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Heat stress in dairy cattle: effects and mitigation strategies - A comprehensive review

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ABSTRACT

Heat stress has serious physiological and economic consequences in dairy farming. It occurs when ambient temperature exceeds thermoneutral zone, typically above 24°C along with high humidity. Crossbred dairy cows are vulnerable to heat stress due to their low adaptation capacity and higher metabolic heat production. Heat stress results a marked decline in milk production (10-25%), milk fat and protein level as well as reduced reproductive performances. Additionally, heat stress leads to significant economic losses arising from decreases feed intake (up to 40%), increases water intake (up to 200 liters), greater culling frequency & increases farmer liability with veterinary expenses. Some potential interventions have stated to be effective in limiting the adverse effects of heat stress e.g., appropriate housing fitted with optimum ventilation and right amount of shade covers. Others include cooling systems like fans and sprinklers as well as proper nutritional management. Moreover, high-energy diets, electrolyte and antioxidant supplementation, and addition of rumen-protected nutrients, and long-term genetic selection of heat-tolerant animals are also an option. Cost-effective and integrated heat stress mitigations focused on prompt management interventions, are necessary to alleviate heat stress and make dairy production sustainable.

INTRODUCTION

Like all other mammals, bovines are homeothermic animals. They are normally able to maintain a relatively constant body temperature within a range termed Thermo-Neutral Zone. However, when the ambient temperature exceeds thermo-neutral zone, a condition emerged which is commonly known as Heat Stress. Heat Stress in dairy cows is a condition when an animal loses its capability to dissipate heat from its metabolism; due to both severe ambient heat and humidity, thus leads the animals spending extra energy to cool down themselves.

Nowadays, heat stress in livestock stands as the primary challenge for sustainable production in tropical and subtropical regions including

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Bangladesh. It is primarily an emerging situation in these areas due to extreme climatic vulnerability in terms of both increased heat wave and humidity. Lack of heat dissipation can lead to increased disease susceptibility and decreases normal metabolism, thus reduced milk yield and growth. Undergoing thermal stress, animal's appetite decreases, it produces more fluids, and its heart and respiratory rates increase.

The detrimental effects of heat stress on livestock are well-documented. When the THI exceeds the optimum level, water consumption increases by approximately 21%, daily dry matter intake (DMI) decreases about 15% and milk yield may decline by 10–25% (Giannone et al., 2023; Kim et al., 2023; Int. Livestockhousing Guide, 2025). Due to ‘heat stress’ milk production is reported to be dropped by 17 to 53% (Sammad et al., 2020), reduced milk protein and fat contents and considerably increased somatic cell count in milk (Besteiro et al., 2025). Globally, at the herd level heat stress can dropped milk yield about 7 to 9% (Sammad et al., 2020). Heat stress affect animal welfare, health and immunity as well. Cows in hypothermic condition showed rapid breathing, panting, show restlessness with longer standing time, excessive thirst and drooling or excessive salivation is a common sign of heat stress (Polsky and von Keyserlingk, 2017). Heat stress caused suppressed immune function with higher risk of mastitis, metritis, ‘lameness’ metabolic disorder and mortality (Oliveira et al., 2025). The same study reported in reproduction, fertility and conception rate fall; embryonic loss and abortions increase.

Heat stress poses a significant threat to the livestock industry in Bangladesh, primarily due to its hot and humid climate, inadequate housing, and limited mitigation strategies in place. During the hot season, dairy farms, especially those with crossbred and high-yielding cows, experience significant declines in milk yield by 10-25% and quality (Int. Livestockhousing Guide, 2025). Moreover, due to no or a lack of measures of heat stress management, it causes increased disease susceptibility, leading to further costs of veterinary intervention.

Though observing raised concerns in Bangladesh, there are limited data are available on the current trend of heat waves on livestock productivity and health and hence, no specific guidelines are available regarding heat stress management in dairy cows. Therefore, this review is aim to compile the impact of heat stress on the productivity and health of dairy cows and its mitigation specially in context of Bangladesh.

REVIEW METHODOLOGY

An extensive literature search was performed using Google Scholar, complemented by pertinent institutional websites and organizational reports, to ensure comprehensive inclusion of both peer-reviewed studies and grey literature on heat stress in dairy cattle. The literature search was conducted using multiple keyword combinations, including “heat stress in dairy cows,” “heat stress mitigation strategies,” “cooling systems for dairy cattle,” “Temperature–Humidity Index (THI),” and “milk production and heat stress,” and was conducted without rigid constraints on geographical scope or temporal limitations. The final literature pool 135 consisted of 128 peer-reviewed journal articles, 5 credible web-based sources, and 2 technical or institutional reports. A substantial proportion of the literature was published after 2000, reflecting the expanding scientific emphasis on this topic in recent decades. The inclusion criteria required that selected sources with evidence-based findings addressed at least one of three core domains, such as the physiological, productive, reproductive, and immunological consequences of heat stress in dairy cattle. Non-English publications, anecdotal sources, and materials lacking clear relevance to the predefined scope of the review were systematically removed during the selection process.

Thermoneutral Zone, LCT & UCT

The Thermoneutral zone (TNZ) (Figure 1) refers to the "range of temperature within which metabolic rate is minimum, and where temperature regulation is entirely by non-evaporative physical means". A lower critical temperature (LCT) is the temperature of the material below the thermo-equilibrium (Kumar et al., 2018). Meanwhile, under each of these factors, an upper critical temperature (UCT) can be set on the basis of a) metabolic rate is elevated; b) evaporative heat loss is increased; or c) tissue insulation is reduced. The cumulative effects of temperature and humidity appear to be a reliable indicator of the likelihood of high temperature-humidity index (THI) (Figure 2). The THI below 75 can be mild or no stress in general to the ruminants. However, danger begins at THI above 84 with alert begins at 79 (Spiers, 2000) (Table 1). Moreover, body temperature in dairy cattle is to be kept between 38.4° and 38.7⁰C according to fundamental concept. Although heat dissipation is compromised in hot and humid conditions, cattle can withstand higher temperatures at lower humidity levels (Basak et al., 2013).

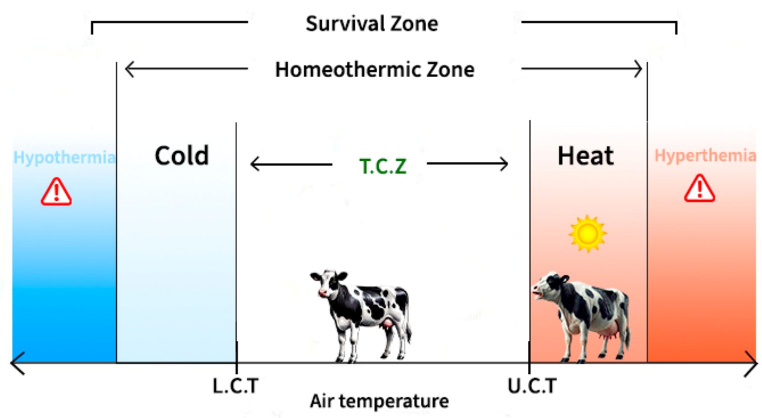

Fig 1: **Schematic figure of animal comfort, homeothermic, and survival zones (Oliveira et al., 2025)**

Table 1: Heat Stress severity (Atrian and Shahryar, 2012)

THI	Heat Stress Severity
72-78	Mild stress
79-88	Moderate stress
89-98	Severe stress
More than 98	Very Severe stress

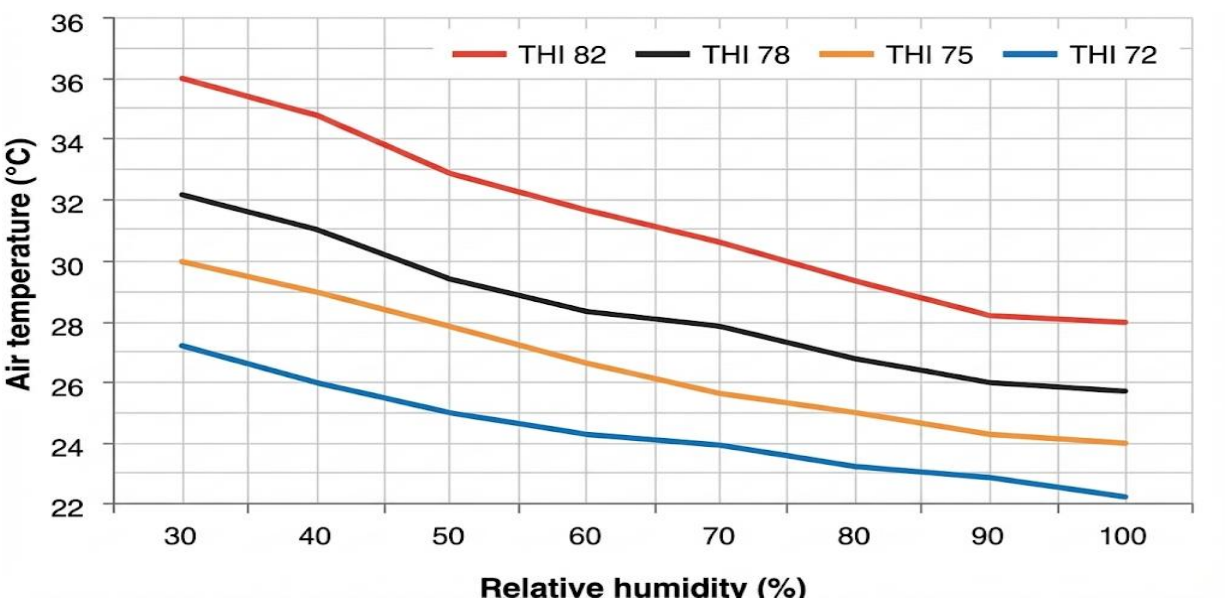

Fig 2: Calculated THI from air temperature and relative humidity (Habeeb et al., 2018)

Heat Dissipation Mechanism in Ruminants

Animals can generate heat in three different ways: thermally, mechanically and chemically.

Mechanical and chemical heat transfer, which are associated with metabolic processes, are the body's main sources of heat (Kumar et al., 2018). Physical activity, digestion and metabolism all contribute to the production of endogenous body heat.

Through the transfer of "sensible" heat between objects; radiation, convection, and conduction cause a change in the "latent" temperature of both objects (Shephard and Maloney, 2023) (Figure 3). The direction of heat exchange is determined by the temperature difference between the cow and its environment. Heat transfer through conductive, convective, and radiative exchanges will eventually become ineffective if the ambient temperature keeps rising & thus evaporation takes place. Sweating accounts for 70% of all evaporative heat loss, while breathing accounts for 30% as evaporative actions (Dairy Australia, 2023). When water evaporates from the body's surface, heat is lost for every gram of water. Compared to European breeds, Zebus sweated a lot more hence, they are well adapted to the environment.

Visible factors that makes heat dissipation difficult that actually onset heat stress primarily are as follows:

☐ Increased Air temperature and relative humidity.

☐ Higher rate of solar radiation.

☐ Less/No Ventilation and air flow.

☐ Longer hot situations.

☐ Increased movement of animal.

☐ Less water & shade availability.

☐ Darker-colored animals and those with long hair or wool are more likely to become overheated.

☐ Young pregnant, and milk-producing animals have faster body processes than adult animals making them more likely to overheat.

☐ Animals with more fat tend to make more body heat and find it harder to cool down.

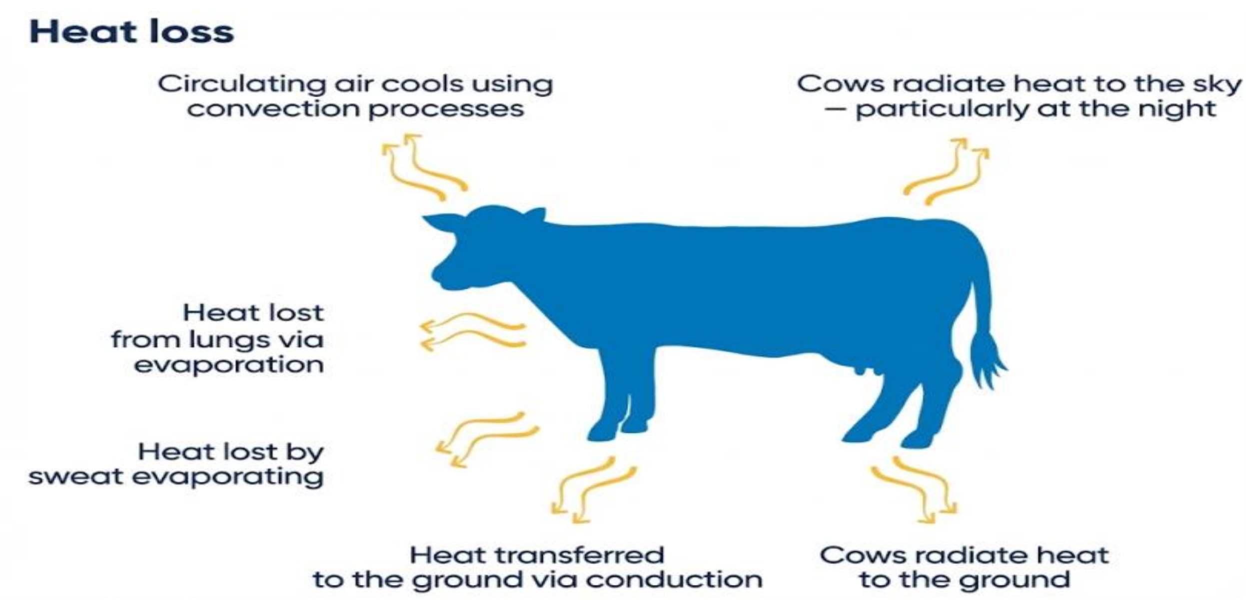

Fig 3: Sources of heat loss in dairy cows (Dairy Australia, 2023)

IMPACTS OF HEAT STRESS

Physiological Response to Heat

An animal's reaction may involve physiological adaptations that result in behavioral changes. Like drooling, panting, tongue protrusion, and neck extension all manifests to excessive heat. Due to higher metabolic heat load, dairy cattle are especially vulnerable (Carabaño et al., 2017). Depending on their body surface temperature, cattle exposed to the extra heat from direct and indirect reflected radiation in addition to the heat they generate internally. According to (Piccione and Refinetti, 2003), the body temperature of cattle exhibits a clear circadian rhythm, fluctuating between 0.2 and 0.9°C but the rhythm destroys in excess heat. Heat stress causes perspiration and panting above 35°C, though thermoregulation maintains core temperature between 38 and 39.2°C (Collier et al., 2012). Meanwhile Panting can brought on by excessive THI results in respiratory alkalosis and rumen pH imbalance (Teisberg, 2020).

There are genetically specific temperature thresholds above which cattle's respiration rate increases, and these thresholds are primarily related to ambient conditions. Heat stress in nursing dairy cows is indicated by respiration rate of greater than 60 breaths per minute (Berman, 2005). Generally, under heat stress, respiration rate of an adult cow can rise up to 150 breaths per minute (Figure 4).

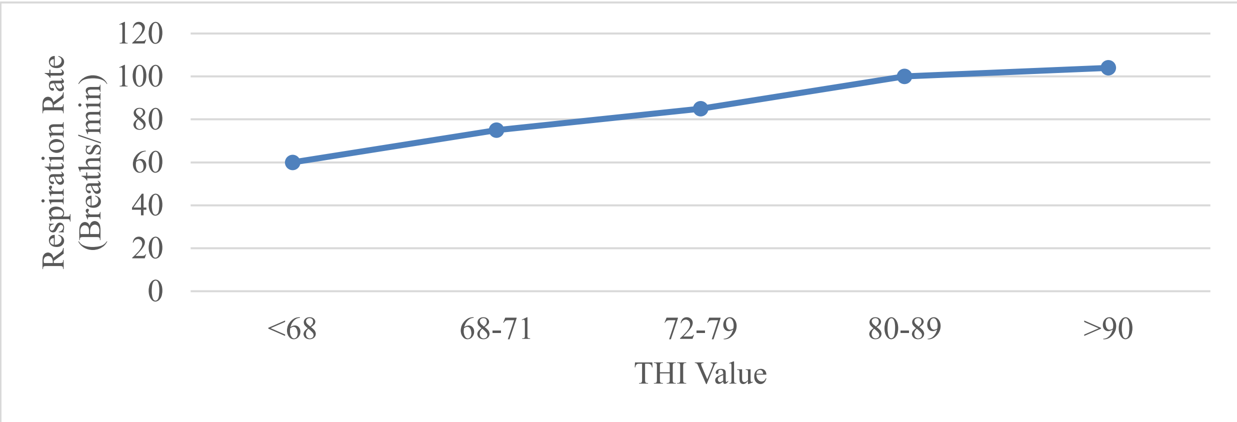

Fig 4: Mean value of Respiration rate within THI range (The University of Minnesota, 2020)

Increased breathing and perspiration are examples of evaporative mechanisms of heat loss. Short, thin hair promotes adaptability, while white coats increase heat tolerance. Heart rate tend to increase the respiration rate. In fundamental concept the approximate HR rises by 15% when temperature over 30°C aligned with respective THI (Kim et al., 2022) (Figure 5).

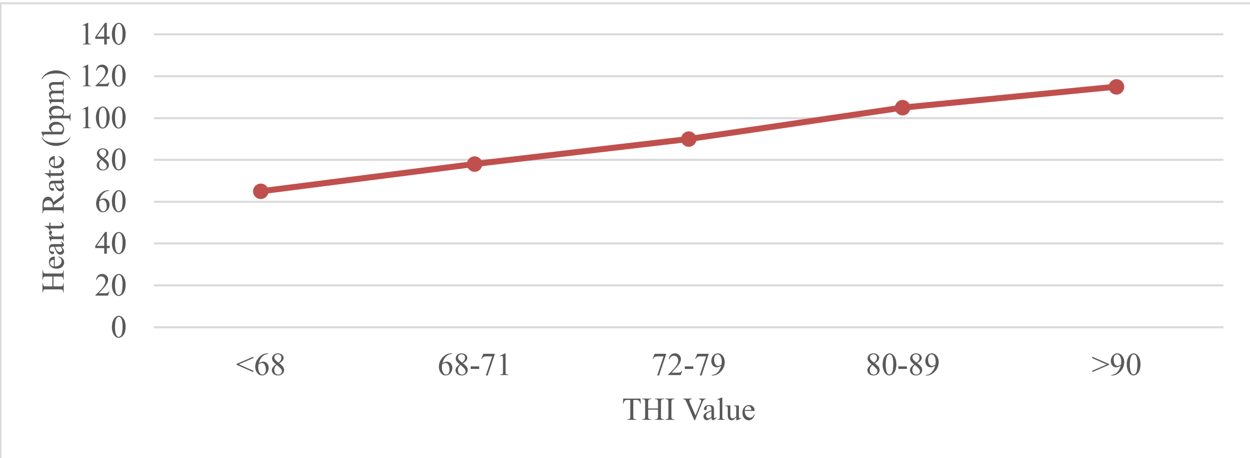

Fig 5: Heart Rate vs THI (Umar et al., 2021)

Effect of Heat stress on Behavioral Changes

As a results of heat stress; seeking shade, refusing to lie down, drinking more water and consuming less feed are considered as early indicators. Cattle under heat stress increased standing bouts and drank more to maintain evaporative water loss, which is believed to improve cooling by exposing more surface area. In order to increase their body surface area, dairy cows in hot weather reduce their lying time by 30% (Schutz et al., 2011). This longer standing periods may lead to decreased milk production and increased disease prevalence.

Effect of heat stress on dry matter intake and dairy water consumption are summarized in Table 2. In general, cattle under heat stress double their water intake. When THI rises from 72, drinking increases by 21% (Giannone et al., 2023). Specifically, dairy cows with high yields under heat stress condition can consume up to 200 liters of water every day (Atrian and Shahryar, 2012).

Heat stress is linked to fewer eating frequency and agonistic behaviors. Animals usually eat in the early morning, late afternoon and at night rather than during the hottest times of the day. In lactating cows, feed intake decreases at 25–26°C and can drop by 40% at 40°C (Rhoads et al., 2013). While reducing feed intake leads to weight loss and a negative energy balance hence, reduces heat production. Therefore, it’s common to observe that summertime maximum THI (>72) is negatively correlated with daily rumination time, with over 60% of rumination taking place at night (Soriani et al., 2013). In extreme situations, the core body temperature may rise above 41°C, and frothy discharge from the mouth or nose may be a sign of pulmonary edema (Vermunt and Tranter, 2010).

Table 2: Effects of THI on Dry Matter Intake (DMI) and Water Intake in Dairy Cattle

THI Range	Heat Stress Category	Dry Matter Intake (DMI) (kg/day)	Water Intake (L/day)	Physiological Response / Remarks	References
64–71	Thermoneutral (Threshold)	9.94	60–100	Represents baseline intake; values vary with body size and milk production potential.	(Kim et al., 2023; Parish and Rhinehart, 2008)
72–78	Mild to Moderate Heat Stress	9.59	72-120	Drinking frequency increases and feeding volume decreases to support evaporative cooling mechanisms.	(Giannone et al., 2023; Kim et al., 2023)
78–82	Elevated Heat Stress	9.43	Peak intake observed	Maximum drinking behavior recorded; cows exhibit increased frequency and duration of water intake.	(Kim et al., 2023; Parish and Rhinehart, 2008)
82–87	Severe Heat Stress	9.22	Up to ~200	High-yielding dairy cows exhibit significantly elevated water demand depending on heat load. And feed intake level stands lowest.	(Kim et al., 2023; Atrian and Shahryar, 2012)

Heat Stress on Production

Milk production is negatively affected by heat stress in dairy cows (Table 3). Due to their higher metabolic heat production, high productive cows are more susceptible to heat stress than low productive cows. Dairy cows experience heat stress when ambient temperatures rise above 25°C (Correa-Calderon et al., 2004); as a result, about 20% to 40% daily feed intake is declined than usual. So, milk yield is gradually reduced by this reduction in feed intake and rising ambient temperatures.

The effect of increased THI and milk production and milk quality is summarized in Table 3. For every unit of THI increase, milk production dropped by 0.69 kg and 0.45 kg, in Holstein Friesian and Jersey cows, respectively (West et al., 2003). When compared to non-stressed cows feeding same diet, heat-stressed cows show a difference in fatty acid concentration (Liu et al., 2017).

Therefore, the composition of milk is changed by heat stress, which lowers the yield of total protein and fat. Another study reported milk protein decreases from 3.02 g/100 g to 2.89 g/100 g and milk fat decreases from 3.46 g/100 g to 3.17 g/100 g when THI surpasses 75 (Abeni et al., 1993). Interestingly after two days of exposure in heat stress, milk fat's polar lipid content drops by 43% (Liu et al., 2017). Heat stress reduces other milk components too, such as SNF%, Milk Urea, immunoglobulins (IgG, IgA), casein, and lactalbumin (Chen et al., 2023). Also, it affects mammary function by increasing oxidative stress and the somatic cell count in milk.

Additionally, higher temperatures slow down the breakdown of lignin in plant tissues, which lowers the digestibility and rates at which fodder degrades. Thus, exert negative energy balance and ultimately affect body condition Score.

Table 3: Effects of Temperature-Humidity Index (THI) on Dairy Cattle Production and Milk Composition

THI Range & Stress Level	Milk Yield Change (kg/cow/day)	Milk Fat (%)	Milk Protein (%)	Milk Urea (mg/dL)	SNF (%)	Somatic Cell Count (SCC)	Dry Matter Intake Change	Remark	References
<68 (No Stress)	+0.089 kg/d	3.51	3.19	10.9	8.98	Normal (baseline)	Baseline	Thermoneutral zone; optimal production. No physiological alterations.	Oliveira et al., 2025; Yadav et al., 2025; Besteiro et al., 2025; Chen et al., 2024; Habimana et al., 2023; West, 2003; Bohmanova et al., 2007
68–71 (Mild Stress)	+0.040 kg/d	3.46	3.15	10.4	8.97	Begins to rise	Slight reduction (~2–3%)	Mild heat load; early physiological adjustments. Cooling strategies recommended.	
72–76 (Moderate Stress)	−0.023 kg/d	3.42	3.13	10.8	8.96	Elevated; SCC critical threshold at THI ≥72	Reduced ~4–5%	Milk yield declines; feed intake notably reduced. Fat & protein threshold critical THI ≈63–64.	
≥77 (Severe Stress)	−0.123 kg/d	3.37	3.09	11.0	8.79	Markedly elevated; SCC critical at THI ≥78	Reduced ~4.13% per THI unit	Severe production losses (10–25%). Risk of mastitis elevated. Milk composition significantly reduced.	
THI >threshold (per unit increase)	Up to −0.249 kg/d	−0.006 kg/d	−0.008 kg/d	Rises with HS	Decreases	↑ mastitis risk; SCC increases 36% from low to high THI	−4.13%/THI unit (mid-lactation)	Cumulative HS effect lasts 7–12 days post-exposure. Multiparous cows in mid-lactation most affected.	

Effect of Heat Stress on Reproduction

One of the most significant problems related to the reproductive performance of dairy cattle is heat stress, which leads to a chain of physiological and behavioral disorders. At the herd level heat stress enhances the incidence of anestrus and moderately raises repeat breeding, but does not raise abortion (Wolfenson and Roth, 2018). While dystocia seems to be mostly unaffected by heat stress, and occurrences of retained placenta increase after moderate heat stress. These results suggest that rather than affecting abortion or calving difficulties, heat stress mainly affects ovarian activity (Figure 6) and postpartum problems (Sumi et al., 2022). When THI is higher than 72, fertility is further decreased, especially if the animal exposed to heat stress prior to, during, or soon after breeding (Dash et al., 2016). During winter cows display five times more mounting and more than seven times more standing events, while heat-stressed cows show nearly no estrus during the day and very little mounting at night (Szalai et al., 2025).

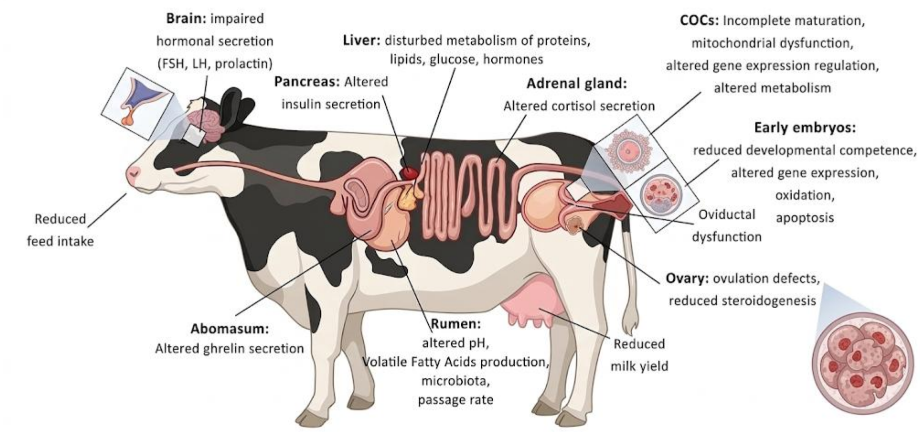

Fig 6: Schematic representation of key sites of heat stress affecting reproductive performance in dairy cows (Dovolou et al., 2023)

During times of high heat, there are significant hormonal risks such as low progesterone levels, and early corpora lutea regression (Nanas et al., 2021). Heat stress severely impairs ovarian function in cows because it suppresses LH secretion and reduces estradiol synthesis, which results in underdeveloped follicles and mostly inactive ovaries (PJ, 2007). Conception rates drastically decline from 40–60% in thermoneutral settings to just 10–20% in summer, reflecting these physiological disruptions, and over 80% of estrus cycles go unnoticed (Rutledge, 2000).

Heat stress also significantly changes follicular dynamics. Reproductive time is further complicated by the 53% rise in big follicles (≥10 mm) yet the delayed follicular dominance process (Wolfenson et al., 1995). Prematurely elevated levels of progesterone afterwards day 16 extend the luteal phase which influences synchronization (Lucy, 2001). Heat stress suppresses sexual behaviors stimulated by estradiol which increased the levels of ACTH and cortisol, lowering the chances of cows having normal estrus behaviors (Das et al., 2016). The success rate of artificial insemination is reduced by 15% when body temperatures exceed 40^{0}C (Pereira et al., 2013).

Reduced interferon-tau production (Das et al., 2016), oxidative cell damage (Wolfenson et al., 2000), and altered apoptosis-related gene expression (Fear and Hansen, 2011) all impair embryonic development. Compared to 32.6% in thermoneutral settings, only 20.5% of cows exposed to HS conceive (Khan et al., 2013).

Heat stress also impaired male reproductive efficiency. Heat stress has a great impact on the integrity of the sperm acrosome, motility and concentration as well as abnormal sperm (Lyrio et al., 2023). Under mild heat stress, some recovery is being seen and breed differences are beginning to appear with the Yanbian bulls showing the greatest tolerance. Interestingly, the sperms are a little higher in the early autumn than in the early summer implying adaptation to extended heat exposures (Cheng et al., 2016). Heat stress also has an adverse effect on male fertility, raising levels of sperm chromatin fragmentation, lipid peroxidation, and reducing membrane integrity especially in younger bulls (Prastowo et al., 2019).

The hypothalamic pituitary axis is also disturbed by the effect of heat stress. While decreased blood flow, higher uterine temperature, and altered prostaglandin secretion deteriorate the uterine environment, inhibited GnRH/LH secretion along with increased ACTH and cortisol impair neuroendocrine regulation. Under these stressful conditions, the majority of embryonic losses happen before day 42 of gestation (Sammad et al., 2020). The requirement for heat mitigation in high-producing herd is highlighted by the fact that pregnancy rates decrease by 1.03% for every unit increase in THI over 72 (Liu et al., 2019). While service lengths are substantially longer for February-calving cows (299±11 days) than for October-November calving cows (133±7 days), late-stage heat stress also decreases fetal growth and adversely affects subsequent lactation (Kaewlamun et al., 2011).

The combination of elevated metabolism generates high heat that makes lactating cows particularly sensitive to heat-related risks (Koch et al., 2016). Heat stress causes both a greater number of silent heats and anestrous to appear and shortens and intensifies estrus in agricultural animals (Krishnan et al., 2017).

Molecular Mechanism and Aspects on Physiological Effects

Heat stress initially interferes with the oxidative balance of dairy cows and stimulates the hypothalamic-pituitary-adrenal (HPA) axis, and both causes in a synergistic situation that worsens physiological destructions (West, 2003). On the other hand, heat stress leads to the abnormal functioning of the mitochondrial electron transport chain, augmenting the generation of reactive oxygen species (ROS), including superoxide anions and hydrogen peroxide, by 2–3 times (Marquez-Acevedo et al., 2023). This accumulation exceeds the antioxidant activity of enzymes, like as superoxide dismutase (SOD) and catalase (CAT) (Zeng et al., 2022).

Endocrine & Metabolic Changes

In order to preserve internal homeostasis, animal's body instantly detects the growing temperature and launches a defense system with a series of internal adaptations when they are subjected to heat stress mechanism. A range of hormones that aid in adaptation are released by the endocrine glands. This complex network of endocrinological changes form the foundation to preserve balance during high environmental temperatures (Sejian et al., 2013). The body responds quickly to the abrupt heat load in the early stages (Figure 7).

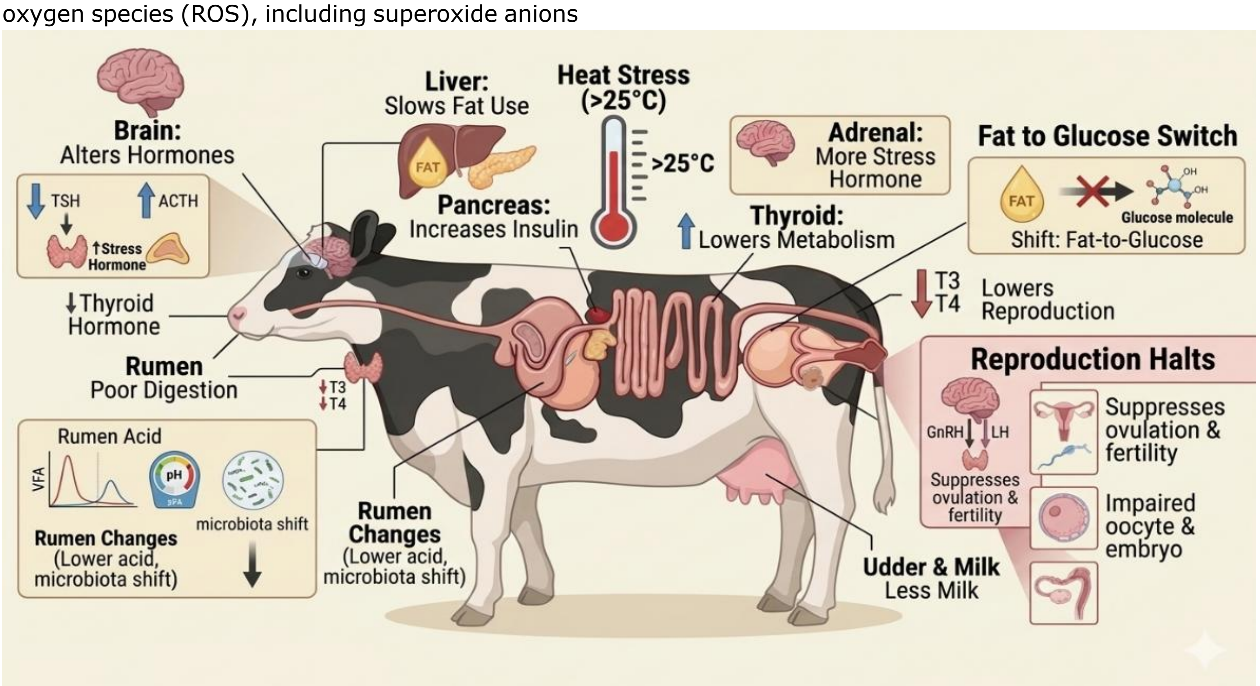

Fig 1: Systemic impacts of heat stress on dairy cow metabolism and endocrine function (Blond et al., 2024; Chen et al., 2024; Xiong et al., 2025)

Since heat stress may lead to a temporary decrease in blood pressure, the body secretes hormones, including antidiuretic hormone, prolactin, glucocorticoids and catecholamines. These hormones work together to stabilize blood pressure, retain water, and circulatory functions (Idris et al., 2021). Conversely, the levels of aldosterone decrease which influence the sodium and fluid retention, contributing to the difficulty of the body in maintaining normal hydration levels. The body starts to reduce internal hormone production in order to save energy if the heat stress situation continues. Growth hormone, thyroxine, and glucocorticoids secretion slowly decrease (Das et al., 2016). Consequently, growth, metabolism, and natural resistance of the animal to stress are greatly affected. The animal uses the process to lose excess heat by sweating and panting although this will cause loss of important water and electrolytes. Here, prolactin plays an additional role beyond its usual functions it helps regulate sodium and potassium balance, ensuring that the animal's internal fluid composition remains stable despite dehydration.

The effects of heat stress, however, are not uniform across sexes. The long periods of exposure to high temperatures in males decrease the level of testosterone that reduces the quality of sperms and overall fertility (Pérez-Crespo et al., 2008). In females, it interferes with the growth of follicles, reduces conception rates, and elevates embryonic wastage, and eventually, the reproductive achievement is impaired (Ozawa et al., 2005).

Cellular function is affected as a result of its interference with protein synthesis, enzyme activity, and cell membrane stability (Sonna et al., 2002). Consequently, erythropoietin, hemoglobin, and packed cell volume (PCV) levels as well as thyroid activity decline, which results in a decrease in vital metabolic enzymes such as ALP and LDH (Patel et al., 2016).

Among the breeds, Jersey cows have one of the most noticeable hormonal changes, with growth hormone levels dropping dramatically from 18.2 ng/ml to 13.5 ng/ml. The body tries to maintain breastfeeding in the face of stress by raising prolactin levels to support mammary gland growth and milk secretion (Farooq et al., 2010). Whereas, the thyroid hormones show opposite profile (Figure 7); T3 levels for instance reduce from 2.2 ng/ml to 1.16 ng/ml corresponding with an anti- metabolic condition (Johnson et al., 1988). These physiological responses have also been confirmed through experimental studies. The major stress hormone plasma cortisol rose significantly in 42°C exposed steers for 160 min, evidence of profound physiological strain. Furthermore, rumen fermentation pattern also altered, resulting higher concentrations of propionate and butyrate as compared to acetate which hampered the normal metabolism of energy (Chaidanya et al., 2017).

In deserve mention, among these hormonal players is also the catecholamines. The adrenal medulla and neuronal endings principally discharge these substances when the body is under stress namely dopamine, norepinephrine and adrenaline. They are emergency messengers by elevating the heart rate fast, enhancing blood circulation, and emitting energy stored in the form of nutrients. In doing so, they help cattle remain alert and cool under pressure (Bhimte et al., 2018). The glucocorticoids a different group of stress hormones, however, do not react the same way, and this is dependent on the length of time the animal is exposed to heat stress.

The combination of these hormonal changes is meant to reduce as much internal heat as possible and maintain essential functions. But there is a hefty price for this adaption. As the body diverts energy toward thermoregulation, essential productive functions begin to decline. Despite having high insulin levels, animals acquire insulin resistance, and milk yield and reproductive efficiency decline (Baumgard and Rhoads, 2013). At the same time, the animal experiences a decrease in feed intake (Rhoads et al., 2009), and changes glucose/lipid metabolism. At the same time, the animal experiences a decrease in feed intake, restricted fat mobilization (Sammad et al., 2020), and a negative energy balance, which forces it to spend its bodily reserves in order to survive.

According to (Herbut et al., 2019), prolonged exposure to heat also causes oxidative stress, which depletes antioxidants like vitamins E and C that shield cells from harm. Heat shock proteins (HSP70 and HSP90) are unique molecules that serve as a protective barrier to stabilize and repair damaged proteins. Cells begin generating these molecules in defense (Volloch and Rits, 1999). Nevertheless, when the stress exceeds the ability of the body to handle it, the intestinal lining becomes weaker, which permits the penetration of harmful endotoxins into the blood and contributes to an even greater imbalance in the metabolism (Pearce et al., 2013).

These all inter-related processes are demonstrated the constant struggle of the body to achieve thermal balance and homeostasis. These responses aid in frequent hyperthermia but result in a reduction in productivity and metabolic efficiency. This disturbance can potentially lead to serious metabolic disorders such as hepatic lipidosis and ketosis with chronic exposure (De and Cunha, 2024). In many ways, the impact of heat stress is a story of sacrifice for survival. Each hormone, enzyme, and cell in the body must be carefully balanced to save the animal's life, at the cost of growth, milk production and reproduction.

Effect of Heat Stress on Health and Immune Response

When the dairy cattle exposed to heat stress, a series of physiological and immunological responses roll within their bodies, changes that in silence undermine the health and productivity. The first one is the immune system. Neutrophil phagocytosis and lymphocyte proliferation are reduced by heat stress (Tejaswi et al., 2020), thus leaving the animal with a lower ability to fight infections. The WC1+, γ cells T cells in Jerseys decrease whereas the CD21+MHCII+ B cells in Holsteins reduce dramatically, indicating that the heat stress severely affects the immunity of the dairy cattle. Sahiwal is particularly affected by the reduced phagocytic activity and elevated cortisol levels (Alhussien and Dang, 2018).

The immune destruction persists in the mammary glands. Production of cytokines and essential synthesis of immunoglobulins IgA, IgM and IgG are impaired (Safa et al., 2018) and neutrophil activity is defective, having an impact on the clearance of bacteria (Alhussien et al., 2016). Reactive oxygen species (ROS) also go up (Figure 8) under the pressure of the stress and this oxidative pressure destroys mitochondria, hence, decreasing the level of milk protein synthesis and increasing the chances of mastitis (Giannone et al., 2023).

Blood composition is also modified in heat stress. The red blood cells (RBCs) decrease by approximately 1220 per cent and the white blood cells (WBCs) increase by 2126 per cent (Das et al., 2016). Cortisol hormone increases and reduces the synthesis of L-selectin leading to the weakening of neutrophil migration (Alhussien et al., 2016). Meanwhile, the level of heat shock proteins (HSPs) rise, which makes the immune cells more effective in killing germs (Tao et al., 2011). Nevertheless, the equilibrium is not so perfect - levels of IgG, IgM, and IgA decrease drastically in hot cows (Safa et al., 2018), and cortisol and HSP increase further and disrupt the fragile immunological project. The mammary gland has neutrophils that carry out important phagocytosis functions (Alhussien et al., 2016), but this does not work effectively when cows are under heat stress condition.

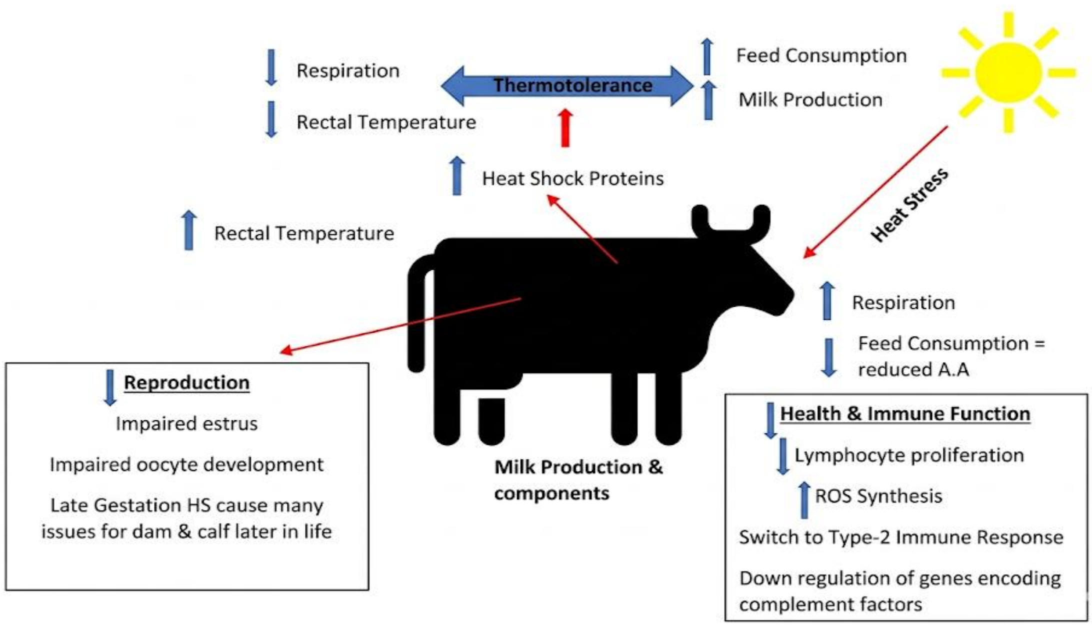

Fig 8: Heat stress-induced immune alterations and health consequences in dairy cows (Cartwright et al., 2023)

The actual physical conditions due to heat stress over a long period will be manifested on the exterior as well. Cows are likely to get lame, develop liver issues, and also get ketosis (Das et al., 2016). The occurrence of mastitis might be higher due to the weakened immunity. Functional alterations also take place in the rumen making them susceptible to metabolic disorders. When calving cows are exposed under a hot climate, the case is worse since due to hypocalcemia, they are unable to maintain body temperature.

Heat stress does not just end with the mother but it extends to the other generation. Heat-stressed dams give birth to calves with reduced TNF-2/TLR2 expression (Strong et al., 2015), distorted blood measurements including increased platelets and hemoglobin and decreased lymphocytes (Skibiel et al., 2017), and retarded IgG transfer. The immune deficiencies in these calves often become lifelong. The stress can be induced during pregnancy and lower the rate of birth weight along with exposing the fetus to the risk of encountering other illnesses such as pneumonia and diarrhea (Gupta et al., 2023).

HEAT STRESS MITIGATION STRATEGIES

Livestock Housing

Housing and Space Management

To reduce solar radiation one of the best ways is providing shade. It lowers the surface temperatures and decreases the respiration rate in heat-stressed cattle (West, 2003). Shaded areas allow cows to eat more and rest better during hot times, which helps prevent production losses (Polsky and von Keyserlingk, 2017).

Thermal Management

By using reflective roofing, proper farm orientation, and shaded sidewalls reduces the amount of solar radiation entering the farm and helps lower the internal temperature. This increases conductive and convective heat loss (West, 2003). Good natural or mechanical ventilation raises air speed around the body, which helps reduce heat load by promoting convective heat loss (Polsky and von Keyserlingk, 2017). In hot and humid climates, ventilation alone is less effective. However, even small increases in airflow can significantly lower respiration rates and rectal temperature (Giannone et al., 2023).

Cooling Fans

Cooling fans help improve convective heat loss and support feed intake and overall comfort in heat-stressed cows when installed and used properly (West, 2003). Using fans with sprinklers or misters makes evaporative cooling operate considerably better. This cools down the rectum and slows down the respiration, which makes the body feel better overall (Polsky and von Keyserlingk, 2017). Fan-sprinkler systems are one of the greatest short-term remedies for quickly lowering high heat load, especially for cows that are nursing (Tabler, 2025).

Nutritional Strategies

By changing the diet of animals and their feeding habits, a strategic change can be implemented to reduce some of the effects of heat stress. These strategies are elaborated in the in the following points.

One way to meet the nutritional demands of your animals when the temperature increases is to change their feed to provide more energy. It is also important to provide a proper balance of other nutrients so that the rumen can function effectively. When reducing the fiber level of the diet, it is critical to reduce it through a strategic way so that excessive metabolic heat production can be avoided. Increasing protein in the diet may cause a decrease in milk yield and an increase in the concentration of ammonia produced; using a form of protein that is not degradable in the rumen (RUP) will result in more amino acids being available for the production of milk (Arieli et al., 2006; Wheelock et al., 2010; Belibasakis and Tsirgogianni, 1995). Adding fat to the diet can help with heat stress (Moallem et al., 2010; Wang et al., 2010), and having the appropriate balance of electrolytes—especially potassium, sodium, magnesium, and a DCAD of +20–30 meq/100g DM (Table 4) that helps keep the body in balance, eat more, and create more milk (West, 2002; Baumgard and Rhoads, 2007; Wildman et al., 2007). Cold water and electrolytes aid with heat stress and milk production straight away, too (Milam et al., 1986; Kadzere et al., 2002). These feeding strategies are highly significant to lower the temperature.

Table 4: Feed Additives, Bioactive Compounds & Essential Oils for Heat Stress Mitigation in Bangladesh

Category	Additive / Compound	Active Bioactive Component	BD Brands / Availability	Dose	Key Research Findings	Reference(s)
Antioxidant Vitamins & Minerals	Vitamin E + Selenium (Se+VitE)	α-Tocopherol + organic Se; GPx1–4 activation; VitE recycles membrane lipids; Nrf2/NF-κB modulation	Selvet (ACME); E-Sel (ACI); Selemax (Renata); SeleVit (Square) [Inj./Bolus/Liq.]	Se: 0.3 mg/kg DM VitE: 80 IU/kg DM or 3,000 IU IM (pre-calving)	Milk yield↑ ($p<0.05$); mastitis↓; SCC↓; neutrophil function↑; reproductive perf. ↑; SOD↑ synergy with Zn+Cu+Mn	(Chen et al., 2023; Khatti et al., 2017)

	Vitamin C (Ascorbic Acid)	L-Ascorbic acid; ROS scavenger; recycles VitE; NF-κB/IL-6 inhibitor; depleted under HS	Rena-C Aqua (Renata); Civit Vet (ACI); Ascorvet (Square) [Water premix/Liq.]	50–100 mg/kg BW/d in water (aqueous premix for stability)	Plasma VitC significantly depleted under HS; neutrophil function↑; SCC↓; VitE synergy → TAC↑ multiplicatively	(Padilla et al., 2006; Trejo-Lizama et al., 2021)
	Zinc + Copper + Mn (Organic Trace Minerals)	Organic Zn/Cu/Mn chelates; SOD cofactors; Zn → metallothionein; Mn-SOD: mitochondrial antioxidant	Biogut Vet (ACME); Zincvet (ACME); Zn-forte (ACI) [Multi-vitamin combos]	Zn: 50–80 mg/kg DM Cu: 10–15 mg/kg DM Mn: 30–40 mg/kg DM (TMR or bolus)	SOD↑ in high Se+Cu+Zn +Mn group; SCC↓ with Zn 50–100 mg/d; mastitis↓; oxidative stress markers↓	(Chen et al., 2023; Bicalho et al., 2014)
Electrolytes & Osmolytes	Oral Electrolyte Solution ($NaHCO_3$ +NaCl+KCl + Dextrose)	$NaHCO_3$: rumen pH buffer; counters respiratory alkalosis; NaCl+KCl: replace sweat losses; Dextrose: energy source	Acilyte (ACI); ElectroPlus (Techno); Electromin (Square); Eskalyte (SKF); Dexolyte (Navana)	50–100 g/animal/d in drinking water; per DGDA BDNVF 2023 guidelines	$NaHCO_3$ 0.7–1.5% DM: rumen pH↑; SARA↓; K^+ losses up to 59% in severe HS; DMI↑; electrolyte balance restored	(West, 2003; Rhoads et al., 2013)
	Betaine Anhydrous (TMG)	Trimethylglycine; osmolyte + methyl donor; BCCT cotransporter: intracellular water retention; ↓ metabolic heat generation	BetaMax (SKF) [AHD feed additive powder; commercially available in BD]	15–30 g/cow/day (top-dress or TMR); optimal: 15 g/d	Meta-analysis (n=13 studies, 261 cows): DMI +0.584 kg/d; ECM +1.36 kg/d; milk fat +0.040 kg/d; grazing: milk +6.4%	(Malik et al., 2024; Singh et al., 2022)
Rumen- Protected Fat	Rumen-Protected Fat (Bypass Fat) C16:0 palm FA	Fractionated palm FA; MP ~56°C → rumen-inert; 2.5× energy density vs. starch; lower heat increment; no trans FA	BergaFat F-100 (Berg+Schmidt; via India importers) MegaFat [Agro-import BD]	150–200 g/cow/day in TMR (max ≤6–7% total fat DM)	Tropical crossbred RCT: cumulative milk +132 L over 15 wks; milk fat% maintained when DMI↓; BCS loss↓; heat increment↓	(Ranaweera et al., 2020; Rhoads et al., 2013)
Probiotics & Prebiotics	Probiotic Blend (S. cerevisiae + Lactobacillus + Bacillus spp.)	Live yeast + LAB; MOS/β-glucans (prebiotic); O_2 scavenging in rumen; tight junction protection (ZO-1/occludin)	Biolact (Square); Biogut Vet (ACME); Probolux (Incepta); Reset (Popular); Gut Pro (SKF)	S. cerevisiae: 5–10 g/cow/day; LAB: $\geq 50\times10^6$ CFU; use ≥4–8 wks	Rumen pH stable; SARA↓; NDF/ADF digestibility↑; DMI↑ in HS cows; calf ADG +40–80 g/d; E. coli shedding↓43%; mastitis 18.7→9.2%	(Habimana et al., 2023; Perdomo et al., 2020)
Herbals & Phytogenics (Locally Grown in BD)	Turmeric / Curcumin (Curcuma longa)	Curcuminoids (77%); Nrf2-ARE activation; NF-κB+COX-2 dual inhibition; HSP70 modulation	Widely grown in BD; Carcumed (Total Herbal & Nutra.); Turmeric caps (Drug Intl.)	Fresh: 20–50 g/d Dry powder: 5–15 g Curcumin extract: 1–5 g/day	Buffalo mammary cells: apoptosis↓, thermotolerance↑; Nrf2/NF-κB confirmed in vitro; broilers: MDA↓, TNF-α↓, FCR↑; gut villus height↑	(Grewal et al., 2022; Tuong et al., 2023)

Tulsi (Ocimum sanctum) + Neem (Azadirachta indica)	Eugenol: COX-2+NF-κB inhibitor; antipyretic; Azadirachtin: anti-inflammatory + hepato-protective; adaptogenic	Both locally grown in BD; Herbovet (Eskayef AHD); Ayurvet products	Tulsi: 10–50 g/d Neem: 20–50 g/d (fresh/dried; mixed in feed)	Antipyretic + immuno-modulatory confirmed in animals; polyherbal blends: cortisol↓ in HS; COX-2↓; IL-6↓; adaptogenic effect	(Jamshidi & Cohen, 2017; Singh et al., 2010)
Ginger (Zingiber officinale)	Gingerols/shogaols; COX-2 inhibition; prostaglandin↓; gut motility↑; appetite stimulant	Widely grown in BD; Herbovet (Eskayef) includes ginger EO [Fresh/dried available]	Fresh: 10–30 g/d Dry powder: 5–15 g (mixed in feed/TMR)	COX-2 inhibition; prostaglandin↓; DMI improved in HS; gut motility↑; appetite stimulant; anti-inflammatory confirmed	
Black Cumin (Nigella sativa) + Polyherbal EO Blend (Garlic/Thymol/Menthol)	Thymoquinone: Nrf2↑; Allicin: NF-κB/MAPK↓; LPS barrier↑; Menthol: vasodilation → heat dissipation↑; Thymol: COX-2↓, antimicrobial	Black cumin grown in BD; Herbovet (Eskayef); PVS Labs herbal blends [Encapsulated EO form preferred]	Black cumin: 10–30 g/d EO blend: 2–5 g/d in TMR (encapsulated form preferred)	N. sativa (calves): TAC↑, CAT↑, IL-10↑, MDA↓; Polyherbal EO: haptoglobin ↓44%, LBP↓38% within HS day 1; TBARS↓; protein carbonyl↓	(Wickramasinghe et al., 2023; Sadeghi et al., 2023; Wang et al., 2024)

Feed intake reduced during heat stress (Umar et al., 2021), therefore, feed should be offered during the cooler part of the day. The nutrient concentration particularly energy and protein should be condensed so that the nutrient demand could be fulfill even through the reduced daily dry matter intake. In terms of energy, diets should be concentrated with more energy by increasing concentrates and adding fats. This will provide a lower heat increment than forages. However, adequate fiber is still necessary to maintain rumen health (Reddy et al., 2023). For instance, slowly degradable starch (e.g., corn vs. wheat) would reduce metabolic heat increment during digestion and support higher dry matter intake and milk yield (Garner et al., 2022). In terms of protein, excess degradable protein should be minimized as it associated with increased metabolic heat generation. Instead, supplying more rumen-undegradable protein and essential amino acids would support better milk yield and immune function (Reddy et al., 2023). Supplementation of protected amino acids (e.g., methionine) and rumen-protected zinc-methionine (Table 4) can improve milk yield and immune response under heat stress condition (Kotsampasi et al., 2024).

Heat stress increases mineral losses such as potassium, sodium, and bicarbonate through sweat and urine. Supplementation of these, along with selenium and chromium, helps in maintaining acid-base balance, thermoregulation, and immune status (Reddy et al., 2023). Additionally, adjusting dietary cation-anion difference can improve blood acid-base status and milk fat yield (Bertens et al., 2024). Yeast cultures, plant extracts, organic acids, and antioxidants (e.g., vitamins E, niacin, selenium) can enhance rumen function, reduce oxidative stress, and improve immune functions (Wang et al., 2025; Abeyta et al., 2022; Nzeyimana et al., 2023). Other herbal formulas and live yeast supplementation have shown benefits in milk yield, antioxidant capacity, and physiological resilience (Wang et al., 2025). Unlimited access to clean, cool water is critical for thermoregulation and maintaining intake (Reddy et al., 2023), as tendency of water consumption increased as one of the immediate steps to reduce heat loss.

Cooling Strategies

The calmness of cows depends on the fact that environmental changes are brought in a planned manner and the cooling with the help of fans and sprinklers is a good idea. To achieve maximum evaporative cooling and to prevent excessive moisture, the water must be sprayed to one or two minutes two times a day then after five minutes, it must be dried. Larger farms benefit from fans with higher air-holding capacity and temperature-responsive speed control (Schutz et al., 2011). These cooling methods improve the ability of regulating body temperature in cattle thus enhance health, welfare and productivity. Since the design of farm, ambient temperature, humidity and others affect heat stress, several related cooling technologies may be combined to minimize the total thermal load and maintain high milk production. The open-sided farm which are more than 12 feet high offer the right amount of airflow and is advisable during planning of farm construction keep the possible thermal stress. Having higher average humidity year-round in Bangladesh, sprinklers are more effective than mistresses. Since the sprinklers produce larger size droplets, it’s associated with wet bedding, therefore, proper planning and monitoring is crucial (Kadzere et al., 2002). Sprinkler and fans allow cows to cool down through wetting of the hair coat and enhancing losses of cold through evaporation that leads to increased feed and milk production. High-pressure foggers are most effective in hot and dry environments (Armstrong, 1994; Collier et al., 2006); however, it is yet to be implemented in Bangladesh.

Long-term Plan

In Bangladesh, where it's hot and wet, heat stress has become one of the biggest concerns to dairy productivity. Farmers frequently see the first signs in the summer when their cows don't eat or make as much milk as they should. We need a mix of environmental control, nutrition, and genetics to help us adapt over the long term, not just one of these things.

Genetical Methods

Crossbreeding to improve the breed

Crossbreeding is one of the most useful ways to deal with tropical heat. Studies show that adding heat-tolerant genes to temperate breeds can boost both fertility and milk production. For instance, adding Senepol genetics to Holstein lines has been shown to boost fertility by 5–25% and milk yield by 0–10% (Swan and Kinghorn, 1992). Bangladesh already works a lot with Bos indicus breeds shown to be heat tolerant (McDowell et al., 1996). Crossing this to high milk producing breeds may be the initial steps towards heat tolerant dairy crossbred cows in Bangladesh.

Choosing genes that help with heat tolerance

Recent genomic technologies have created new possibilities for breeding cattle that are naturally more heat-resistant. Whole-genome sequencing and SNP microarrays are two tools that breeders can use to find specific genes that are linked to thermotolerance (Ventura et al., 2020). Genomic selection, which was once not available to most dairy systems, is now becoming more important for improving this trait (Weller et al., 2017). Brazil's Girolando breed is a good example because it was made for hot climates (Negri et al., 2023). But there are trade-offs cows that are genetically suited to repel heat naturally make lesser milk when they're stressed (Bohmanova et al., 2008). Hence, when developing reproductive plans, it's essential to establish a balance between productivity and adaptability.

New Technologies

Dairy farms in Bangladesh are gradually moving towards automation. Sensor based automated monitoring system has already been employed in some of the renowned farms that assist in identifying climatic condition as well as cows stress condition. For instance, fever Tags, rumen boluses and infrared thermography. These devices can also be fitted with AI assisted appropriate algorithm that can provide the situation specific management decisions to mitigate heat stress.

Integration of Environmental, Nutritional & Genetic strategies

The most efficient environmental strategies to alleviate heat stress are by offering shade, evaporative cooling and ventilation (Atrian and Shahryar, 2012). Cross ventilation along with evaporative cooling is used as combined systems, resulting in enhance milk yield, reproduction and feed efficiency (Kadokawa et al., 2012). The higher the temperature, the higher the water consumption, therefore, constant availability of cold drinking water is a necessity.

Drought decreases protein and dry matter consumption of cows (West et al., 2003). High protein diets of above 18% or high rumen-undegraded protein will enhance the yield of milk in hot environment (Zimbelman et al., 2010). The fat supplementation along with essential minerals and fatty acids is useful to decrease heat production (Atrian and Shahryar, 2012). Vitamin

C, vitamin E, vitamin A, and minerals like zinc reduce oxidative stress due to heat stress (Das et al., 2016). Yeast products increase the fermentation process of the rumen; meanwhile, Niacin enhances metabolism (Panda et al., 2017) even during extreme heat waves. An increase in the rate of potassium and sodium losses under the effect of heat stress, thus, supplementation is encouraged (Kadzere et al., 2002). Heat load may decrease by increasing the frequency of feeding (Ominski et al., 2002).

Genetic selection has an important role to play in enhancing heat tolerance. Cattle that have desirable attributes of coat color i.e. lighter color or coarse hair are more thermostatically resilient (Bernabucci et al., 2010). Genes conserving HSP involved in the heat shock response that protects cells when they are exposed to heat (Collier et al., 2008). It was reported that the breeds with a higher expression of HSP70, such as Sahiwal and Tharparkar, have a greater thermal adaptability (Kumar et al., 2006).

CHALLENGES IN HEAT STRESS MITIGATION

Heat stress is becoming a growing challenge for animal industry in Bangladesh, especially for dairy farms. When cows are exposed to heat and humidity for a long time, they eat less, make less milk, and show more indicators of poor health over time. Farmers operate farms with limited resources, don’t have technical settings and sometimes don't know how to appropriately defend their animals from extreme weather conditions.

Majority of dairy farms in Bangladesh are smallholder dairy farms, and rarely have the economic ability to invest modern heat stress management system. A considerable number of farmers farming in the rural areas does not recognize heat stress as a problem and they are still uninformed about straightforward mitigation strategies (Pashudhan Praharee, 2021). Along with these, lack of access to the new technologies is another factor that hinder better management of the animals during heat stress condition.

Heat stress management in developing countries is a challenge in developing countries due to the economic, infrastructural, and climatic constraints. The key challenges can be classified as follows:

Climatic Factors

High humidity in many subtropical countries like Bangladesh, in conjunction with temperature exert excessive heat load to the animals. In this condition, commonly practiced evaporative cooling e.g., sweating or bathing become less effective, as the air is already saturated with moisture.

Access to power and infrastructural limitations

Majority of the small-scale farmers have limited or no access to uninterrupted electricity for operating fans, pumps and other cooling system. Therefore, heat load management becomes challenging. Renewable energy like solar power could be a promising alternative, however, it demands higher initial costs. Unplanned Housing design often offer additional challenges as traditional shed with poor natural ventilation, low roof heights, inadequate orientation trapped incremental heat and humidity.

Economic and resource limitations

Small scale farmers who dominate the dairy industry in Bangladesh are unable to adopt advance technologies such as tunnel ventilation or cross ventilation. This is applicable for the bigger farms, however, requires high capital and operational costs. Heat stress condition reduce dry matter intake. To compensate this situation, high quality nutrient-dense diet is required. These are often expensive and increase the overall feed cost. Unable to manage this situation leads to negative energy balance of the cows and ultimately affect milk production.

CONCLUSION

Heat stress has become one of the key obstacles for sustainable dairy farming. It affects not only the production and reproduction of dairy animals but also health, immunity and welfare of the animals. Having a growing dairy industry in Bangladesh, most of the farmers are not aware about heat stress, and subconsciously facing economic losses due to lower production. Effective mitigation measures can alleviate heat stress and maintain optimum productivity of the animals. Awareness must be raised among the farmers through campaigning or effective training. Early detection of heat stress should be in place using digital technologies, including low-cost detectors and real-time monitoring tools. A combination of practical interventions with long-term inheritable and infrastructural planning will be the most feasible way to manage a more heat-resilient dairy sector.

Author’s Contribution

Mirza Asfaqur Rahman: Conceptualization, collecting and selecting relevant articles, writing, preparation, revision and finalization; Md. Ahatashamul Huq Tanvir: writing, preparation and revision; Abdul Muyed: writing, preparation and revision; Ebnul Hasan Shatabdi: writing, preparation and revision; Md. Najmul Haque: conceptualization, outlining, writing, reviewing and finalization.

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