Original scientific paper
Journal of Central European Agriculture, 2026, 27(1), p.21-29
DOI: /10.5513/JCEA01/27.1.4921

The effect of housing type on the risk of heat stress in dairy calves in central European conditions

Vliv typu ustájení na riziko tepelného stresu u telat ve středoevropských podmínkách

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Received: July 3, 2025; accepted: December 13, 2025

ABSTRACT

Heat stress is an increasing concern for dairy farming in Central Europe. Individual calf housing, while common, can create microclimates that either mitigate or exacerbate the thermal load. The present study was conducted to quantify the effect of housing type (wooden, white plastic, blue plastic) and location (under a shelter vs. outdoors) on the risk of heat stress in pre-weaned dairy calves under typical Central European conditions. A total of 1,200 observations were collected over a year, and the thermal load was assessed using the Equivalent Temperature Index for Cattle (ETIC). Results showed that the housing location was the single most critical factor (shade vs. no shade). All 72 recorded cases of moderate heat stress (ETIC > 26 °C) transpired exclusively in unsheltered, outdoor hutches, with no cases observed under the shelter. Furthermore, within the unsheltered group, housing material was a significant factor in preventing extreme thermal events: while all cases of moderate stress occurred in plastic hutches (40.3% in white, 59.7% in blue), no cases were recorded in wooden hutches. The overall thermal load, measured by the Equivalent Temperature Index for Cattle, confirmed these findings. The three most thermally challenging combinations were statistically grouped (Group a): the unsheltered blue plastic hutches (LS-Mean ETIC = 12.09 °C), the unsheltered white plastic hutches (11.15 °C), and, surprisingly, the sheltered blue plastic hutches (10.46 °C). The LS-Mean for the optimal scenario, represented by the outdoor wooden hutches (8.85 °C), was significantly lower (P<0.0001) than that of the high-risk group. This study provides quantitative evidence that giving shade is the most effective strategy for preventing severe heat stress. When shade is unavailable, using wooden or, to a lesser extent, white plastic hutches is preferable to dark-coloured plastic alternatives. The findings of the present study offer practical, data-driven recommendations for improving calf welfare and management practices on dairy farms in the region.

Keywords: calves, calf hutch, heat stress, equivalent temperature index for cattle

ABSTRAKT

Tepelný stres je v chovu mléčného skotu ve střední Evropě stále větším problémem. Individuální ustájení telat, ačkoli je běžné, může vytvářet mikroklima, které buď zmírní, nebo zhorší tepelnou zátěž. Cílem této studie bylo kvantifikovat vliv typu venkovních individuálních boud pro telata (dřevěné, bílé plastové, modré plastové) a umístění (pod přístřeškem vs. venku) na riziko tepelného stresu u telat před odstavem za typických středoevropských podmínek. Během jednoho roku bylo shromážděno celkem 1 200 pozorování a tepelná zátěž byla posouzena pomocí Indexu ekvivalentní teploty pro skot (ETIC). Výsledky ukázaly, že umístění boudy (přístřeší vs. bez přístřeší) bylo tím nejdůležitějším faktorem. Všech 72 zaznamenaných případů mírného tepelného stresu (ETIC > 26 °C) nastalo výhradně ve venkovních boudách bez přístřeší, přičemž v boudách pod přístřeškem nebyl zaznamenán žádný takový případ. Dále se ukázalo, že v rámci venkovní skupiny byl materiál boudy významným faktorem pro zamezení extrémním tepelným událostem: zatímco všechny případy mírného stresu se objevily v plastových boudách (40,3% v bílých, 59,7% v modrých), v dřevěných boudách nebyl zaznamenán žádný případ. Celková tepelná zátěž, měřená indexem Equivalent Temperature Index for Cattle, tato zjištění potvrdila. Tři nejvíce tepelně náročné kombinace byly statisticky seskupeny dohromady (Skupina a): venkovní modré plastové boudy (LS-Mean ETIC = 12.09 °C), venkovní bílé plastové boudy (11.15 °C) a, překvapivě, modré plastové boudy pod přístřeškem (10.46 °C). LS-Mean pro optimální scénář, který představovaly venkovní dřevěné boudy (8.85 °C), bylo statisticky významně nižší ($P<0.0001$) než u vysoce rizikové skupiny. Tato studie poskytuje kvantitativní důkazy o tom, že nejúčinnější strategií pro prevenci závažného tepelného stresu je zastínění. Pokud stín není k dispozici, je vhodnější použít dřevěné nebo v menší míře bílé plastové boudy než tmavé plastové. Tato zjištění nabízejí praktická, datově podložená doporučení pro zlepšení welfare telat a postupů managementu na mléčných farmách v regionu.

Klíčová slova: telata, ustájení telat, tepelný stres, ETIC

INTRODUCTION

The global climate change that is occurring at present represents one of the most significant and urgent challenges facing contemporary agriculture, with projections indicating further increases in global temperature and the frequency of extreme weather events (IPCC, 2023). Rising global average temperatures, longer and more intense heatwaves, and an increased frequency of extreme weather events directly and negatively impact livestock production systems worldwide (Rojas-Downing et al., 2017; Lacetera, 2019). In this context, heat stress, defined as a state where the sum of environmental and metabolic heat loads exceeds the animal's ability to dissipate heat, is becoming a key limiting factor for the sustainability and efficiency of animal husbandry (Bernabucci et al., 2010; Renaudeau et al., 2012; Gauly and Ammer, 2020).

Although most of the research in this field has historically focused on adult cattle, particularly high-yielding lactating dairy cows, the scientific community is increasingly recognizing that calves are the most vulnerable and often overlooked category (Hillman et al., 2005; Costa et al., 2016). Calves in the early postnatal phase are uniquely predisposed to the negative impacts of environmental extremes from a physiological standpoint. Their thermoregulatory system is still developing; they have a higher body surface area-to-mass ratio, which facilitates heat loss in cold conditions but also heat gain in hot conditions, and their metabolic heat production is high relative to their size, making them highly susceptible to both hypothermia and hyperthermia (Carstens, 1994; Brouček et al., 2009; Silva et al., 2021). Furthermore, their capacity for behavioural adaptation, such as seeking shade or water, can be considerably constrained by the housing system, thereby increasing their reliance on human-provided management (Polsky and von Keyserlingk, 2017).

The experience of heat stress during the early stages of life exerts a significant impact on the immediate consequences, manifesting in various physiological and pathological manifestations. These include, but are not limited to, reduced average daily gains, dehydration, and an augmented susceptibility to health disorders, such as diarrhoea and respiratory infections (Nonaka et al., 2008; Nonaka et al., 2012). A mounting body of evidence indicates that stress during this critical period can exert long-term "developmental programming" effects, exerting a detrimental influence on future growth, mammary gland development, the onset of puberty, and even milk production in the first lactation (Soberon et al., 2013; Monteiro et al., 2016). Consequently, the protection of calves from heat stress is not merely a matter of animal welfare, but also a crucial investment in the future productivity and longevity of the entire herd.

The effective management of heat stress necessitates precise tools for its assessment, which can be divided into environmental and physiological categories. Environmental indices, such as the historically used Temperature-Humidity Index (THI), often lack a component for radiant heat. More comprehensive indices like the Equivalent Temperature for Cattle (ETIC) are therefore essential for evaluating thermal microclimate, as they integrate solar radiation (SR) in addition to temperature and humidity (Mader et al., 2010; Gaughan et al., 2008). Physiological indicators, including respiratory rate, body temperature, heart rate, and stress hormone levels, offer direct insight into an animal's response to the prevailing conditions. Understanding the relationship between these two groups of indicators, particularly the sensitivity and dynamics of thermal responses, is crucial for developing reliable warning systems and intervention strategies (Polsky and von Keyserlingk, 2017; Davison et al., 2020; Ji et al., 2020). Individual hutches, while providing protection from adverse weather and preventing the spread of infections, can themselves create extreme thermal microclimate conditions if not properly designed and located (Hillmann et al., 2005). Factors such as material, colour, the size of ventilation openings, and especially the placement of the hutch (in the sun vs. in the shade) can dramatically influence the internal temperature and the radiant heat load, which is often the primary contributor to the total thermal load (Collier et al., 2017).

However, while these factors are recognized, there is a lack of comprehensive studies that systematically quantify the combined effect of hutch material and location on the microclimate using advanced thermal indices such as ETIC across different seasons. This knowledge gap hinders the development of evidence-based, practical guidelines for producers on optimal hutch selection and placement. The study was thus designed with the following specific objectives in mind:

- To analyze and quantify in detail the influence of the type (material) and location (shade vs. sun) of individual hutches on the thermal load of calves, as assessed by the ETIC index.
- To examine the effect of seasonality every month and to identify the highest-risk periods and combinations of conditions.

MATERIAL AND METHODS

Study site and animals

All procedures involving animals were conducted in accordance with the ethical guidelines for animal experimentation and were approved by the Institutional Animal Care and Use Committee of Mendel University in Brno (Approval No. 1/12/2023/MENDELU).

The study was conducted on a commercial dairy farm located in the Vysočina Region of the Czech Republic (altitude 550 m a.s.l.). This location is representative of the temperate continental climate and common dairy management practices found across Central European conditions. The experimental subjects were clinically healthy Holstein calves, aged between two and six weeks post-partum. The calves were housed individually and received a standardised feeding regimen. They were fed Multimilk Premium milk replacer at a concentration of 150 g/L. The replacer was prepared by adding the powder to two-thirds of the required volume of water (50–55 °C) and then filling with room temperature water to ensure the final feeding temperature did not exceed 39 °C. Calves were fed this mixture four times daily at a total daily amount of 7 litres/day. Calves had ad libitum access to fresh water and VVS Start Müsli starter feed, a highly palatable mixture used from the fifth to seventh day post-partum to promote early rumen development.

Housing and experimental design

The study followed a 3 × 2 factorial design, investigating the effects of hutch type and location. The calves were individually housed in one of three hutch types: wooden (natural brown colour), white or blue plastic. The comparison between these materials evaluated two distinct mechanisms of thermal load mitigation: (1) surface color (affecting solar reflectance/absorptance, primary focus for plastic hutches) and (2) material insulation properties (affecting thermal resistance, primary focus for the wooden hutch). In order to evaluate the impact of shade, these hutches were allocated to two distinct locations:

- Sheltered: Hutches were positioned under a permanent, open-sided shelter with a roof constructed from fiber cement sheeting at a height of 5 meters, providing continuous shade.
- Unsheltered: Hutches were placed in an open area, fully exposed to direct solar radiation.

Environmental data collection and thermal load calculation

The collection of data was conducted over the course of the entire year of 2024 to capture seasonal variability. In order to standardise for diurnal temperature fluctuations and obtain a robust relative comparison between housing types, environmental measurements were performed daily for each calf, always at 2:00 p.m. (CET). This specific time was selected because it consistently approximates the period of maximum daily thermal load (peak solar radiation and temperature in Central European conditions). This method allowed us to accurately compare the peak heat mitigation effectiveness of different housing locations and materials.

For each measurement, two instruments were utilised in tandem. The air temperature (Tdb), relative humidity (RH), and air velocity (v) were recorded using a multifunction instrument Testo 440 (Testo SE & Co. KGaA, Lenzkirch, Germany), equipped with a corresponding humidity/temperature probe and a hot-wire anemometer probe. Solar radiation (SR) was measured using a dedicated pyranometer CEM DT-1307 (CEM, Shenzhen, China). Both instruments were positioned within the calf's occupied space (approximately in the centre of the hutch at a height of 0.6 m from the bedding surface) in order to accurately represent the thermal environment.

From these environmental variables, a comprehensive heat load index, the Equivalent Temperature Index for Cattle (ETIC), was calculated for each observation using the formula established by Wang et al. (2018):

$$ETIC = T_{db} - 0.0038 \cdot T_{db} \cdot (100 - RH) - 0.1173 \cdot v^{0.707} \cdot (39.2 - T_{db}) + 1.86 \cdot 10^{-4} \cdot T_{db} \cdot sr$$

where:

T_{db} denotes air temperature (°C), *RH* denotes relative humidity (%), *v* denotes air velocity (m/s), and *sr* denotes solar radiation (W/m²).

For the purpose of this study, the severity of the thermal load based on the ETIC was classified using thresholds adapted from Wang et al. (2018). Cold stress was defined as ETIC < 0 °C. The heat stress thresholds were categorized as: Mild (23 °C ≤ ETIC < 26 °C), Moderate (26 °C ≤ ETIC < 31 °C), Severe (31 °C ≤ ETIC < 37 °C), and Emergency (ETIC ≥ 37 °C).

The initial dataset comprised 1,240 discrete observations. After excluding records with incomplete data and measurements used for calibration or testing, a total of 1,200 complete observations were used for the final analysis. The core dataset was derived from 10 individual calf hutches (experimental units) observed across 12 consecutive months. The final number of complete observations (1,200) was calculated as (10 data collection days per month) × (10 housing units) × (12 months), resulting in 100 measurements for each month for the entire set of housing types.

Statistical evaluation

All statistical analyses were performed using SAS software (version 9.4, SAS Institute Inc., Cary, NC). The statistical significance for all tests was set at a level of $P<0.05$.

Descriptive statistics (means, standard deviations, frequencies) were calculated to summarize the data using standard procedures (PROC MEANS, PROC FREQ). The association between categorical variables (e.g., hutch type and the incidence of heat stress) was assessed using Chi-square analysis.

Analysis of variance and General Linear Models (GLM)

To evaluate the effects of the experimental factors on the thermal load, the ETIC values were analyzed using a General Linear Model (PROC GLM). The statistical model was as follows:

$$Y_{ijkl} = u + HT_i + L_j + M_k + (HT \times L)_{ij} + (HT \times M)_{ik} + (L \times M)_{jk} + \varepsilon_{ijkl}$$

where:

- Y_{ijkl} is the dependent variable (ETIC)
- u is the overall mean
- HT_i is the fixed effect of **Hutch Type** (i = wooden, white, blue)
- L_j is the fixed effect of **Location** (j = sheltered, unsheltered)
- M_k is the fixed effect of the **Month** of measurement (k = 1 to 12)
- $(HT \times L)_{ij}$, $(HT \times M)_{ik}$, and $(L \times M)_{jk}$ are the **interaction terms** included to precisely quantify the seasonal dependencies of the housing effects
- ε_{ijkl} is the random residual error.

For the purpose of post-hoc comparisons of means between individual categories and to identify statistically significant differences, the Tukey-Kramer test, which is a standard part of the LSMEANS output, was used.

RESULTS AND DISCUSSION

An analysis of 1,200 observations revealed significant variations in the thermal load experienced by calves, contingent on housing management. The overall mean Equivalent Temperature Index for Cattle (ETIC) was 10.20 ± 10.10 °C, with observed values ranging from a minimum of -11.95 °C (Cold Stress) to a maximum of 30.23 °C (Moderate Heat Stress). The experimental design was well-balanced, with approximately half of the observations being sourced from sheltered locations (48.2%) and a relatively even distribution across hutch types (wooden: 38.8%; white plastic: 32.2%; blue plastic: 29.0%), allowing for robust comparisons. While the majority of observations (88.7%) were recorded within the thermoneutral zone, the distribution of mild (5.3%) and moderate (6.0%) heat stress events was highly dependent on the housing stratégy employed.

Influence of shade and material on heat stress incidence

The analysis of contingency tables indicated that housing location emerged as the most critical factor in preventing heat stress (Table 1). The most striking finding is that 100% of all 72 cases of moderate heat stress (ETIC > 26) occurred exclusively in unsheltered hutches. No instances of moderate stress were observed in calves under the shelter, providing unequivocal evidence of the protective effect of shade. This observation was supported by the finding that the distribution of stress categories in the unsheltered group was highly dependent on hutch type (Chi-Square = 74.91, $P<0.0001$), whereas no instances of moderate stress were found in the sheltered group. This finding aligns with the conclusions of previous research, which indicated that the most effective strategy for mitigating heat stress is to reduce radiant heat load (Nonnecke et al., 2009; Collier et al., 2017). By physically blocking direct solar radiation, shade dramatically lowers the thermal challenge to the animal, allowing its innate thermoregulatory mechanisms to function more effectively. Slayi et al. (2025) demonstrated that even simple shade structures significantly reduce physiological stress indicators like respiration rate, reinforcing that providing shade is the single most impactful management decision for calf welfare in warm conditions.

Hutch material played a crucial and statistically significant secondary role, but only in the unsheltered group. As outlined in Table 1, moderate heat stress was confined exclusively to plastic hutches. The risk was highest in dark (blue) plastic hutches (26.7% of observations), followed by white plastic (14.8%). In contrast, wooden hutches were found to be highly effective in preventing instances of moderate heat stress (0.0% incidence in the unsheltered group).

Table 1. Distribution of observations (n and %) across heat stress categories[1] based on the location and type of individual calf hutch

Location	Hutch type	No stress (OK) n (%)[2]	Mild stress n (%)[2]	Moderate stress n (%)[2]	Total n
Shelter	White plastic	182 (95.8)	8 (4.2)	0 (0.0)	190
	Wooden	193 (96.0)	8 (4.0)	0 (0.0)	201
	Blue plastic	187 (100.0)	0 (0.0)	0 (0.0)	187
	Subtotal	562 (97.2)	16 (2.8)	0 (0.0)	578
Outdoor	White plastic	157 (80.1)	10 (5.1)	29 (14.8)	196
	Wooden	239 (90.2)	26 (9.8)	0 (0.0)	265
	Blue plastic	106 (65.8)	12 (7.5)	43 (26.7)	161
	Subtotal	502 (80.7)	48 (7.7)	72 (11.6)	622
Overall total		1064	64	72	1200

[1] Heat stress categories were defined based on the Equivalent Temperature Index for Cattle (ETIC): no stress (OK) = ETIC < 22; mild stress = ETIC 22–26; moderate stress = ETIC > 26.

[2] Percentages represent the row percentage within each housing type and location combination.

This phenomenon can be attributed to the physical properties of the materials: dark surfaces, like the blue plastic, have a low albedo and absorb the largest amount of solar radiation, while wood possesses superior insulating properties and higher thermal inertia, buffering daily temperature peaks more effectively than the thin-walled plastic alternatives (Hillman et al., 2005). These findings emphasise that in the absence of shade, material choice constitutes a fundamental component of calf welfare (Marcillac-Embertson et al., 2009). Conversely, under the shelter, where direct solar radiation was eliminated, the differences between materials became negligible, highlighting that material properties play a much smaller role once the primary thermal load from the sun is removed.

Beyond shade and materials, our results highlight the importance of a holistically managed microclimate, which must include effective ventilation. While our study did not directly measure ventilation rates, the limited or passive ventilation characteristic of the single-opening hutches used in our study likely contributed to internal heat buildup across all material types. Recent research by Reuscher et al. (2023) compellingly demonstrated that even simple passive ventilation, such as open rear windows in hutches, significantly reduces the temperature-humidity index gain and lowers calf respiration rates.

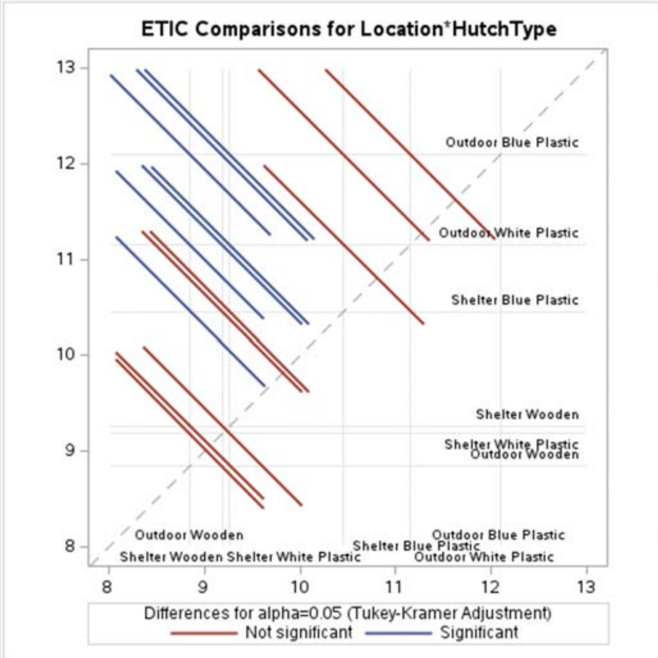
Quantifying the influence using a General Linear Model (GLM)

In order to robustly quantify the observed differences, a General Linear Model (GLM) was employed to analyse the value of the ETIC index as a function of month, location, and hutch type. The model demonstrated statistical significance for all main effects and interactions at the $P<0.0001$ level, and the factors incorporated into the model collectively accounted for 92.9% of the variability in ETIC values ($R^2 = 0.929$), thereby substantiating its considerable predictive capacity. This confirms that the complex heat indices are a sensitive tool for capturing the complex interplay of environmental variables impacting calves, a finding supported by the work of Wang et al. (2020), who validated their use in cattle breeding.

The analysis of least-squares means (LS-Means) for the interaction of location and hutch type revealed two distinct clusters of thermal risk (Table 2). The groups identified as being at the highest statistical risk of thermal load (Group a) included the unsheltered blue plastic (LS-Mean ETIC = 12.09 ± 0.29 °C), unsheltered white plastic (11.15 ± 0.27 °C), and the sheltered blue plastic (10.46 ± 0.27 °C). All three were statistically similar (P>0.05 based on Tukey-Kramer) but were significantly higher than all housing combinations in the low-risk category (Group b), as visualized by the pairwise comparisons in Figure 1. This statistical grouping, which includes the sheltered dark plastic hutch in the high-risk group, suggests that the color and material of the hutch contribute significantly to internal heat load even when direct solar radiation is removed.

Conversely, the low-risk group (Group b) included all other sheltered hutches (White Plastic, Wooden) and the wooden hutches outdoors, with no significant differences among these options. The difference of 3.24 ETIC points between the suboptimal (unsheltered blue plastic, 12.09 ± 0.29 °C) and optimal (outdoor wooden, 8.85 ± 0.23 °C) scenarios is physiologically significant. This magnitude of difference can represent the threshold between comfort and the onset of a stress response, forcing the calf to expend energy on thermoregulation rather than on growth and immune function (Von Keyserlingk et al., 2009).

Furthermore, the environment within a hutch is not defined solely by thermal factors. Poor ventilation can increase the concentration of airborne pollutants like ammonia, creating a dual stressor. The goal of housing design should therefore be the holistic management of the calf's microclimate, considering all factors affecting health and comfort.



Each line represents the comparison between two groups. Blue lines that do not intersect the diagonal reference line indicate a significant difference (*P*<0.05). Red lines that intersect the reference line indicate a non-significant difference.

Figure 1. Multiple comparison plot (Diffogram – SAS) of pairwise comparisons of least-squares means (LS-Means) for the Equivalent Temperature Index for Cattle (ETIC) among different combinations of hutch location and type

However, a truly holistic view of calf welfare must also extend beyond the physical environment to include the animal's social needs. While our study focused on individually housed calves to isolate environmental effects, it is crucial to acknowledge that current housing solutions designed for simplified microclimate management and heat mitigation often conflict with the calves'

Table 2. Adjusted least-squares means (± SEM) for the Equivalent Temperature Index for Cattle (ETIC) for different combinations of hutch location and type, calculated across the entire 12-month study period

Location	Hutch type	n	LS-Mean[1]	SEM
Outdoor	Blue plastic	161	12.09[a]	0.29
Outdoor	White plastic	196	11.15[a]	0.27
Shelter	Blue plastic	187	10.46a	0.27
Outdoor	Wooden	265	8.85b	0.23
Shelter	White plastic	190	9.19[b]	0.27
Shelter	Wooden	201	9.27[b]	0.26

[1] Least-squares means within a column with different superscript letters (a, b) are significantly different (*P*<0.05) based on the Tukey-Kramer test. SEM = standard error of the mean.

innate motivation for social contact. For instance, Malá et al. (2023) found that group-housed calves exhibited more natural behaviors, such as social play, and had significantly higher starter intake and improved growth compared to their individually housed counterparts, without adverse health effects. This highlights a key management challenge: designing housing systems that successfully mitigate environmental stressors like heat (the focus of our study) while simultaneously fulfilling the calves' essential social and behavioral needs (Reuscher et al., 2023).

As anticipated, the month of the year also had a highly significant effect on thermal load (P<0.0001, Table 3). The highest average ETIC was observed in July (LS-Mean = 25.00 ± 0.37 °C, Group a), which was statistically higher than all other months. The summer period, from May (19.91 b) to July, represented the period of highest risk, underscoring the importance of implementing heat stress mitigation strategies during these critical months.

Table 3. Adjusted least-squares means (± SEM) for the Equivalent Temperature Index for Cattle (ETIC) by month, averaged across all hutch types and locations

Month	n	LS-Mean[1]	SEM
July	100	25.0^{a}	0.37
May	100	19.9^{b}	0.37
June	100	19.8^{b}	0.37
November	100	15.4^{c}	0.37
August	100	13.0^{d}	0.37
September	100	12.7^{d}	0.37
October	100	12.3^{d}	0.37
April	100	6.4^{e}	0.37
March	100	2.6^{f}	0.37
December	100	-2.5^{g}	0.37
February	100	-3.0^{g}	0.37
January	100	-4.2^{h}	0.37

[1] Least-squares means within the column with different superscript letters (a, b, c, d, e, f, g, h) are significantly different (P<0.05) based on the Tukey-Kramer test. SEM = standard error of the mean.

A prolonged period of moderate thermal load was identified from August, September, and October (Group d), emphasizing the need to extend heat management beyond the peak summer period.

CONCLUSION

The practical implications of these results are evident and directly applicable. For farmers in temperate and warmer climates, investing in roofing for outdoor areas for individual hutches is the most effective and reliable strategy among those analyzed in this work for minimizing the impact of summer heat stress. This measure not only reduces the average thermal load but, above all, eliminates the risk of extreme events that pose a significant welfare challenge.

The general linear model further confirmed that dark-colored materials pose a risk even when shaded, as the sheltered blue plastic hutch was statistically grouped with the two riskiest unsheltered options (Outdoor Blue Plastic and Outdoor White Plastic). If full shade is not feasible for operational or economic reasons, the choice of hutch material and colour is crucial. Based on our data, wooden hutches or, at a minimum, hutches made of white, highly reflective plastic should be preferred. The use of dark plastic hutches in direct sunlight exposes calves to an unacceptably high risk of heat stress and should be considered an inappropriate husbandry practice. The present study provides quantitative data to inform decision-making when purchasing new equipment and for the strategic placement of existing hutches on the farm. While these findings are based on a substantial dataset collected over a full year, we acknowledge that the single-farm design warrants further validation across different geographical locations. Future research should also aim to integrate these environmental risk assessments with direct physiological measurements of the calves to create a more comprehensive picture of their adaptive response. Nevertheless, this study provides a robust, evidence-based foundation for improving hutch management practices and mitigating the growing challenge of heat stress on regional dairy farms.

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