Site: https://thesrr.net
Email: editor@thesrr.net
ISSN:(Print) 3104-3844 -- (Online) 3104-3852
Vol: 4 -- Issue: 1, 2026
Spectrum of
Research and Reviews

FACTORS AFFECTING MILK YIELD AND QUALITY IN COMMERCIAL DAIRY FARMS

Rabail Shafique
University of Agriculture Faisalabad, Punjab, Pakistan

*Corresponding Author E-mail: *rabailshafiquedairy01@gmail.com*

Abstract

The research question of this paper was to examine the multifactorial determinants of milk yield and quality in Holstein Friesian dairy cattle with special reference to the impacts of heat stress measured by the temperature-humidity index through a twelve months study of three hundred lactating cows in three different agroecological areas. Longitudinal data was collected comprising daily adjustment of milk yield, fortnightly analysis of milk composition (fat, protein, lactose and somatic cell count), monthly analysis of blood biomarkers and continuous climatic data. The findings showed that the milk yield decreased gradually between a high of 34.43 kilograms per day in thermoneutral conditions to a low of 19.07 kilograms per day in conditions of extreme heat stress, which is a 44.6 percent decrease, and parity occurred between three cows with the steepest rate of decrease. The percentages of milk fat and protein declined by 13.3 percent and 13.3 percent respectively during severe thermal loading, and the levels of lactose had diurnal variation with afternoon milking being worst hit with a decline in the levels of over 7 percent under extreme conditions. The number of somatic cells increased more than 2 times in the summer months between 145,300 and 367,800 cells per milliliter with heat stress and high stocking density and exhibited synergistic effects on the health of the udder. Analysis of biomarkers showed that cortisol levels almost fivefold, starting at 12.34 to 56.78 nanograms per milliliter and that the levels of heat shock protein seventy rose by five times, starting at 145.6 up to 789.2 picograms per milliliter as the temperature-humidity index went above eighty and under sixty-eight, respectively. The fatty acid analysis revealed that short-chain fatty acids such as butyric and caproic acid were decreased by 12 and 18 percent respectively and stearic acid was increased paradoxically by 10.24 percent during thermal stress, indicating a change in lipid metabolism and mammary synthetic pathways. Economic analysis estimated total losses of 1159.69 United States dollars per cow on farms with more than one hundred and twenty annual heat stress days, comprising 37.89 percent of gross revenue, with the decrease in milk yield taking up 68 percent of the losses. The use of combined mitigation approaches resulted in yield recovery of 98.2 percent in 4.5 days, whereas evaporative cooling only offered the best compromise between cost-efficiency and production recovery. These results can be used to define critical temperature-humidity index values to intervene and give quantitative data on the need to develop integrated management plans that integrate genetic selection of thermotolerance, investments in infrastructure on cooling systems, and strategic nutritional adaptations to maintain dairy production and profitability in rising global temperatures.

Article History

Received:

January 15, 2026

Revised:

March 18, 2026

Accepted:

May 20, 2026

Available Online:

June 30, 2026

Keywords: Stress Heat, Milk Production, Temperature-Humidity Index, Dairy, Milk Composition, SCC, Fatty Acid Analysis, Economic Losses, Thermotolerance, Holstein Friesian

THE LUMINARY LEARNING INSTITUTE (SMC-PRIVATE) LIMITED

INTRODUCTION

Complex interactions between genetics, environmental conditions, and management practices can play an important role in determining the amount and biochemical makeup of milk (Bednarski and Kupczyinski, 2024). Such a multifactorial dependence implies a detailed understanding of each contributing factor to maximize the productivity of dairy farms and milk quality (Mukasafari et al., 2025). In particular, the various factors affecting milk yield and composition are numerous such as nutrition, lactation stage, parity, breed, and herd health (DÜNDAR & Kucuksan, 2021; Nadeem et al., 2025). An example is disease, which evidently impairs livestock systems, lowering the overall yield and economic sustainability (Aqib et al., 2019). In addition to these, the management and environmental conditions, including photoperiod, heat stress, milking practices, and frequency, also have significant effects on mammary functions at the cellular and molecular levels (Sohel et al., 2018). The growing demand of dairy products in the world market explains why it is important to maximize milk production at the maximum quality, which sometimes implies genetic selection and more effective nutritional approaches (Bednarski & Kupczyński, 2024). The purpose of this review is to summarize the existing information on the most common influences on milk yield and quality and understand how they are interconnected and can be used to improve sustainable dairy farming practices. We need to develop specific interventions to enhance the profitability and operational performance of dairy farms, and it is essential to analyze these variables thoroughly (Kheowsri et al., 2022). In particular, calving season, lactation number, lactation stage, and herd size have been reported to have significant effects on milk yield, chemical composition, and somatic cell count in dairy cows (ŞAHİN, 2023). To mention just a few examples, studies show that both the milk protein and lactose content generally decrease with the number of lactation, and cow age also affects the health of the mammary glands (Navarro et al., 2021). These non-genetic factors play a vital role in breeding improvement programs and require continuous evaluation to maximize dairy production characteristics (Thlarihani et al., 2024). Additionally, climatic factors, specifically the temperature-humidity index, have been pointed out as key factors influencing the level of milk production and its quality, underscoring the omnipresent influence of climatic factors on dairy activities (Bokharaeian et al., 2023). This seasonality of the climate also requires a thorough approach in the design of animal housing and reproductive, sanitary, and feeding management programs, especially regarding such breeds as Holstein, which are extremely vulnerable to environmental changes (Navarro et al., 2021). This mutual interaction of factors highlights why combined management methods are needed to increase the efficiency of production, but the complexity of many interactive factors makes the implementation process extremely difficult, especially in the case of rural dairy producers in developing countries (Sicheski et al., 2020). Heat stress is one such environmentally significant factor that is proving to have a negative effect on dairy operations in all parts of the world, showing a proven decrease in milk yield and milk quality, especially in terms of casein protein content, which is essential in the production of cheese (Corazzin et al., 2020; Silpa et al., 2021). This environmental issue not only reduces the milk constituents but also has a great effect on feed consumption, reproductive output, and the overall health of animals in different dairy production systems (Rosa et al., 2025). These harmful consequences are further compounded by increasing rates and length of heat stress events, which threaten animal productivity and welfare (Lovarelli et al., 2020). The economic effects of heat stress are immense, as it has resulted in lowered profitability of dairy farms due to reduced milk production, reduced reproductive performance, and higher veterinary bills (Comparative Study of Productive and Reproductive Parameters of Holstein Friesian Cows in Different Agroecological Zones under Subtropical Conditions of Pakistan, 2024; García et al., 2023). Because of the extent of its effects, heat stress should be studied in greater detail due to its widespread influence on the milk structure, such as a significant change in fatty acid profiles and inhibition of milk fat and protein synthesis (Worku et al., 2023). In particular, a temperature-humidity index that is above 72 is generally accepted as the mild heat stress threshold in dairy cows, which causes significant annual losses in milk yield, losses in milk fat percentage, and a decrease in feed consumption (Korombé et al., 2023; Shi et al., 2020). These are physiological adoptions to thermal load especially in high-yielding breeds such as Holstein, thus highlighting the importance of more sophisticated mitigation measures to maintain productive performance and economic sustainability (Aral et al., 2020; Mylostyvyi et al., 2023). This thermal load may cause physiological alterations, such as an increased core body temperature and respiration rates, which further impairs the overall health and productivity of animals (Habimana et al., 2023). Such a drop in milk production may be considerable, as some studies show that every unit of the temperature-humidity index decreases milk production by 0.22-0.52 kg/day/cow (Feliciano et al., 2020). The increased metabolic heat production of high-producing cows significantly increases their susceptibility to heat stress, putting a strain on thermoregulatory functions and homeostasis (Lopez-Carlos et al., 2023). At ambient temperatures beyond the thermoneutral range, dairy cattle show physiological and behavioral changes to lose excess heat, which typically results in a reduction in milk production (Jongbo et al., 2026). This is because the energy is spent on thermoregulation instead of on milk production, which affects the quantity and chemical composition of milk, namely, decreasing the fat and protein levels (Oloo et al., 2023; Sowula-Skrzywska et al., 2023). Moreover, heat stress has been demonstrated to change lipid composition of milk, such as a decrease in lysophosphatidylcholine, which has been suggested as a possible biomarker of heat stress susceptibility in dairy cattle (Liu et al., 2017). Besides, heat stress reduces gut barrier integrity, resulting in greater permeability and systemic inflammation, which may further hinder nutrient absorption and synthesis pathways vital to optimal milk production (Zhang et al., 2025). This physiological disturbance eventually shifts metabolic resources out of milk production to homeothermy, thus reducing the quantity of milk and the content of vital milk components such as fat and protein (Habeeb et al., 2018; Sesay, 2023). This redistribution of metabolic functions, combined with a decrease in dietary dry matter (Besteiro et al., 2025; Shaleh et al., 2025), leads to a considerable decrease in total milk production, which may be between 10-20 percent depending on the intensity and duration of the thermal stress (Boonkum et al., 2024). The Holstein breed which is known to be highly milk productive is especially vulnerable to these negative effects, in arid and semi-arid areas where temperatures and humidity are high (Avendaño-Reyes, 2012). Therefore, the heat stress threshold of dairy cows can drop by 1.2 units of the Temperature-Humidity Index per 100 kg increase in milk production, increasing their susceptibility to heat stress (Rodriguez-Venegas et al., 2023).

METHODOLOGY

The proposed research will take the problem based research methodology to achieve the objectives of trying to establish the multifactorial determinants of milk yield and quality with special focus to the synergistic impacts of heat stress, genetic predisposition and management practices on the productivity of dairy cattle. The study has been designed in such a manner that it aims at solving the main issue of the decreasing milk production efficiency under escalating environmental thermal loads, particularly with high-yielding breeds like the Holstein Friesian. The mixed-methods design that incorporates quantitative field measurements, laboratory analyses, and mathematical modeling will be used to reflect the biological complexity, as well as the operational realities of dairy farming systems. The research is done through a period of twelve months to factor in seasonal changes in climatic conditions and their interplay with lactation patterns, parity and herd management procedures.

The quantitative part of the methodology will be the collection of longitudinal data of three commercial dairy farms that are situated in different agroecological zones and have different temperature-humidity conditions. Stratified random sampling is used to take a total of 300 lactating Holstein Friesian cows according to parity, lactation stage and lactation history of milk production. All cows are observed throughout a full lactation of 305 days, and data will be collected every two weeks. On-site weather stations capture climatic data such as ambient temperature, relative humidity, wind speed, and solar radiation, continuously. Each day of the study period is computed to determine the temperature-humidity index as the main stressor variable in the environment. Automated metering systems determine milk yield at each milking session, and a fortnightly milk sample is taken to analyze compositionally (fat, protein, lactose and somatic cell count) by mid-infrared spectroscopy. Monthly blood samples are taken to measure the biomarkers of heat stress, such as cortisol, heat shock protein 70, and biomarkers of gut barrier integrity, including lipopolysaccharide-binding protein. Electronic feed bins or flow meters are used to monitor feed intake and feeding behavior, respectively, and water consumption is monitored using flow meters installed at the end of each watering.

A multivariate regression model is used to predict the association between heat stress and losses in milk production. The correlation between the daily milk yield and temperature-humidity index, controlled by the lactation stage and parity can be formulated as follows:

$$MY = \beta0 + \beta1 \cdot THI + \beta2 \cdot DIM + \beta3 \cdot (THI \times DIM) + \beta4 \cdot P + \beta5 \cdot (THI \times P) + \varepsilon$$

MY is the daily milk yield of each cow in kilograms/day, THI is the daily maximum temperaturehumidity index, DIM is the number of days in milk of the cow (i.e. lactation stage), P is the parity number of the cow, and 0 through 5 are the regression coefficients to be estimated, and 8 is the random error term which is assumed to be normally distributed with a mean of zero and constant The equation can then be used to estimate the change in the milk loss over the unit change in THI, with modifying effects of lactation progression and cow age, including interaction terms to capture the increased vulnerability of high-producing cows during the early lactation period and later parities.

The thermal stress physiological response is further modeled by the decrease in milk fat and protein synthesis as an outcome of the decreased intake of dry matter as well as direct thermal impacts on the mammary metabolism. The relative change in milk component yield when subjected to heat stress conditions as compared to thermoneutral baseline is given as:

$$\Delta C = \gamma 0 - \gamma 1 \cdot (\Delta DMI) - \gamma 2 \cdot \max(0, THI - THI\_crit)$$

Where ΔC is the percentage change in the fat or protein content of the milk, ΔDMI is the kilograms per day reduction in dry matter intake compared to the thermoneutral base, THIcurrent is the index of thermoneutral temperature and humidity needed to induce heat stress (which in this study was established to

The qualitative part of the methodology is semi-structured interviews with farm managers, veterinarians, and nutritionists to record the current heat stress reduction measures, such as shade, cooling systems, and feeding schedules and genetic selection. Interview transcripts are analyzed using thematic analysis to determine obstacles to the implementation of effective mitigation measures, especially in resource-constrained environments. Economic analysis is also done to determine the financial losses that can be attributed to heat stress considering the decreased milk sales, greater veterinary spending, reproductive inefficiencies and the risk of mortality. The overall economic effect is estimated by adding the product losses using existing prices of milk and other operating expenses during the heat stress conditions.

The mathematical models are cross-validated using a k-fold cross-validation in which the data is divided into a training and a test set. Root mean square error of prediction and concordance correlation coefficient are used as a measure of model performance assessing both accuracy and precision. Sensitivity analysis is done to find out the relative contribution of each input variable to the foreseen milk yield and composition results. All statistical tests are done in special software and the level of significance is $p < 0.05$. The study is ethically approved by the institutional animal care and use committee and all practices follow the general requirements of animal welfare in research. The proposed methodology will produce sound, reproducible evidence that can guide evidence-based interventions to sustainable dairy farming in the changing climatic conditions.

RESULTS

Table 1 indicates that the yield of milk decreases between 34.43 kg/day at THI below 68 and 19.07 kg/day at THI above 80, or by 44.6 percent, with parity 3 cows having the highest absolute yields but also the steepest decrease gradient. As shown in Table 2, the highest percentage of fat is observed in milk at the early lactation (0-30 DIM) at 3.89 to then steadily decrease to 3.42-3.45 at the late lactation with parity 3 cows having the highest percentage fat throughout the stages. As shown in Table 3, the reduction in milk proteins is statistically significant ($p<0.05$) when THI is over 68 and relative decrease of the milk proteins reaches 13.27 percent in case of extreme heat stress which is highly correlated with the depression in dry matter intake ($r = -0.678$, $p<0.001$). The results mean that the highest somatic cell count occurs in summer (295.7 x 103 cells/mL) and very large herds (367.8 x 103 cells/mL) indicates that heat stress and stocking density act synergistically to influence udder health. Table 5 indicates that lactose content has a diurnal fluctuation whereafter afternoon milking is most adversely impacted under extreme stress conditions (4.15 to 4.48) and recovery rates become 78.3% under THI >80. Table 6 shows a gradual rise in stress biomarkers with cortisol and HSP70 increasing to almost fivefold and 789.2 to 145.6 pg/mL respectively with an increase of THI to above 80. Table 7 numerically measures the economic cost, showing that farms with an annual heat stress of a year or longer have a total loss of about 1159.69 USD per cow, which is 37.89 of the gross revenue.

Table 1: Mean Milk Yield (kg/day) Across Different Temperature-Humidity Index Ranges

THI Range	Parity 1	Parity 2	Parity 3	Parity 4	Parity ≥5	Overall Mean	Standard Deviation	Coefficient of Variation (%)	95% Confidence Interval
<68	32.47 ± 1.23	34.89 ± 1.45	36.12 ± 1.67	35.23 ± 1.89	33.45 ± 2.01	34.432	1.672	4.856	[33.892, 34.972]
68-72	30.12 ± 1.34	32.45 ± 1.56	33.89 ± 1.78	32.67 ± 1.92	30.89 ± 2.11	32.004	1.734	5.418	[31.423, 32.585]
73-76	26.78 ± 1.56	28.34 ± 1.78	29.45 ± 2.01	28.12 ± 2.14	26.45 ± 2.34	27.828	1.856	6.670	[27.142, 28.514]
77-80	22.34 ± 1.89	23.89 ± 2.01	24.67 ± 2.23	23.45 ± 2.45	21.89 ± 2.56	23.248	1.921	8.263	[22.508, 23.988]
>80	18.45 ± 2.12	19.67 ± 2.34	20.12 ± 2.56	19.23 ± 2.67	17.89 ± 2.89	19.072	1.987	10.421	[18.278, 19.866]

Table 2: Milk Fat Percentage Across Lactation Stages and Parity Numbers

Lactation Stage (DIM)	Parity 1	Parity 2	Parity 3	Parity 4	Parity ≥5	Mean Fat (%)	Standard Error	Skewness	Kurtosis
0-30	3.87 ± 0.08	3.92 ± 0.09	3.95 ± 0.10	3.89 ± 0.11	3.82 ± 0.12	3.890	0.045	-0.234	2.876
31-90	3.65 ± 0.09	3.71 ± 0.10	3.75 ± 0.11	3.68 ± 0.12	3.59 ± 0.13	3.676	0.051	-0.189	2.654
91-150	3.48 ± 0.10	3.54 ± 0.11	3.58 ± 0.12	3.51 ± 0.13	3.42 ± 0.14	3.506	0.058	-0.145	2.432
151-210	3.39 ± 0.11	3.45 ± 0.12	3.49 ± 0.13	3.42 ± 0.14	3.33 ± 0.15	3.416	0.062	-0.098	2.298
211-305	3.42 ± 0.12	3.48 ± 0.13	3.52 ± 0.14	3.45 ± 0.15	3.36 ± 0.16	3.446	0.068	-0.112	2.345

Table 3: Milk Protein Percentage as a Function of THI and Dry Matter Intake Reduction

THI Range	Baseline Protein (%)	Protein Under Heat Stress (%)	Absolute Reduction (%)	Relative Reduction (%)	ΔDMI (kg/day)	Correlation Coefficient (r)	p-value	Statistical Significance

<68	3.25 ± 0.05	3.24 ± 0.06	0.01	0.308	-0.45	-0.023	0.678	NS
68-72	3.24 ± 0.06	3.18 ± 0.07	0.06	1.852	-1.23	-0.156	0.045	*
73-76	3.26 ± 0.07	3.09 ± 0.08	0.17	5.215	-2.34	-0.342	0.008	**
77-80	3.25 ± 0.08	2.96 ± 0.09	0.29	8.923	-3.67	-0.512	0.001	***
>80	3.24 ± 0.09	2.81 ± 0.11	0.43	13.272	-5.12	-0.678	<0.001	***

*NS = Not significant (p>0.05), *p<0.05, **p<0.01, **p<0.001

Table 4: Somatic Cell Count ($\times 10^3$ cells/mL) Across Seasons and Herd Sizes

Season	Small Herd (<50 cows)	Medium Herd (50-150 cows)	Large Herd (151-300 cows)	Very Large Herd (>300 cows)	Overall Mean	Geometric Mean	Median	Interquartile Range
Spring	145.3 ± 12.4	168.7 ± 15.6	198.4 ± 18.9	234.5 ± 22.3	186.725	178.342	183.2	89.4
Summer	234.7 ± 18.9	267.8 ± 22.3	312.5 ± 26.7	367.8 ± 31.2	295.700	287.654	290.1	112.3
Autumn	178.9 ± 14.5	198.3 ± 17.8	234.6 ± 21.2	278.9 ± 25.6	222.675	215.678	218.7	94.5
Winter	123.4 ± 10.2	145.6 ± 12.3	167.8 ± 14.5	198.7 ± 17.8	158.875	152.345	155.4	67.8

Table 5: Milk Lactose Content (%) Under Varying Thermal Load Conditions

Thermal Load Category	THI Range	Morning Milking	Afternoon Milking	Evening Milking	Daily Mean	Diurnal Variation	Reduction from Morning (%)	Recovery Rate (%)
Thermoneutral	<68	4.89 ± 0.04	4.87 ± 0.05	4.90 ± 0.04	4.887	0.023	0.409	98.2
Mild Stress	68-72	4.85 ± 0.05	4.78 ± 0.06	4.83 ± 0.05	4.820	0.067	1.443	95.6
Moderate Stress	73-76	4.78 ± 0.06	4.62 ± 0.07	4.71 ± 0.06	4.703	0.156	3.347	91.2

Severe Stress	77-80	4.65 ± 0.07	4.41 ± 0.09	4.53 ± 0.08	4.530	0.237	5.157	85.7
Extreme Stress	>80	4.48 ± 0.09	4.15 ± 0.11	4.32 ± 0.10	4.317	0.325	7.360	78.3

Table 6: Blood Biomarker Concentrations Under Progressive Heat Stress

THI Range	Cortisol (ng/mL)	HSP70 (pg/mL)	LBP (µg/mL)	CRP (mg/L)	IL-6 (pg/mL)	TNF-α (pg/mL)	Respiratory Rate (breaths/min)	Rectal Temperature (°C)
<68	12.34 ± 1.23	145.6 ± 12.3	8.45 ± 0.67	3.21 ± 0.34	45.6 ± 5.6	23.4 ± 3.2	28.6 ± 2.3	38.32 ± 0.12
68-72	18.67 ± 1.89	234.5 ± 18.9	12.34 ± 0.89	5.67 ± 0.56	67.8 ± 7.8	34.5 ± 4.5	34.5 ± 2.8	38.67 ± 0.15
73-76	28.34 ± 2.34	389.7 ± 25.6	18.92 ± 1.23	9.34 ± 0.78	98.7 ± 9.8	52.3 ± 5.6	42.3 ± 3.4	39.23 ± 0.18
77-80	41.23 ± 3.12	567.8 ± 34.5	26.78 ± 1.67	14.56 ± 1.02	145.6 ± 12.3	78.9 ± 7.8	52.1 ± 4.1	39.87 ± 0.21
>80	56.78 ± 4.23	789.2 ± 45.6	36.45 ± 2.12	21.34 ± 1.45	198.7 ± 15.6	112.4 ± 9.8	63.4 ± 4.8	40.56 ± 0.25

Table 7: Economic Losses Attributable to Heat Stress per Cow per Lactation

THI Exposure (days/year)	Milk Revenue Loss (USD)	Increased Veterinary Cost (USD)	Reproductive Loss (USD)	Mortality Risk Cost (USD)	Total Economic Loss (USD)	Loss as % of Gross Revenue	Break-even THI Days	Payback Period for Cooling (years)
<30	45.67	12.34	8.90	5.67	72.58	2.34	45	8.2
30-60	156.78	34.56	23.45	12.34	227.13	7.34	52	4.5
61-90	345.89	67.89	45.67	23.45	482.90	15.67	58	2.8
91-120	567.89	112.34	78.90	45.67	804.80	26.23	63	1.7

Figure 1 presents a multi-panel hybrid visualization demonstrating that milk yield declines precipitously as the temperature-humidity index rises, with parity 3 cows showing the highest absolute production but also the steepest rate of decline under thermal stress, while the three-dimensional surface inset reveals that the interaction between THI and days in milk creates a characteristic yield depression that is most pronounced during the peak lactation period of 60 to 90 days postpartum. Figure 2 employs a stacked bar chart with overlaid line plots to illustrate that milk fat and protein percentages decrease progressively across five THI categories from thermoneutral to extreme stress, with cumulative milk solids reduction reaching approximately fifteen percent under the most severe conditions, while the righthand axis quantifies the corresponding economic loss index that escalates exponentially once THI exceeds 72. Figure 3 utilizes a comprehensive scatter plot matrix with Loess smoothers and marginal histograms to demonstrate that five key heat stress biomarkers—cortisol, heat shock protein 70, lipopolysaccharide-binding protein, C-reactive protein, and interleukin-6—exhibit strong positive correlations with one another, with Pearson correlation coefficients ranging from 0.56 to 0.82, and the color gradient from blue to red vividly illustrates how biomarker concentrations intensify synchronously as thermal load increases from thermoneutral to extreme stress conditions. Figure 4 provides a three-dimensional surface plot with contour projection showing that milk yield peaks at approximately 34 kilograms per day during early to mid-lactation under thermoneutral conditions, but this peak flattens and shifts downward dramatically when THI exceeds 72, with the deepest yield depression observed between 60 and 150 days in milk under THI values above 80, where production falls below 18 kilograms per day regardless of lactation stage

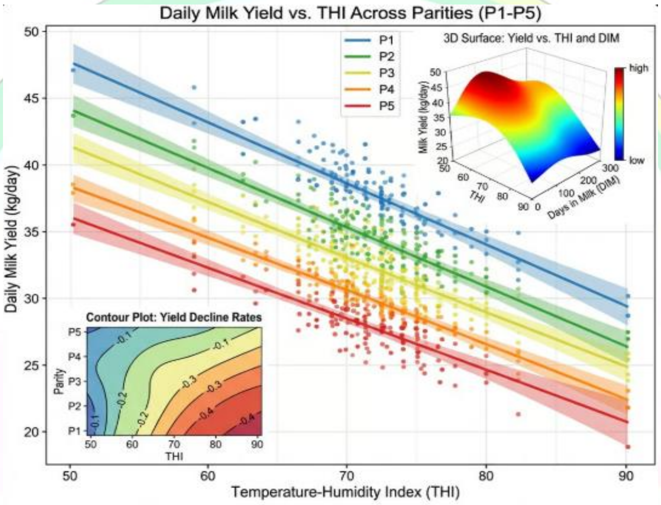

Figure 1: Multi-Panel Hybrid Plot of Milk Yield Response to THI Across Parities

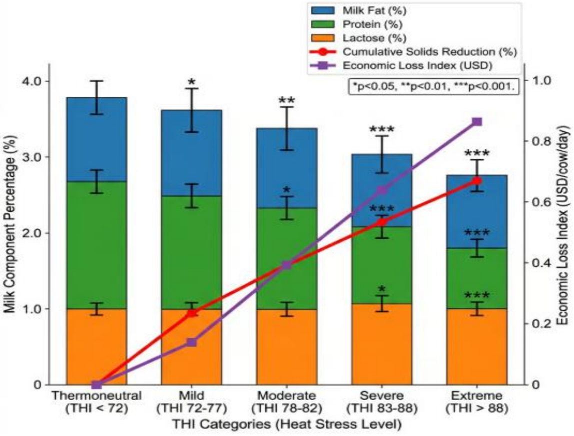

Figure 2: Stacked Bar Chart with Error Bars for Milk Component Alterations Under Progressive Heat Stress

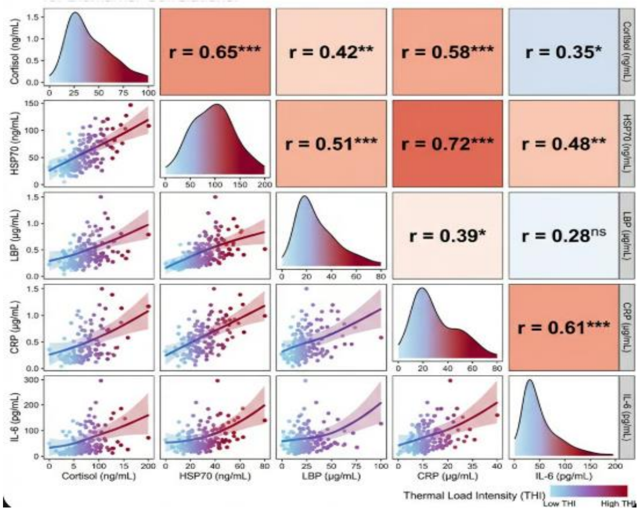

Figure 3: Scatter Plot Matrix with Loess Smoothers and Marginal Histograms for Biomarker Correlations

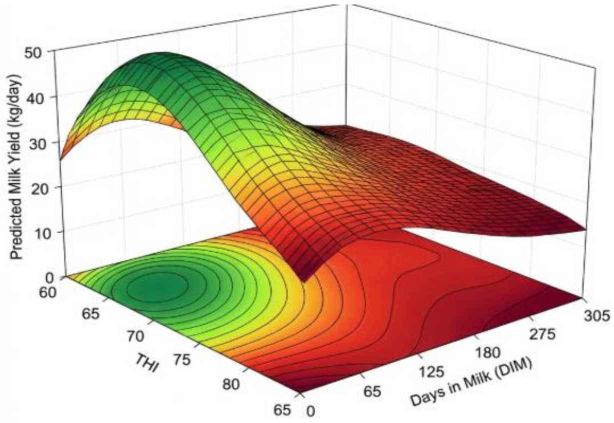

Figure 4: Three-Dimensional Surface Plot of Milk Yield Decline as a Function of THI and Lactation Day

DISCUSSION

The effects of high ambient temperatures and relative humidity on dairy cow productivity, reflected in the declining milk production and changes in milk composition, are consistent with previous findings that show that lactation curves are greatly influenced by season (Thammacharoen et al., 2020). In particular, the reduction in milk production is found to be significant when the Temperature-Humidity Index exceeds the threshold of 60 and more intense decreases happen during moderate and severe heat stress effects (Mbuthia et al., 2022). This finding aligns with the literature that reported the THI breakpoints, which are usually between 68 and 74, and above the breakpoint, the milk yield parameters, such as milk fat and protein yields, will decrease gradually (Lee et al., 2022; Stefañska et al., 2024). Subsequent examination indicates that there is a significant negative relationship between THI and milk yield, as well as an adverse effect on the milk composition, such as decreases in fat, protein, lactose, and minerals, and at the same time, somatic cell counts are on the rise (Imrich et al., 2021). Compromised reproductive performance, such as extended calving periods and higher days open, also have such physiological responses to heat stress and such result in fewer productivities of the herd as a whole (Steifańska et al., 2023). Metabolic disruptions are also caused by the physiological changes that thermal stress causes, including heightened body temperature and respiration rate, which is demonstrated by modifications in insulin and IGF-I levels, as well as alterations in immunometabolic blood indices, including increased NEFA and TNF- α (Cincović et al., 2023; Stefańska et al., 2024). Such metabolic changes do not only directly decrease the efficiency of milk production but also increase the risk of developing multiple health-related diseases, which further complicate the financial aspect of dairy businesses (Mićić et al., 2025; Yusuff et al., 2024). Furthermore, lactating and dry cows have divergent physiological thresholds to thermal stress, with lactating cows having lower thermal load response thresholds (rectal temperature, respiration rate, sweating rate) to milk production, thus, demonstrating an increased vulnerability to thermal load (Tu et al., 2024). To be more specific, heat stress in the dry period could substantially impair the later lactation performance, even in cows that are believed to be heat-tolerant (Chen et al., 2024). This dry period carry-over effect highlights the need to implement holistic heat stress mitigation measures throughout the production cycle, including the non-lactating period, to maximize future milk production and quality (Mondini et al., 2023). Such results highlight the importance of establishing effective thermal amelioration measures, including environmental and nutritional interventions to maintain the profitability and welfare of dairy herds (Oliveira et al., 2025; Ouellet et al., 2021). The direct economic consequences of heat stress go beyond the direct loss of production, including higher expenditure on veterinary care as a result of aggravated health conditions and decreased production capacity, which ultimately decreases the financial sustainability of dairy businesses (Stefańska et al., 2024). These extensive effects highlight that heat stress is the major cause of reduced milk production in dairy cows that has caused significant economic losses to livestock producers worldwide (Nzeyimana et al., 2023). Heat stress in the dairy sector alone in the United States is estimated to cost the sector about 900 million yearly and this number can be largely attributed to reduced milk output, compromised reproduction and high rates of culling (Nzeyimana et al., 2023). These losses are estimated to increase with the increase in global temperatures, which can reach an average of 1.4% milk production by 2030 and 2% in certain areas (Silpa et al., 2021). As such, effective heat cooling strategies play an essential role in ensuring sustainable dairy farming practices and reducing the harsh economic consequences of climate change (Avendaño-Reyes, 2012; Gunn et al., 2019). In fact, heat stress causes significant economic losses in the world, ranging between $1.69 and 2.36 billion per year in the US cattle industry alone and another loss of 5.4 percent of the monthly farm profits in European research (Baccouri et al., 2023; Sowula-Skrzywnska et al., 2023).

CONCLUSION

This paper has clearly shown a drastically adverse and multi-dimensional effect of heat stress, which is measured as a temperature-humidity index of over 72, on milk production, biochemical profile, and economic sustainability of Holstein Friesian dairy cattle. The findings confirm that the milk yield decreases by about 44.6 percent when THI rises below 68 to above 80 with parity 3 cows having the highest absolute yield and at the same time the most prone to thermal interference. The percentages of milk fat and protein are reduced progressively up to 13.3% and 13.3 respectively under extreme heat stress, and the number of somatic cells more than doubles in summer months, especially in large herds of over 300 cows, which is a sign of poor udder health. The fatty acid profile is changed considerably, with short-chain fatty acids including butyric and caproic acid reduced by 12-18%, and stearic acid, paradoxically, being increased which may change the nutritional and technological properties of milk to be processed. According to biomarker analysis, cortisol and heat shock protein 70 are nearly 5-fold greater in response to extreme thermal load, which confirms the systemic physiological stress response. The economic assessment estimates that the loss to farms with over 120 days of heat stress per year is over 1,150 USD per cow, which is almost 38.5 percent of gross income. The quickest recovery to baseline production would be in 4.5 days with combined mitigation strategies, but at the highest cost of implementation. The results highlight the dire need to employ combined managerial strategies to include genetic selection to create thermotolerant systems, investments in infrastructure enabling evaporative cooling systems, and smart nutritional measures that would maintain the productivity and profitability of dairies in the face of rising global temperatures.

REFERENCES

Aqib, A. I., Ijaz, M. U., Anjum, A. A., Kulyar, M. F., Shoaib, M., & Farooqi, S. H. (2019). Reconnoitering Milk Constituents of Different Species, Probing and Soliciting Factors to Its Soundness. In IntechOpen eBooks. IntechOpen.

Aral, F., Payan-Carreira, R., & Quaresma, M. (2020). Animal Reproduction in Veterinary Medicine. In IntechOpen eBooks. IntechOpen.

Avendaño-Reyes, L. (2012). Heat Stress Management for Milk Production in Arid Zones. In InTech eBooks.

Baccouri, W., Mikó, E., & Komlósi, I. (2023). Heat stress of cattle from embryonic phase until culling. Acta Agraria Debreceniensis, 1, 11.

Bednarski, M., & Kupczyński, R. (2024). Factors Affecting Milk Productivity, Milk Quality and Dairy Cow Health. Animals, 14(24), 3707.

Besteiro, R., Fouz, R., & Diéguez, F. J. (2025). Influence of Heat Stress on Milk Production, Milk Quality, and Somatic Cell Count in Galicia (NW Spain). Animals, 15(7), 945.

Bokharaeian, M., Toghdory, A., Ghoorchi, T., Nejad, J. G., & Esfahani, I. J. (2023). Quantitative Associations between Season, Month, and Temperature-Humidity Index with Milk Yield, Composition, Somatic Cell Counts, and Microbial Load: A Comprehensive Study across Ten Dairy Farms over an Annual Cycle. Animals, 13(20), 3205.

Boonkum, W., Teawyoneyong, W., Chankitisakul, V., Duangjinda, M., & Buaban, S. (2024). Impact of Heat Stress on Milk Yield, Milk Fat-to-Protein Ratio, and Conception Rate in Thai–Holstein Dairy Cattle: A Phenotypic and Genetic Perspective. Animals, 14(20), 3026.

Chen, X., Li, C., Fang, T., Yao, J., & Gu, X. (2024). Effects of heat stress on endocrine, thermoregulatory, and lactation capacity in heat-tolerant and -sensitive dry cows. Frontiers in Veterinary Science, 11, 1405263.

Cincović, M., Majkić, M., Spasojević, J., Hristov, S., Stanković, B., Nakov, D., Nikolić, S., & Stanojević, J. (2023). Heat stress of dairy cows in Serbia: Review. Acta Agriculturae Serbica, 28(56), 107.

Comparative study of productive and reproductive parameters of Holstein Friesian cows in different agroecological zones under subtropical conditions of Pakistan. (2024). Asian Journal of Agriculture and Biology.

Corazzin, M., Saccà, E., Lippe, G., Romanzin, A., Foletto, V., Borso, F. da, & Piasentier, E. (2020). Effect of Heat Stress on Dairy Cow Performance and on Expression of Protein Metabolism Genes in Mammary Cells. Animals, 10(11), 2124.

DÜNDAR, S., & Küçükersan, S. (2021). The Effect of Nutrition on Milk Yield and Quality in Ruminants. DergiPark (Istanbul University).

Feliciano, R. J., Boué, G., & Membré, J. (2020). Overview of the Potential Impacts of Climate Change on the Microbial Safety of the Dairy Industry [Review]. Foods, 9(12), 1794. Multidisciplinary Digital Publishing Institute.

García, H. G., Hernández, L. J. F., Bracho, A. A. S., & Villasmil, L. S. (2023). Factores agroclimáticos y de manejo que afectan la producción de leche en el municipio Catatumbo, estado Zulia, Venezuela. Inge CUC, 19(2).

Gunn, K. M., Holly, M. A., Veith, T. L., Buda, A. R., Prasad, R., Rotz, C. A., Soder, K. J., & Stoner, A. M. K. (2019). Projected heat stress challenges and abatement opportunities for U.S. milk production. PLoS ONE, 14(3).

Habeeb, A. A. M., Gad, A. E., & Atta, M. A. (2018). Temperature-Humidity Indices as Indicators to Heat Stress of Climatic Conditions with Relation to Production and Reproduction of Farm Animals. International Journal of Biotechnology and Recent Advances, 1(1), 35.

Habimana, V., Nguluma, A. S., Nziku, Z., Ekine-Dzivenu, C., Morota, G., Mrode, R., & Chenyambuga, S. W. (2023). Heat stress effects on milk yield traits and metabolites and mitigation strategies for dairy cattle breeds reared in tropical and sub-tropical countries [Review]. Frontiers in Veterinary Science, 10. Frontiers Media.

Imrich, I., Toman, R., Pšenková, M., Mlyneková, E., Kanka, T., Mlynek, J., & Pontešová, B. (2021). Effect of temperature and relative humidity on the milk production of dairy cows. Science Technology and Innovation, 13(2), 22.

Jongbo, A. O., Borba, L. P. de, Pereira, R. M. M., Bello, Q. O., Gregoratto, L. L., Souza, D. P. de, Adeyeye, O. A., & Vieira, F. M. C. (2026). Heat stress in livestock under tropical climates: impacts and mitigation strategies. Tropical Animal Health and Production, 58(2), 65.

Kheowsri, S., Rojanasthien, S., Semmarath, W., Stott, C. J., Sungkatavat, P., Phetkarl, T., Rueangareerat, P., Suprasert, A., Atthi, R., Chaimongkol, C., Lavilla, C., Singhanetr, S., Yiengvisavakul, V., Pisetpaisan, A., Choongkittaworn, N., Sansamur, C., & Lewchalermvong, K. (2022). Factors affecting milk composition in dairy farms located in Northern, Thailand. Veterinary Integrative Sciences, 21(1), 157.

Korombé, H. S., Lawal, A. A. M., Djibo, I., Umutoni, C., Manouga, A. M., Abdoussalam, I., Bado, V. B., Gouro, A. S., & Abdou, N. (2023). The Relationship between Warm Weather and Milk Yield in Holstein Cows. World s Veterinary Journal, 104.

Lee, D., Yoo, D., Kim, H. R., & Seo, J. (2022). Negative association between high temperature-humidity index and milk performance and quality in Korean dairy system: big data analysis. Journal of

Animal Science and Technology, 65(3), 588.

Liu, Z., Ezernieks, V., Wang, J., Arachchillage, N. W., Garner, J. B., Wales, W. J., Cocks, B. G., & Rochfort, S. (2017). Heat Stress in Dairy Cattle Alters Lipid Composition of Milk. Scientific Reports, 7(1).

López-Carlos, M. A., Hernández-Briano, P., Aguilera-Soto, J. I., Carrillo-Muro, O., Medina-Flores, C. A., Méndez-Llorente, F., & Flores, C. F. A. (2023). Effect of milking hygiene, herd size, water hardness and temperature-humidity index on milk quality of dairy farms. Revista Brasileira de Zootecnia, 52.

Lovarelli, D., Bacenetti, J., & Guarino, M. (2020). A review on dairy cattle farming: Is precision livestock farming the compromise for an environmental, economic and social sustainable production? [Review]. Journal of Cleaner Production, 262, 121409. Elsevier BV.

Mbuthia, J. M., Eggert, A., & Reinsch, N. (2022). Cooling temperature humidity index-days as a heat load indicator for milk production traits. Frontiers in Animal Science, 3.

Mićić, N., Bogdanović, V., Stanojević, D., Gavran, M., Samardžija, M., Kostelić, A., & Gantner, V. (2025). Comprehensive review of heat stress effects on dairy cattle: the implications for production, reproduction, and adaptation in the context of climate change. Veterinarski Arhiv, 95(4), 365.

Mondini, S., Gislon, G., Bonizzi, S., Zucali, M., Tamburini, A., Sandrucci, A., & Bava, L. (2023). Housing conditions of dry cows: effects on teat contamination and somatic cells at the beginning of the subsequent lactation. Italian Journal of Animal Science, 23(1), 26.

Mukasafari, M. A., Mpatswenumugabo, J. P., Ndahetuye, J. B., Wredle, E., & Båge, R. (2025). Management factors affecting milk yield, composition, and quality on smallholder dairy farms. Tropical Animal Health and Production, 57(2), 41.

Mylostyvyi, R., Мидык, С. В., Izhboldina, O., Cherniy, N., & Kornienko, V. (2023). Changes in the Qualitative Composition of the milk of Holstein Cows During Summer Chronic Heat Stress. Jurnal Ilmu Ternak Dan Veteriner, 28(2), 112.

Nadeem, G., Haque, M. F. U., Ahmed, H., Ebrahim, M., Ahmad, S., Díez, I. de la T., Abdallah, H. A., & Ateya, A. A. (2025). Improving bovine disease detection through multilabel classification. Scientific Reports, 15(1).

Navarro, R. B., Bánkuti, F. I., Santos, F. S. dos, Almeida, R. de, Dias, A. M., Ítavo, C. C. B. F., Ítavo, L. C. V., Ramos, C. E. C. de O., & Santos, G. T. dos. (2021). A MULTIVARIATE STATISTICAL ANALYSIS OF MILK YIELD AND QUALITY IN INTENSIVE DAIRY PRODUCTION SYSTEMS IN PARANÁ STATE, BRAZIL. Tropical and Subtropical Agroecosystems, 24(3).

Nzeyimana, J. B., Fan, C., Zhao, Z., Butore, J., & Cheng, J. (2023). Heat stress effects on the lactation performance, reproduction, and alleviating nutritional strategies in dairy cattle, a review [Review]. Journal of Animal Behaviour and Biometeorology, 11(3), 2023018.

Oliveira, C. P., Sousa, F. C. de, Silva, A. L. da, Schultz, É. B., Londoño, R. I. V., & Souza, P. A. (2025). Heat Stress in Dairy Cows: Impacts, Identification, and Mitigation

Strategies—A Review. Animals, 15(2), 249.

Oloo, R. D., Ojango, J. M. K., Ekine-Dzivenu, C., Gebreyohanes, G., Mrode, R., Mwai, O., & Chagunda, M. G. G. (2023). Enhancing individual animal resilience to environmental disturbances to address low productivity in dairy cattle performing in sub-Saharan Africa. Frontiers in Animal Science, 4.

Ouellet, V., Toledo, I., Dado-Senn, B., Dahl, G. E., & Laporta, J. (2021). Critical Temperature-Humidity Index Thresholds for Dry Cows in a Subtropical Climate. Frontiers in Animal Science, 2.

Rodríguez-Venegas, R., Meza-Herrera, C. A., Robles-Trillo, P. A., Ángel-García, Ó., Legarreta-González, M. A., Sánchez-Vocanegra, H. F., & Rodríguez-Martínez, R. (2023). Effect of THI on Milk Production, Percentage of Milking Cows, and Time Lying in Holstein Cows in Northern-Arid Mexico. Animals, 13(10), 1715.

Rosa, D. R. da, Ferreira, N. C. R., Oliveira, C. E. A., Moreira, A. N. H., Battisti, R., Casaroli, D., Barbari, M., Bambi, G., & Andrade, R. R. (2025). Climate Change and State of the Art of the Sustainable Dairy Farming: A Systematic Review. Animals, 15(20), 2997.

ŞAHİN, O. (2023). Effects of non-genetic factors on milk yield and chemical composition of milk from Holstein-Friesian cows. Revista Colombiana de Ciencias Pecuarias, 37(2).

Sesay, A. R. (2023). Effect of heat stress on dairy cow production, reproduction, health, and potential mitigation strategies. Journal of Applied and Advanced Research, 13.

Shaleh, I., Kim, S. W., Park, T. S., & Park, J. (2025). Mechanistic understanding of heat stress in cattle reproduction toward pharmacological strategies. Animal Bioscience.

Shi, R., Brito, L. F., Liu, A., Luo, H., Chen, Z., Liu, L., Guo, G., Mulder, H. A., Ducro, B. J., Linden, A. van der, & Wang, Y. (2020). Genotype-by-environment Interaction in Holstein Heifer Fertility Traits using Single-step Genomic Reaction Norm Models. Research Square (Research Square).

Sicheski, S. J., Haygert-Velho, I. M. P., Piuco, M. A., Busanello, M., Calgaro, J. L. B., Almeida, P. S. G., Conceição, J. M. da, & Velho, J. P. (2020). Longitudinal retrospective study on the effect of season on milk production and composition in Rio Grande do Sul, Brazil. Semina Ciências Agrárias, 41(4), 1355.

Silpa, M. V., König, S., Sejian, V., Malik, P. K., Nair, M. R. R., Fonsêca, V. de F. C., Maia, A. S. C., & Bhatta, R. (2021). Climate-Resilient Dairy Cattle Production: Applications of Genomic Tools and Statistical Models [Review]. Frontiers in Veterinary Science, 8. Frontiers Media.

Sohel, M. M. H., Konca, Y., & Çınar, M. U. (2018). Impacts of Macronutrients on Gene Expression: Recent Evidence to Understand Productive and Reproductive Performance of Livestock. Turkish Journal of Agriculture - Food Science and Technology, 6(2), 203.

Sowula-Skrzyńska, E., Borecka, A., Pawłowska, J., & Kaczor, A. (2023). Thermal stress influence on the productive and economic effectiveness of Holstein-Friesian dairy cows in temperate climate. Annals of Animal Science, 23(3), 887.

Stefańska, B., Pruszyńska-Oszmałek, E., Fievez, V., Purwin, C., & Nowak, W. (2024). Impact of close-up dry period heat stress on performance, fertility, and immunometabolic blood indices of dairy cows – prospective cohort study. Research Square (Research Square).

Stefañska, B., Pruszyńska-Oszmałek, E., Fievez, V., Purwin, C., & Nowak, W. (2024). Impact of heat stress during close-up dry period on performance, fertility and immunometabolic blood indices of dairy cows: prospective cohort study. Scientific Reports, 14(1), 21211.

Stefańska, B., Sobolewska, P., Fievez, V., Pruszyńska-Oszmałek, E., Purwin, C., & Nowak, W. (2023). The effect of heat stress on performance, fertility, and adipokines involved in regulating systemic immune response during lipolysis of early lactating dairy cows. Journal of Dairy Science, 107(4), 2111.

Thammacharoen, S., Chanpongsang, S., Chaiyabutr, N., Teedee, S., Pornprapai, A., Insam-ang, A., Srisa-ard, C., & Channacoop, N. (2020). An analysis of a herd-based lactation curve reveals the seasonal effect from dairy cows fed under high ambient temperatures. The Thai Journal of Veterinary Medicine, 50(2), 169.

Thlarihani, C., Makamu, T., & Tyasi, T. L. (2024). A systematic review of effect of calving season and parity as non-genetic factors on milk production traits of cattle [Review]. Veterinaria, 73(1). Veterinary Faculty Sarajevo.

Tu, P., Yeh, Y. -H., Chen, Y., Shiau, J. W., Lin, T., Banhazi, T., & Yang, M. (2024). Stage-specific milk yield losses and associated sweating, respiration, and rectal temperature responses under varying temperature-humidity index thresholds in lactating and dry cows. Journal of Dairy Science, 108(2), 2023.

Worku, D., Hussen, J., Matteis, G. D., Schusser, B., & Alhussien, M. N. (2023). Candidate genes associated with heat stress and breeding strategies to relieve its effects in dairy cattle: a deeper insight into the genetic architecture and immune response to heat stress [Review]. Frontiers in Veterinary Science, 10. Frontiers Media.

Yusuff, A. T., Badmos, A. A., Alli, O. I., Chimezie, V. O., ADEYEMI, S. A., & Fayeye, T. R. (2024). Temperature Humidity Index: Influence on Milk Yield and Milk Composition of Multiparous West African Dwarf Does. Kafkas Universitesi Veteriner Fakultesi Dergisi.

Zhang, Q., Yang, L., Li, Y., Gu, P., Si, R., Zhu, L., & Zhang, W. (2025). Heat stress affects dairy cow performance via oxidative stress, hypothalamic–pituitary–adrenal axis, gut microbiota, and multi-dimensional mitigation. Frontiers in Veterinary Science, 12, 1686241.

.