide a key element for interpreting the interaction among thermal load, DFI, and energy mobilization, as they allow the independent contribution of interrelated variables to be isolated. After adjusting for DFI, the persistent associations between THI and NEFA indicate that the effect of thermal load on lipid mobilization cannot be explained solely by reduced feed intake, but rather suggests a direct physiological effect of heat stress on

peripheral metabolism. This finding is consistent with that reported by Prunier et al. (1997), who demonstrated that heat stress exerts effects on metabolic and reproductive function independently of feed intake. Consequently, partial correlations strengthen the interpretation that thermal load acts as a direct metabolic modulator, rather than merely as a factor that reduces feed intake and secondarily induces negative energy balance.

The regression models demonstrated that thermal load and DFI exert significant and directional effects on metabolic variables beyond simple associations. The positive slope observed between THI and NEFA indicates that progressive increases in thermal load translate into a proportional increase in lipid mobilization, confirming that heat stress intensifies the maternal catabolic state. Complementarily, the negative slope between DFI and NEFA supports the role of energy balance as a central modulator of metabolism, whereby lower levels of feed intake are associated with increased NEFA release. This pattern is consistent with that described by Williams et al. (2013), who reported that reduced DFI under heat stress is accompanied by decreased insulin signaling and increased lipid mobilization, and with the adaptive model proposed by Renaudeau et al. (2011), in which heat alters energy partitioning beyond the immediate nutritional effect.

Conclusion

The thermal control system significantly influenced the metabolic and productive responses of sows during late gestation and lactation. Higher thermal load was associated with an intensification of negative energy balance and increased lipid mobilization, whereas environmental stabilization reduced catabolic activation and promoted improved litter performance and reproductive recovery. Overall, the findings demonstrate that thermal load acts as a systemic modulator of maternal energy partitioning and that automated thermal stabilization contributes to preserving metabolic and reproductive efficiency under commercial conditions.

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Data availability. Data used in the manuscript are available from the corresponding author upon reasonable request.

Conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics approval. The experimental protocol was reviewed and approved by the Scientific and Technical Committee of the CENID-Fisiología y Mejoramiento Animal. Animal handling followed the guidelines established by the Mexican Official Standard for the production, care, and use of laboratory animals, as well as the International Guiding Principles for Biomedical Research Involving Animals.

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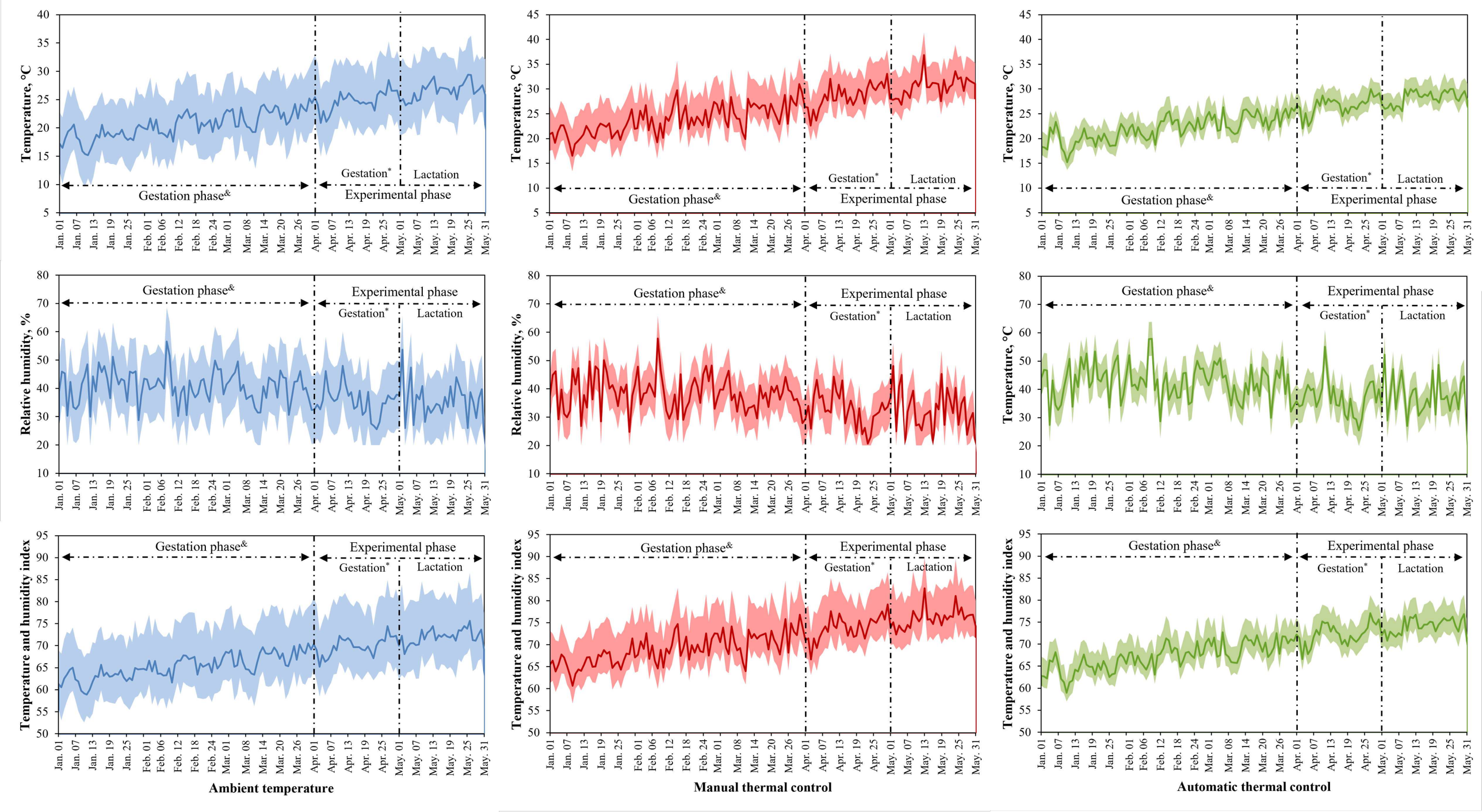
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Figure legends

Fig. 1. Dynamics of temperature, relative humidity, and temperature–humidity index (THI) in the external environment and in manual and automated thermal control systems during the experimental period. &Corresponds to the first two-thirds of gestation; *Corresponds to the last third of gestation (experimental loss).


Temperature, °C
Relative humidity, %
Temperature and humidity index
Gestation phase&
Experimental phase
Gestation*
Lactation
Ambient temperature
Manual thermal control
Automatic thermal control

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