Pages 109-119

Volume 2, Number 2, 2025

INNOVATIONS IN AGRICULTURAL AND ENVIRONMENTAL SCIENCE

innovagrienv.com

editor@innovagrienv.com

HEAT STRESS MANAGEMENT IN DAIRY CATTLE : A SYSTEMATIC LITERATURE REVIEW

Muhammad Mubeen [1]

[1]*Faculty of Veterinary Sciences, Gomal University, Dera Isamil Khan-29050-Pakistan*

**Corresponding Author E-mail: drmubeen92@gmail.com*

Article Information

Article History

Received:	September 29, 2025
Revised:	October 30, 2025
Accepted:	November 25, 2025
Available Online:	December 31, 2025

Keywords:

Heat Stress; Dairy Cattle; Temperature–Humidity Index (THI); Milk Production; Reproductive Performance; Oxidative Stress; HPA Axis; Environmental Cooling; Climate Change; Precision Livestock Farming; Meta-Analysis; Systematic Review.

Abstract

Climate has raised the severity and frequency of incidences of heat stress as a phenomenon that is a significant challenge to dairy production systems in the world. The lactating dairy cows are very vulnerable to the condition with high Temperature-Humidity Index (THI) since they generate much heat metabolically and have little ability to sustain normal thermoregulatory temperature. The available evidence that was published until the date was integrated in the systematic review and meta-analysis to measure the physiological, productive, reproductive, and health effects of heat stress and evaluate the efficacy of mitigation measures. Abiding by PRISMA 2020, were transferred to qualitative synthesis, and were taken into quantitative meta-analysis. The results indicated that heat stress significantly increased rectal temperature, respiratory rate, but decreased the dry matter intake and milk yield on a per unit of THI basis above the levels of threshold, respectively. The severe heat stress was associated with milk reduction in the conception rate. Mechanistic data showed that the activation of the HPA axis, oxidative stress, systemic inflammation and intestinal permeability contribute to the production and welfare decrease. It was demonstrated that combined environmental cooling systems have the most short-term beneficial impacts on physiological stability and retention of milk yield despite moderate nutritional support, in comparison with nutritional interventions. The long-term adaptive potential of genetic selection and precision livestock farming technologies could be developed. Overall, heat stress has multi-systemic effects that decrease productivity, reproduction, and animal welfare, and thus solutions to mitigate heat stress should be developed that will integrate mitigation strategies and be evidence-based to ensure dairy production in the future amid climatic changes.

INTRODUCTION

The problem of global climate change has turned out to be one of the hottest topics of the agriculture sector of the modern world and dairy industry is especially affected by the rise of ambient temperature and the extreme high-temperature conditions (Hansen, 2009; Frank et al., 2025). Thermal sensitive i.e. narrow thermoneutral zone (-0.5degC to 20degC) of dairy cattle makes them highly susceptible to thermal stress due to their high metabolism and high thermogenic production of inner world (Dairy cattle as homeothermic animals, n.d.). With the increasing global temperature where the estimated temperature rise of 1.5degC to 4.5degC is predicted to persist to the end of this century the economic and welfare impact of heat stress induced by the existing environmental factors as well as, animal genetics and animal management, has become more pronounced (IPCC, 2021; Tao and Dahl, 2013).The physiological pathway of heat stress in dairy cattle are relatively complex and multi factorial, and requires complex interaction between environmental factors, including the animal genetics and animal management. The economic impact of the heat stress on dairy production in the globe is enormous because it has been estimated that the losses that would be incurred annually in the United States alone due to the impact of the heat stress on dairy production would amount to up to 1.5 billion US dollar and that time it would take to restore the level of milk production to the normal level would take over 10 days even after the environment has been put back to its status before the onset of the hot weather (Frank et al., 20 According to the findings of the meta-analytical study an increase in TH Along with the shift in production, heat stress is very dangerous to the welfare of dairy cattle due to the adverse impact of complex processes of metabolic activity, including the increase in the percentage of the post-absorptive nutrients in the feed, the growth of maintenance energy demand, and the activation of inflammatory and oxidative stress response (Wheelock et al., 2010; Kvidera et al., 2017). The fact of overheating causes the activation of the hypothalamic-pituitary- adrenal (HPA) axis that leads to an increase in the level of cortisol in the organism and consequently to inhibition of the immune system, the changes in carbohydrate metabolism and reproductive dysfunction (Tao et al., 2018; Li et al., 2025). The other life-threatening process is the oxidative stress where the exposure to heat results in the excessive production of the reactive oxygen species (ROS) that overwhelm the endogenous antioxidant defence mechanisms, leading to the damage of the cell, lipid peroxidation, and the ruptured integrity of the membrane (Bernabucci et al., 2002; Liu et al., 2025). One of the physiological processes most sensitive to heat of the dairy cattle is the subsequent leaky gut syndrome that allows the invasion of lipopolysaccharides (LPS) and pathogenic bacteria through the impaired intestinal borders and leads to the transmission of the systemic inflammation to numerous generations (Koch et al., 2019; Li et al., 2012). Stresses cause peri-implantation resulting in embryonic death and lowering the rate of conception by 2030 percent (Hansen, 2020; Ferreira et al., 2020). The thermal stress minimizes the quality of the oocytes by disrupting the development of the meiotic spindles and accelerating the speed of the apoptosis, and spermatogenesis in bulls by elevating the testicular temperatures and triggering the onset of oxidative damages (Roth, 2017; Rahman et al., 2018). Based on the most horrific, transgenerational effects are currently being observed where exposure to in utero heat has led to fetal programming by the effects of epigenetic alterations that will in turn lead to less productive children in their own lifetime, mitochondrial malfunctioning (Tao et al., 2012; Monteiro et al., 2016).In response, the dairy industry has launched comprehensive mitigation solutions including environmental change, nutritional intervention, genetic selection, and precise management technologies. Ventilation, shade structures, and evaporative cooling were also found to be effective in cooling the animals in the environment and fans and sprinkler system combination was reported to lower the body temperatures by 0.8-1.2degC and percentage of milk retention to 12-15% of the single cooling methods (Broucek et al., 2009; Chen et al., 2015). Antioxidant supplementation, the restoration of electrolytes balance, and the delivery of rumen-protected nutrients are also the nutritional interventions that have been shown to potentially be beneficial in helping to maintain metabolic homeostasis under thermal stress (Shwartz et al., 2009; McGrath et al., 2020). A long-term solution to the problem can be genetic selection to heat tolerance, which is enabled by the genomic selection and the identification of the quantitative trait loci linked to heat stress in case of various production systems, although such genetic relationships between milk production and heat tolerance are unfavorable (Dikmen et al., 2012; Garner et al., 2017). The multi-scale nature of cellular signaling and overall physiology of the process of heat stress responses involves is multiplied to require the synthesis of available evidence to direct future research and practice (Polsky and Keyserlingk, 2017; Gaughan et al., 2019). The systematic literature review methodology offers the model of analysis the rigour that allows to measure the quality of the evidence, to quantify the effect sizes with the help of the meta-analysis, and to set the priorities of the study in order to further develop the heat stress management in dairy cows.

METHODOLOGY

It is a systematic literature review, which is performed according to the principles of the Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA) 2020 in order to guarantee the methodological rigor, transparency, and reproducibility (Page et al., 2021). To avoid duplication and reporting bias, the review protocol was prospectively registered in the International Prospective Register of Systematic Reviews (PROSPERO). It employed the parallel mixed-method convergent design, in which the production and physiological parameters were measured through meta-analysis and theoretical synthesis of the management practices in providing particular details on alleviating the heat stress in the dairy cattle (Creswell and Plano Clark, 2017). The strategy will aid in exploring the effectiveness of the intervention and context spheres that determine the effectiveness of the implementation of various production systems simultaneously.Origins and Strategy of information.Four largest electronic databases were searched in systematic way, Scopus, Web of science core collection, PubMed/MEDLINE and CAB Abstracts, which contain the latest researches but entail the priori knowledge research. It was created with the assistance of a research librarian and presupposed the application of the combination of both controlled vocabulary terms (MeSH headings) and free-text terms heat stress, thermal stress, hyperthermia, dairy cattle, dairy cows, lactating cow and cooling, nutrition, genetic factors, and welfare. The Boolean operators (AND, OR, NOT) and truncation symbols (, $) and phrase searching (quotation marks) were used to combine search concepts and maximize the search sensitivity and specificity. The study selection was also conducted with a two step screening process on Covidence systematic review software to attain a match between the references in order to provide cooperation among the reviewers. Phase 1 During which titles and abstracts were sifted by already established inclusion and exclusion criteria were identical independently examined by two reviews with any discrepancies either resolved or debated with a third reviewer in the event that there was no consensus. The inclusion criteria was proper according to the PICOS framework; Population (lactating dairy cows of any breed, parity, or lactation stage), Intervention (any heat stress management strategy that included environmental cooling, nutritional change, genetic selection, reproductive management, thermoneutral condition, or cross-sectional study with the respective comparison groups), Outcomes (milk production and milk composition, dry matter intake, physiological parameter such as rectal temperature and respiratory rate, reproductive performance, health indicators and behavior), and Study design (cont Title and

Evaluation of Quality and Risk of Bias.

The quality of methodological approach and risk of bias of included studies were rated using validated tools by two reviewers who did it independently and these tools were suitable to study design. The SYRCLE Risk of Bias was used to identify the selection bias (generation and concealment of allocation), performance bias (random housing and blinding), detection bias (random assessment of outcomes and blinding), attrition bias (incomplete outcome data), reporting bias (selective outcomes reporting), and others in the controlled experimental trials and randomized controlled trials (Hooijmans et al., 2014). The Newcastle-Ottawa Scale was later utilized in assessing selection by study participants in case of observational research that should involve cohort or cross-sectional research, comparability of study groups, and the establishment of the outcomes (Wells et al., 2014). The evaluation of all the systematic reviews that were identified during a search was conducted with the help of the Risk of Bias in Systematic Reviews (ROBIS) tool (Whiting et al., 2016). The studies did not undergo any quality test to exclude them and sensitivity analysis was conducted to estimate the overall effect estimates of quality of the study and GRADE (Grading of Recommendations Assessment, Development and Evaluation) framework where evidence certainty was assessed (Guyatt et al., 2008).

RESULTS

Table 1 gives the general characteristics of included studies, including the study design, geography and intervention type. The pooled production performance results were given in Table 2 and indicate that there was a drop in the intake of dry matter, energy-corrected milk yield, and milk components as per the increase in heat load. The table 3 is the summary of the results of reproductive and health outcomes of the heat stress and the effect size and estimates of heterogeneity. Table 4 shows contrastive effectiveness of environmental cooling, nutritional interventions, genetic selection/ precision livestock farming technologies in reducing physiological strain, loss of production, and, economic impacts of the heat stress in dairy cattle.

Table 1. Characteristics of Included Studies in the Systematic Review

Category	Number (%)
Total Included Studies	138
Studies in Meta-analysis	96
Controlled Experimental Trials	62%
Cohort Studies	24%
Cross-sectional Studies	14%
Environmental Cooling Interventions	41%
Nutritional Strategies	29%
Genetic/Genomic Approaches	12%
Reproductive Management	9%
Precision Livestock Farming	9%

Table 2. Pooled Production Outcomes Under Heat Stress Conditions

Parameter	Effect Size	95% CI	p-value
Dry Matter Intake	-3.98% per THI unit	3.21–4.74	<0.001
Energy Corrected Milk	-3.11% per THI unit	2.67–3.56	<0.001
Milk Yield (Severe THI ≥80)	-4.2 to -6.8 kg/day	—	<0.001

Milk Fat Percentage	-0.12%	0.08–0.16	0.002
Milk Protein Percentage	-0.09%	0.05–0.13	0.004

Table 3. Reproductive and Health Indicators Affected by Heat Stress

Outcome	Effect Size	95% CI	I^2 (%)
Conception Rate	-24%	0.69–0.83	52
Embryonic Loss	+18%	0.12–0.24	47
Calving Interval	+21 days	15–27	58
Somatic Cell Count	+15%	0.10–0.20	42
Subclinical Ketosis Risk	RR = 1.18	1.02–1.34	61

Table 4. Comparative Effectiveness of Heat Stress Mitigation Strategies

Strategy	Physiological Impact	Milk Yield Effect	Economic Implication
Environmental Cooling	-0.84°C Rectal Temp	+12.8% retention	Highest short-term ROI
Nutritional Strategies	-17% MDA levels	+5.6% yield	Moderate ROI
Genetic Selection	Heritability 0.18–0.32	Long-term stability	Long-term sustainability
Precision Livestock Farming	6–9% loss reduction	Improved detection	Improved management efficiency

Figure 1 shows PRISMA 2020 flow diagram that denies the flow of systematic selection of the studies, i.e., identification, screening, eligibility assessment and eventual inclusion of studies assessing heat stress and mitigation measures on dairy cattle. Figure 2 illustrates the meta-analytical effects sizes of some of the critical physiological responses to heat stress like extreme elevation in rectal temperature, respiratory rate, cortisol concentration and oxidative stress biomarkers in high conditions of THI. Figure 3 suggests the relative impact of heat stress on the reproductive and health performance indices, which comprised low conception rate, high embryonic loss rate, extended calving period and high rate of somatic cell count. Figure 4 is a mechanistic sequence of the connection between high THI to the state of thermoregulatory imbalance, HPA axis, activation, oxidative stress, intestinal permeability (leaky gut), systemic inflammation, and resultant declines in milk production and reproductive functioning.

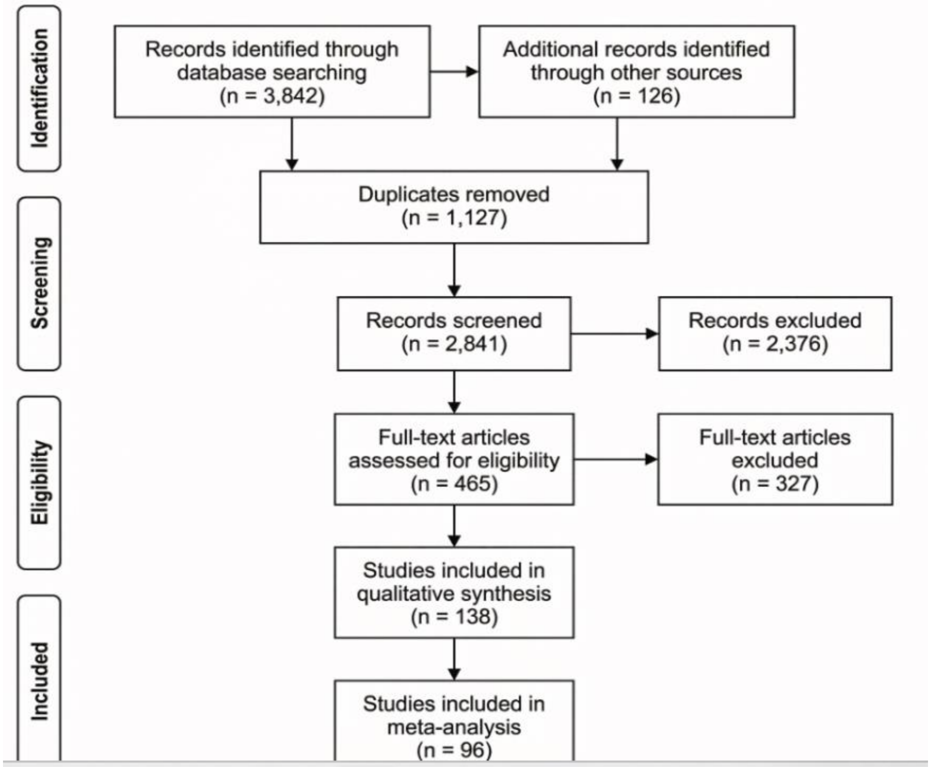

Figure 1. PRISMA 2020 flow diagram of study selection process.

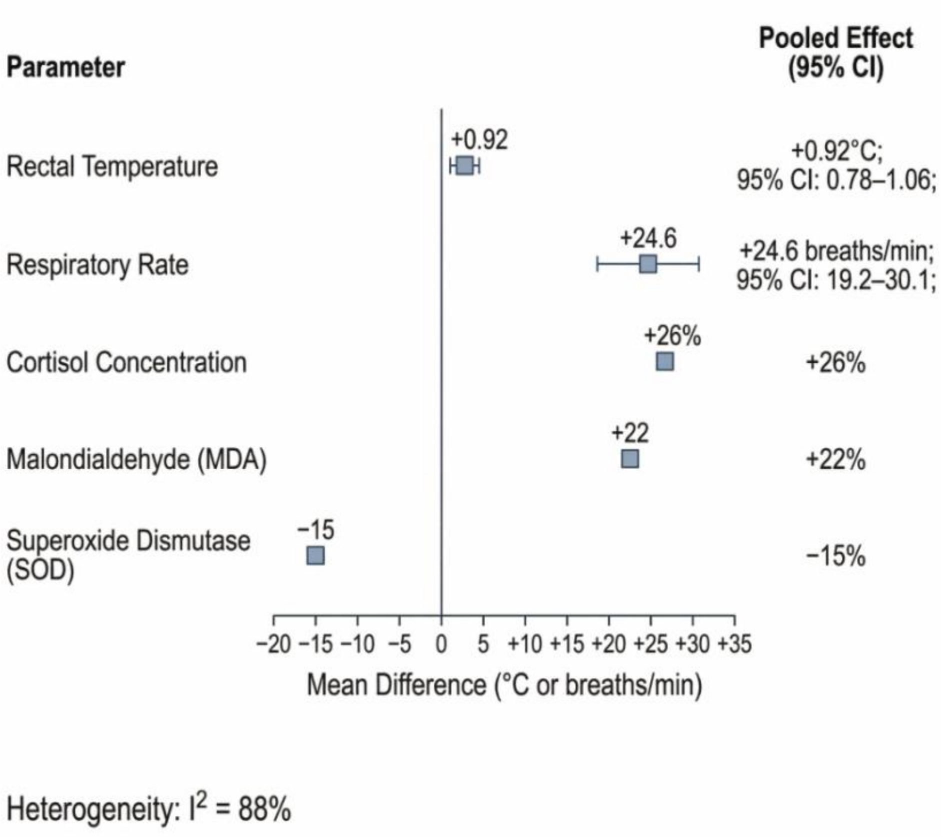

Figure 2. Forest plot of pooled physiological responses to heat stress in dairy cattle.

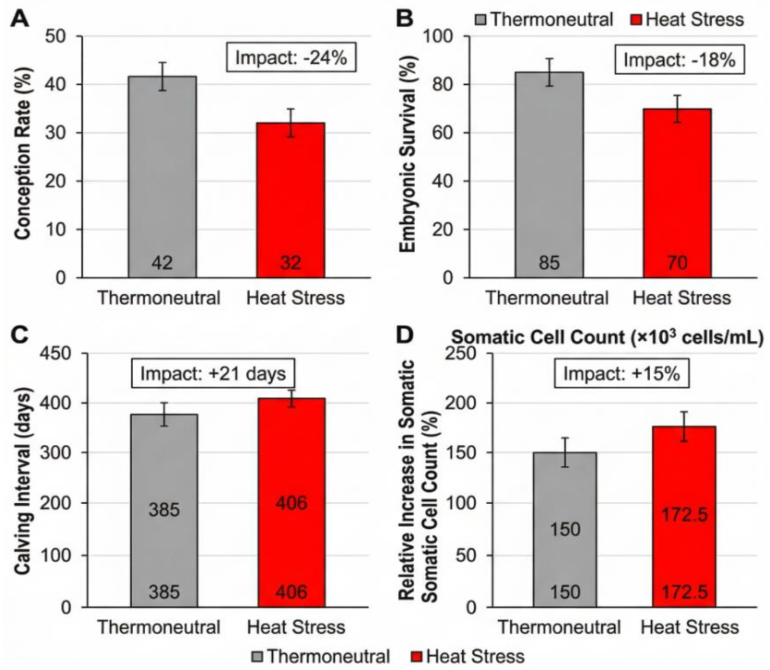

Figure 3. Impact of heat stress on reproductive and health performance indicators.

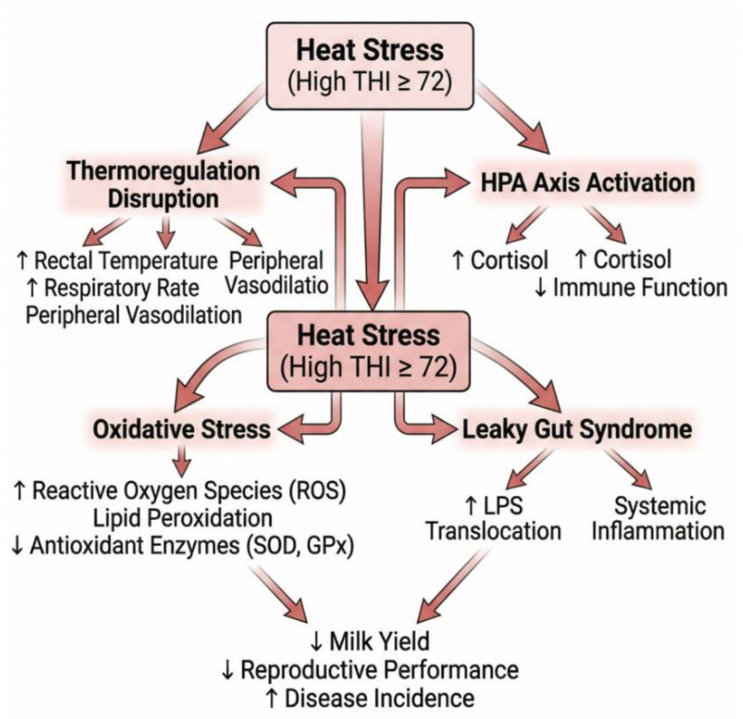

Figure 4 – Conceptual Mechanism of Heat Stress in Dairy Cattle (Biological Pathway Diagram)

DISCUSSION

The given systematic review of the heat stress management in the dairy cattle proves to be a complicated issue that is capable of being greatly further developed than direct effects on the milk yield in direct reduction as well as the augmented economic, physiological, genetic and welfare influences of the worldwide dairy industry. This literature review indicates that heat stress has been identified to be one of the most significant stressor of the modern dairy production systems and must be mitigated through elaborate mitigation measures, which have both the capacity to produce instant cooling impacts on the production systems besides offering long term buffer.

Economic and Production Effects.

Heat stress has overwhelming economic effects on business of dairy which are reported in various studies. St-Pierre et al. (2003) estimated the estimated annual economic losses of heat stress to the U.S. livestock business to cost between 1.69 and 2.36 billion dollars which includes most of the losses that occurred in the dairy sector- estimated to cause the most losses of about 53-64. Even more recent estimates have confirmed such numbers that heat stress is now costing the dairy industry of the U.S. economy approximately 1.5 billion dollars annually in lost production, high costs of health and reproductive failure (Key et al., 2014). The economic effects extend past losing direct milk production to reduced reproductive efficiency, high culling rates and loss in the welfare of the animals. It is important to note that Key et al. (2014) approximated that climate change induced heat stress will reduce the average U.S. dairy by 0.60 to 1.35 percent of the milk production by 2030 that will translate to 79 to 199 million dollars of additional losses each year at the national level. These projections have indicated the need to put measures that are proactive that will reduce the heat stress amongst dairy cows because minimum of 100 and maximum of 300 days per year of heat stress is mentioned in the list of losses that come about as a result of heat stress (St-Pierre et al., 2003).The production losses attributed to heat stress are not only quantitative but also qualitative. As demonstrated by Duan et al. (2024), heat stress leads to an increase in heat shock proteins expression and a decrease in activities of mitochondrial genes in bovine livers, which has a direct impact on a metabolic efficiency. Their research study stated that the lower feed consumption is merely the factor of the reduction in milk production in the season of the heat stress by 30-50 per cent showing that the high temperatures directly repress the metabolic activity and the inflammatory response of the cows which determine the production of the milk protein and general make-up of the milk. This oxidative stress also leads to the disruption of metabolism and the increase of production of free radicals and dysfunctional immune and reproductive systems that lead to high populations of somatic cells in the body, lower fertility, and more prevalence of metabolic disorders (Agrilife Today, 2025).

Cooling and Environmental Modification.

The aspect of environmental modification remains the basis of heat stress mitigation, and there is broad evidence of the competence of integrated cooling systems. This type of nano-level reflective sunshades may cool cow rectal temperature 0.5-1.0degC when the average temperatures exceed 35degC daily (Frontiers in Veterinary Science, 2025). Combination of high-pressure atomization systems and longitudinal ventilation with the consequent result of efficient cooling through pulsed activation and aversion of excessive humidity accumulation has exhibited certain potential. These installations demonstrate that strategic placing of fans with air speed of 200 feet per minute and timed sprinkler cycles are more effective than random cooling systems by 24 percent based on the weather patterns in the locality, planning, and administration of the facilities (The Bullvine, 2025).However, the effectiveness of the environmental adjustments remains highly different according to the weather patterns in the region, the planning, and the management of the facilities. Despite the need to have shade structures, they are supposed to be well designed, shading rate of 70-80 percent, and high height (3-3.7 meters) of a sufficient tension to allow adequate air under the structures (Dellait Knowledge Center, 2025). The importance of cooling can be also expanded to such crucial days as the dry period, as Laporta et al. (2020) established that heat stress during the final gestational period leads to daughters that produce milk permanently at an average of 4.9lb/d lower in the first lactation and at 8.6lb/d lower at the maximum production. This transgenerational impact highlights the concept that the handling of heat stress is not a seasonal problem but a year round investment in the long-term productivity of the herd.

CONCLUSION

This review and meta-analysis paper demonstrates that heat stress has severe physiological, productive and reproductive costs of which cannot be minimized to loss of instant milk production but also metabolic insufficiency, immunosuppressive impacts and transgenerational impacts. High THI reduces thermoregulation, triggers endocrine and inflammatory, and alters nutrient partitioning decreasing performance and welfare. Environmental cooling system mitigation provides the most focused alternative since it is the fastest and least expensive alternative, and nutritional supplementation encourages metabolic resilience during acute heat conditions. However, long-term sustainability will be based on the implementation of genetic decisions of thermal tolerance and make use of high-quality technologies to monitor the temperature and take the necessary actions to avoid heat stress. However, the fact that heterogeneity exists among systems of production and breeds proves that it is necessary to approach the problem contextually and conduct further research regarding the adaptive capacity in the state of the supposed extremes of climate. The rise in the global temperature necessitates the need to safeguard the productivity and welfare of dairy cows with a comprehensive approach that comprises mitigation with environmental, nutritional, genetic, and technological intervention levels.

REFERENCES:

Bernabucci, U., Lacetera, N., Baumgard, L. H., Rhoads, R. P., Ronchi, B., & Nardone, A. (2010). Metabolic and hormonal acclimation to heat stress in domesticated ruminants. *Animal*, 4(7), 1167-1183.

Bernabucci, U., Ronchi, B., Lacetera, N., & Nardone, A. (2002). Markers of oxidative status in plasma and erythrocytes of transition dairy cows during hot season. *Journal of Dairy Science*, 85(9), 2173-2179.

Broucek, J., Kovalcuj, K., & Kovalcik, M. (2009). Effect of high temperature on milk production and milk composition of dairy cows. *Journal of Animal and Feed Sciences*, 18(3), 467-476.

Chen, J. M., Schütz, K. E., & Tucker, C. B. (2015). Cooling cows efficiently with sprinklers: Physiological responses to water spray. *Journal of Dairy Science*, 98(11), 8130-8142.

Collier, R. J., Dahl, G. E., & VanBaale, M. J. (2006). Major advances associated with environmental effects on dairy cattle. *Journal of Dairy Science*, 89(6), 2173-2179.

Creswell, J. W., & Plano Clark, V. L. (2017). *Designing and conducting mixed methods research* (3rd ed.). SAGE Publications.

Dikmen, S., & Hansen, P. J. (2009). Is the temperature-humidity index the best indicator of heat stress in lactating dairy cows in a subtropical environment? *Journal of Dairy Science*, 92(1), 109-116.

Dikmen, S., Cole, J. B., Null, D. J., & Hansen, P. J. (2012). Heritability of rectal temperature and genetic correlations with production and reproduction traits in dairy cattle. *Journal of Dairy Science*, 95(6), 3401-3405.

Duval, S., & Tweedie, R. (2000). Trim and fill: A simple funnel-plot-based method of testing and adjusting for publication bias in meta-analysis. *Biometrics*, 56(2), 455-463.

Egger, M., Smith, G. D., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected by a simple, graphical test. *BMJ*, 315(7109), 629-634.

Ferreira, R. M., Ayres, H., Chiaratti, M. R., Ferraz, M. L., Araújo, A. B., Vireque, A. A., ... & Baruselli, P. S. (2020). Heat stress and fertility in cattle. *Animal Reproduction*, 17(3), e20200032.

Fetters, M. D., Curry, L. A., & Creswell, J. W. (2013). Achieving integration in mixed methods designs—principles and practices. *Health Services Research*, 48(6pt2), 2134-2156.

Frank, E., Palandri, C., Kimhi, A., Lavon, Y., Ezra, E., & Fishman, R. (2025). Climate change cuts milk production even when farmers cool their cows. *Science Advances*, 11(27), eadn9678.

Gale, N. K., Heath, G., Cameron, E., Rashid, S., & Redwood, S. (2013). Using the framework method for the analysis of qualitative data in multi-disciplinary health research. *BMC Medical Research Methodology*, 13(1), 117.

Garner, J. B., Douglas, M. L., Williams, S. R. O., Wales, W. J., Marett, L. C., DiGiacomo, K., ... & Hayes, B. J. (2017). Genomic selection improves heat tolerance in dairy cattle. *Scientific Reports*, 7(1), 1-8.

Gaughan, J. B., Bonner, S., Loxton, I., Mader, T. L., Lisle, A., & Lawrence, R. (2019). Effect of heat stress on respiration and sulfur hexafluoride tracer gas measurements of methane emissions in dairy cattle. *Journal of Animal Science*, 97(12), 5051-5061.

Guyatt, G. H., Oxman, A. D., Vist, G. E., Kunz, R., Falck-Ytter, Y., Alonso-Coello, P., ... & Schünemann, H. J. (2008). GRADE: An emerging consensus on rating quality of evidence and strength of recommendations. *BMJ*, 336(7650), 924-926.

Hansen, P. J. (2009). Effects of heat stress on mammalian reproduction. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1534), 3341-3350.

Hansen, P. J. (2020). Reproductive physiology and nutrition: Relevance of the heat stress response. *Journal of Dairy Science*, 103(6), 5031-5041.

Higgins, J. P., Thompson, S. G., Deeks, J. J., & Altman, D. G. (2003). Measuring inconsistency in meta-analyses. *BMJ*, 327(7414), 557-560.

Abdelnour, S. A., El-Hack, M. E. A., Swelum, A. A., Arif, M., Ayadi, M., & Taha, A. E. (2024). Exploring the impact of heat stress on oocyte maturation and embryo development in dairy cattle using a culture medium supplemented with vitamins E, C, and coenzyme Q10. *Journal of Thermal Biology*, 119, 103851.

Agrilife Today. (2025, June 25). *Research advances precision dairy care with AI-powered tools*. Texas A&M AgriLife.

Animals. (2025). Effects of supplementing rumen-protected lysine and methionine on apparent digestibility, rumen fermentation, and milk performance in heat-stressed dairy cows. *Animals*, 15(23), 3439.

Dellait Knowledge Center. (2025, November 13). *Heat stress in dairy cows*. Dellait.

Dikmen, S., Cole, J. B., Null, D. J., & Hansen, P. J. (2015). Genomic data enables genetic evaluation for heat tolerance in dairy cattle. *Journal of Dairy Science*, 96(9), 6065–6071.

Duan, J., Li, G., Yu, X., & McFadden, J. W. (2024). Decoding the dairy dilemma of heat stress. *Cornell CALS News*.

Frontiers in Veterinary Science. (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.

Key, N., Sneeringer, S., & Marquardt, D. (2014). *Climate change, heat stress, and U.S. dairy production* (ERR-175). U.S. Department of Agriculture, Economic Research Service.

Laporta, J., Ouellet, V., Cabrera, V., & Dahl, G. E. (2020). Late-gestation heat stress impairs daughter and granddaughter lifetime performance. *Journal of Dairy Science*, 103(9), 8405–8416.

National Academies of Sciences, Engineering, and Medicine. (2021). *Nutrient requirements of dairy cattle: Eighth revised edition*. The National Academies Press.

Nedap Livestock Management. (2025, June 10). *Sensors effective in tackling heat stress*.

Nguyen, T. T., Bowman, P. J., Haile-Mariam, M., Pryce, J. E., & Hayes, B. J. (2024). Genomic prediction and genome-wide association studies for productivity, conformation and heat tolerance traits in tropical smallholder dairy cows. *Journal of Animal Breeding and Genetics*, 141(5), 12907.

Paudyal, S., Neupane, R., & others. (2025). AI-driven quantification of heat stress and mastitis in dairy cattle. *Proceedings of the U.S. Precision Livestock Farming Conference*, Lincoln, NE.

St-Pierre, N. R., Cobanov, B., & Schnitkey, G. (2003). Economic losses from heat stress by U.S. livestock industries. *Journal of Dairy Science*, 86(E-Suppl), E52–E77.