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Adaptations of Cattle to Thermal and Transitional Stress-exploration of the Potent Physio-metabolic Markers: A Review

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ABSTRACT

In this review, we tried to align the physio-metabolic changes in dairy cattle during heat stress and, transition period and identify the common stress markers. Heat stress to date remainedone of the major constraints on animal welfare and production, which wasevidenced by huge production losses and high mortality. Animals have evolved different coping strategies, which included behavioral, physiological, and biochemical acclimations, oriented for acute, short-term term and long-term stress. Additionally, the transition period and lactation phase werealso stressful to the dairy cows. Monitoring these indicators couldbe very helpful to validate the animal's stress response and the severity of stress. Animals affected form heat stress commonly have reduced feed intake and drink more water, which wascoupled with changes in behavior like seeking shade, standing more, facing away from the sun, etc. Respiratory changes like panting, variable cardiovascular response like increased heart rate, pulse rate and gradual increase in skin temperatures and core body temperature werenoted thereafter. Heat stress also modulatedand rewiredthe nervous and endocrine system, and there was a major shift in energy metabolism, resulting in higher utilization of fats, evident by high triglyceride, cholesterol and non-esterified fatty acids (NEFA) levels. Hormones like cortisol wereupregulated, and others like thyroid and insulin wereaccordingly modulated, for the cellular and metabolic stress adaptation. The literature on animal response to stress wasexpansive, but here we wouldfocus simply on the common and potent physiological and metabolic indicators, which confirmed the impact of heat and transition stress in dairy cattle.

KEYWORDS: Dairy cattle, thermal stress, cortisol, alkaline phosphatase, glucose

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1. INTRODUCTION

The global climate is changing, as evident by Earth's rising temperatures and unprecedented natural calamities (Anonymous, 2018), and sustained high temperatures can lead to disorders like heat exhaustion and heat stress (Prates et al., 2025). These environmental stressors affect the animal's homeothermy and predispose them to stress, culminating in significant production and economic losses (Nardone et al., 2010; Collier et al., 2019; Wankar et al., 2021 and 2024). Although all animals display adaptation and resilience, it is noteworthy that more productive or exotic breeds succumb easily to heat stress as compared to average-yielding, native animals (Wankar et al., 2021; Singh and Ukey, 2024). The geographical distribution makes the *Bos indicus* breeds more suitable for tropical conditions, while *Bos taurus* breeds are comfortable in cooler, temperate regions (Hernandez et al., 2018). Nevertheless, factors like breed, genetics, age, body condition, diet, pregnancy, influence the acclimatization and adaptation responses in cattle, irrespective of their environment (Ongbo et al., 2026; Giannone et al., 2023). As compared to beef cattle or the smaller ruminants, extensively reared dairy cows are more susceptible to adverse environmental conditions, due to their higher metabolic rates and production potential (Nardone et al., 2010). Further, exposure to heat stress during late gestation, postpartum period or early lactation, disrupts homeothermy and predisposes them in a state of negative energy balance (NEB), characterized by metabolic disorders such as ketosis and fatty liver syndrome, compromising health and productivity (Overton et al., 2004; Menta et al., 2022; Fenwick et al., 2008). During heat stress, animal behavior, respiration rates, heart rate and body temperature alter, followed by reduction in feed intake and increased water consumption and entire metabolism is readjusted, to meet the higher thermoregulatory and production demands (Mader et al., 2010; Chen et al., 2024; Wankar et al., 2019). Sustained periods of hyperthermia exhaust the vital energy, leading to low milk production, lower body growth, poor milk composition and poor performance (Bohmanova et al., 2007; Nardone et al., 2010; Chen et al., 2024). Current research is devoted to identifying molecular mechanisms contributing to acclimatization and heat tolerance in cattle, spurring advancements in breeding practices aimed at reducing heat stress impacts (Ravagnoloand and Misztal, 2000; Cartwright et al., 2023). Also, advanced technologies like infrared thermography and wearable sensors, which offer continuous monitoring of thermal stress, are an integral part of the intensive dairy units (da Silva et al., 2003; Oliveira et al., 2025). Mitigation strategies aimed to combat heat stress include different cooling systems, like fans and sprinklers and optimizing management practices, such as providing shade and adjusting feeding, which have been on the rise in the last two decades, globally (Collier et al., 2008; Sharpe et al., 2020). Transition period and early lactation, demands increase for glucose, and during heat stress, as the fermentation and post-absorptive functions are adversely affected; it leads to the utilization of other substrates for milk synthesis, resulting in metabolic disorders such as hypoglycemia and ketosis (Lamp et al., 2015). Cows displaying low body condition scores (BCS), low plasma glucose levels, and elevated non-esterified fatty acids (NEFA) indicate negative energy balance (Menta et al., 2022). Also, there is a notable positive correlation between plasma NEFA and intracellular heat shock protein 72 (HSP72) levels has been noted, suggesting a link between energy balance and heat stress response (Vaidya et al., 2023). The impact of heat stress on cattle physiology and metabolism has been thoroughly studied, but the adverse effects during the transition period and early lactations are yet to be fully explored. In this review, we tried to align the physio-metabolic changes in dairy cattle during heat stress and, transition period and identify the common stress markers.

2. PHYSIOLOGICAL MARKERS OF THERMAL STRESS

2.1. Respiration (rr), pulse (pr) and heart (hr) rate

Our understanding of cattle thermoregulation has evolved considerably from previous studies investigating the evaporative cooling mechanisms comprehensively (Joshi et al., 1968; McLean, 1963). These essential thermoregulatory changes in the respiratory and cardiovascular system are modulated by the hypothalamus and the endocrine system (Ingram and Mount, 1975). Recent findings suggest that respiratory evaporative heat loss in cattle can account for 20–50% of total heat dissipation capacity, and is influenced by factors like environmental conditions, THI and breed adaptability (Gaughan et al., 2008; Zhou et al., 2023). High environmental temperatures and humidity, as well as the temperature-humidity index (THI) and other factors such as solar radiation and wind speed, further exacerbate the effects of thermal stress on animals (Moran, 1999; Becker, 2020). Indices such as the heat stress index (HIS), heat load index (HLI), and THI are commonly used to predict thermal stress in dairy cows (McCollum et.al, 2017).

Physiological vitals like respiration (RR), pulse (PR) and heart (HR) rate are the first to alter during heat stress, as essential heat dissipation mechanisms (Berman, 2005; Wankar et al., 2019) and when these mechanisms are compromised, the metabolic heat accumulates and the body temperature (BT) rises, gradually (Collier and Gebremedhin, 2015; Yadav et al., 2019). Hence, RR and HR are considered to be the best non-invasive indices to monitor heat stress in livestock and assess welfare and productivity (Lacetera, 2019). But evaporative cooling and associated respiratory changes, can vary, based on factors like breed and acclimatization (Baumgardand Rhoads, 2013; Collier et al., 2018) and studies show that *Bos indicus*, exhibits lower respiration rates than *Bos taurus* under heat stress, reflecting better adaptation capabilities (Hansen, 2004; Das et al., 2016). This acclimatization may stem from anatomical and physiological traits such as increased sweat gland density and more evaporative surface area (Rhoads et al., 2013).

Aggarwal and Upadhyay (1997) documented significant increases in RR, HR and RT in crossbred calves exercised and exposed to hot-dry conditions. Later, they showed that after 4 h of heat exposure, crossbred cattle exhibited significantly elevated RR, while Sahiwal cattle showed comparatively lower RR (Aggarwaland Upadhyay, 1998). Moranet al. (1999) and also Silanikove et al. (2000) confirmed that, increase in RR is one of the earliest signs exhibited by cattle during heat stress. Another contemporary researcher investigated the physiological performance of Brown Swiss cattle, exposed to different environmental conditions. Eleven cattle were kept in a stall barn under controlled conditions (13°C and 65% humidity) for 14 days before being transitioned to challenging conditions (21°C and 85% humidity) for another 14 days. The study found a significant increase (p<0.01) in average rectal temperature and respiration rates in animals at more challenging settings (Maggiolino et al., 2025).

Koubkova et al. (2002) and Oliveira et al. (2025) also reported significant increase in rectal temperature, respiration rate, and pulse rates, while, Bernabucci et al. (2010) found notable differences (p<0.01) only for rectal temperature between hot and non-hot conditions in Holstein cows exposed to high temperatures. Research on Bos taurus and Bos indicus in climate-controlled chambers has highlighted distinct physiological changes during heat exposure (Beatty et al., 2006). Not only are the breed-wise thermoregulatory differences evident, but the animal housing, management, and interactions between factors like nutrition or health, play a crucial role in assessing overall impacts of heat stress on cow productivity (Gaughan et al., 2008). All these factors make a high-producing dairy cow more susceptible to adverse environmental stressors, predisposing them ultimately to heat stress (Prates et al., 2025).

Extensive research over the years, across different species and breeds acclimated to specific environmental or housing conditions, has ascertained that the physiological indicators like RR, PR, HR and RT remain the most promising variables to confirm heat stress in livestock. When the heat gain is greater than that can be effectively dissipated, it raises the body temperature, which can be noticed as increased skin or fur temperatures in cattle (da Silva, 2013) and elevated skin temperature have been observed after prolonged exposure in climatic chambers or natural conditions (Shephard, 2023; Hristov, 2025). Vaidya and Singh (2019) found that during the summer season, physiological responses like rectal temperature, respiration rate, skin temperature, pulse rate, and heat storage were notably higher (p<0.05) in Karan Fries and Sahiwal cows than those observed in the winter season. Chen et al. (2024) reported an increase in respiratory rates by an average of 16.4 breaths per minute when the temperature reaches 38°C compared to 28°C (Chen et al., 2024). Also, Giannone et al. (2023) established the negative relationship between heat stress, lying time and RR and body temperatures in lactating dairy cows. Others have found a negative correlation between high rectal temperatures, with reduced milk yield and altered milk composition (Chen et al., 2024).

2.2. Energy transition markers of thermal stress

2.2.1. Non-esterified fatty acids (nefa)

Thermal stress affects all the phases of energy metabolism, and especially the last trimester, early lactation and postpartum periods are more stressful for dairy animals. Dairy cows are known to utilize more than 30% of total available energy for thermoregulation, thus increasing the energy deficit for production (Anonymous, 2001). Diversion of essential energy for thermoregulation increases the mobilization and utilization of alternative fuels and also reduces the production potential in dairy cows (Wheelock et al., 2010). This metabolic shift often coincides with decreased feed intake and can manifest before or during parturition and lactation (Garnsworthy et al., 2008).

The prepartum period is marked with reduced feed intake, starting at 3–4 weeks before calving, and results in poor nutrient assimilation, poor fetal development and low milk yield (Chen et al., 2024; Bernabucci et al., 2009). The regulation of non-esterified fatty acids (NEFA) is a critical indicator for assessing energy transition in dairy cows, and mobilization of triacylglycerides from adipose tissue is a response typically triggered by negative energy balance (NEB), which results in higher NEFA levels (Grummer, 2008). Elevated NEFA levels, in tandem with reduced blood glucose levels, signify an energy shortfall and the necessity for energy mobilization (Grummer, 2008). Rising NEFA concentrations in the weeks up to calving correlate with fractional feed intake, but the rapid escalation of NEFA in the immediate pre-calving period seems hormonally regulated. In early lactation, around 50% of NEFA are either oxidized to ketone bodies or re-esterified into triacylglycerides, illustrating the liver's critical function in managing energy deficits (Erickson et al., 2020). Plasma NEFA levels rose at around 25 days prepartum, from approximately 0.4 mM, to about 1.1 mM on the day of calving, and declined thereafter to prepartum levels in dairy cows (Vaidya et al., 2015). The same trend was reported in dairy cattle by Pedernera et al. (2008), where the periparturient period NEFA levels reached values near 300 μM before calving, peaked at 1100 μM during calving, and then lowered gradually to about 400 μM by day 20 postpartum.

Variation in NEFA levels throughout the lactation cycle has also been established, and studies have shown consistently higher NEFA levels during early as compared to late lactation (Santos et al., 2009). This can be mostly attributed to high energy demands initiating mobilization of stored fat, resulting in increased NEFA concentrations as primary energy substrate (Garnsworthy et al., 2008). However, it should be taken into consideration that the postpartum NEB varies depending on the cow's response to various stresses, nutrient utilization, body energy depots and the severity of heat stress (Grummer, 2008). The diversification for NEFA metabolism is also influenced by the season of calving and summer calvings, resulting in higher NEFA concentrations as compared to winter seasons in dairy cows (Bach et al., 2013). Highest NEFA values were recorded on days 8 postpartum, with 5.5 mM in summer and 3.4 mM in the winter season (Santos et al., 2009). Similarly, Vaidya et al. (2015) also reported higher plasma NEFA levels during the summer (15^{th} day postpartum) as compared to the winter season, in the high-yielding Karan Fries cows (Vaidya et al., 2015).

One of the key components in commercial dairy farming is early postpartum heat in the dairy cows, with timely mating and initiation of the pregnancy cycle. This fertility is closely associated with body condition score (BCS) and the energy status of the cow, as reflected by the circulating NEFA levels (Raboisson et al., 2014). Plasma NEFA concentrations fluctuate between 100 and 2000 μeq/liter, with lower values seen in cows with reduced productivity and fertility (Kabir et al., 2022). Additionally, a high body condition score (BCS) at calving, increased lipid mobilization, can alleviate the reproductive oxidative stress, adversely affecting the fertility (Bernabucci et al., 2010; de Vries and Veerkamp, 2000). Delayed heat display and other fertility problems are common in cows with higher BCS at calving, confirmed by high plasma NEFA levels and consistent low feed intake (Overton and Waldron, 2004; Santschi et al., 2011).

2.2.2. Glucose

Glucose serves as a primary energy source in all species and is metabolized through glycolysis, the tricarboxylic acid cycle, and oxidative phosphorylation to generate adenosine triphosphate (ATP) required for cellular functions (Nelson and Cox, 2017). When glucose availability exceeds immediate energy demands, it is converted into glycogen for short-term storage, predominantly in the liver and skeletal muscle, thereby maintaining glucose homeostasis (Berg et al., 2015). Excess glucose can also be converted into fatty acids and subsequently esterified to form triacylglycerols, which are stored in adipose tissue and serve as the principal long-term energy reserve of the body (Berg et al., 2015).

Although ruminants rely predominantly on hepatic gluconeogenesis to provide circulating glucose because most dietary carbohydrates are fermented in the rumen, this gluconeogenesis is further upregulated during late gestation and early lactation to meet the increased demands for glucose for fetal growth and lactose and milk synthesis (Wang et al., 2025). Previous studies have reported that exposure to environmental and thermal stress alters plasma glucose concentrations in dairy cows, with heat stress often associated with decreased circulating glucose relative to thermoneutral conditions (Becker et al., 2020). Plasma glucose concentrations in cattle and heifers are significantly reduced during summer or heat-stress conditions compared with thermoneutral or winter periods, reflecting altered carbohydrate metabolism and increased glucose utilization under thermal stress (Bernabucci et al., 2010; Wang et al., 2020). Maintaining homeothermy remains critical during environmental stress, and heat stress profoundly affects glucose metabolism and insulin-regulated pathways in cattle. Heat-stressed dairy cows often exhibit increased circulating insulin concentrations and altered glucose utilization compared with thermoneutral animals, reflecting changes in metabolic partitioning and endocrine responses under thermal load (Abbas et al., 2020). Heat stress has been shown to modulate glucose homeostasis at the molecular and systemic levels, including changes in glucose transporter dynamics, insulin action, and energy metabolism, ultimately impacting circulating glucose levels and tissue sensitivity to insulin (Wheelock et al., 2010).

A recent study by Zhang (2025) confirmed that heat stress increased glucagon-like peptide-1 (GLP-1) concentrations, which might be responsible for changing glucose metabolism in heat-stressed dairy cattle. Plasma glucose levels were significantly lower on the day of calving and the trend continued up to the 45^{th} day postpartum as compared to the prepartum period in both high and low yielding cows across all seasons, confirming similar metabolic pathways irrespective of the production potential (Vaidya et al., 2015). he lower postpartum glucose levels observed in dairy cows are likely due to a substantial decline in dry matter intake (DMI) around calving, which reduces the supply of glucogenic precursors such as propionate from ruminal fermentation while the demand for glucose for milk synthesis increases markedly, contributing to a negative energy balance and hypoglycemia in early lactation (Drackley, 1999).

In dairy cows, plasma glucose concentrations typically decrease during the transition from late gestation to early lactation, reflecting the combination of reduced dry matter intake and increased glucose demand for lactose synthesis in milk (Grummer, 1991; Drackley, 1999). Blood glucose can decline sharply immediately after calving, reaching its lowest values in the first two weeks postpartum, and then gradually increases as feed intake improves and gluconeogenic adaptation progresses (Bell, 1995; Bruinjé et al., 2026). These changes are mediated by endocrine adaptations, including alterations in insulin and glucagon signaling, which help sustain lactation while prioritizing glucose for the mammary gland (Bell, 1995; Baumgard and Rhoads, 2013).

Body condition score (BCS) has been associated with energy balance and circulating metabolites in dairy cows, with higher BCS generally corresponding to more favorable energy status and higher circulating glucose concentrations during early lactation (Roche et al., 2009). In addition, environmental heat stress has been shown to alter glucose metabolism in cattle; heat-stressed animals often exhibit changes in glucose disposal and insulin dynamics compared with thermoneutral controls, including increased insulin response during metabolic challenges, reflecting heat-induced endocrine modulation (Wheelock et al., 2010; Baumgard and Rhoads, 2013).

2.3. Endocrine and enzyme markers of thermal stress

2.3.1. Cortisol

Stress elicits an immediate response in animals, essential for acclimation and survival. This response is collectively mediated by the nervous and endocrine systems and there's activation of the hypothalamic pituitary adrenal axis (HPA), and immediate release of glucocorticoids, which regulate the cellular acclimatization and energy uptake (Ali and Hyder, 2008; Wankar et al., 2014, 2019; Collier and Gebremedhin, 2015). This hyperglycemic and hepatic gluconeogenic role of cortisol becomes essential during stressful conditions, for energy production and utilization (Liu et al., 2022; Hart, 2012). Mostly, the cortisol levels come back to their baseline after an initial increase, suggesting adaptation to chronic stress (Liu et al., 2022).

Cortisol stimulates physiological adjustments that enable an animal to tolerate heat stress, and during the transition period in dairy cows, cortisol levels are elevated before, during, and following parturition, indicating an increased release of adrenocorticotropic hormone (ACTH) (Grummer, 1991). Plasma cortisol levels can increase within 20 minutes of exposure to acute heat stress and reach a plateau within 2 hours (Christisonand Johnson, 1972). Exposure to direct solar radiation during the summer increased plasma cortisol concentration (Yousef, 1985). Similarly, increasing the ambient temperature in a climatic chamber from 24°C to 38°C over 9 h increased cortisol levels (Habeeb et al., 2023). Furthermore, Kadzere et al. (2002) found that cows are sensitive to heat stress even in temperate environments and that basal cortisol concentrations may increase in chronically heat-stressed cows if heat stress intensifies (Wankar et al., 2019). The effect of heat stress and transition stress produces predictable animal responses, which can be confirmed by the cortisol mapping during that period, making cortisol a reliable indicator of stress (Ataallahi et al., 2023). However, recent research has unfolded the complexity of cortisol response and the need to consider multiple factors, the interplay with other hormones and the animal's overall physiological state (Baumgartner et al., 2022).

2.3.2. Thyroid hormones

Thyroid hormones, mainly thyroxine (T_4) and triiodothyronine (T_3), are the primary regulators of metabolism (Niles et al.,1980) and are naturally lower in heat-stressed animals to reduce the metabolic generation (Wankar et al., 2014). Additionally, heat stress-induced metabolic alterations significantly influence carbohydrate absorption, glycogenolysis, gluconeogenesis, lipid metabolism, and protein synthesis, thereby playing a critical role in the regulation of whole-body energy homeostasis in dairy cattle (McFaddenand Rico, 2019; Baumgardand Rhoads, 2013). Fazio et al. (2022) showed how circulating thyroid hormones (T_3, T_4) vary with physiological state, and discusses links between THs and metabolic (energy) status in dairy cows, which relates strongly to energy balance and health.Periods of negative energy balance and heightened lipid mobilization often lead to significant reductions in blood concentrations of thyroid hormones, particularly triiodothyronine (T_3) shortly before and after calving, as observed in dairy cows around the transition period (Fiore et al., 2017). Vaidya et al. (2016) suggested that on the day of calving, plasma T_3 and T_4 levels were significantly reduced in high-yielding cows during both summer and winter seasons, reflecting potential thyroid dysfunction associated with heat stress. Also, the reduction in thyroid hormone levels frequently coincides with increased concentrations of non-esterified fatty acids (NEFA), reflecting the mobilization of stored fat to meet escalating energy demands (Fiore et al., 2017).

The thyroid hormones play a significant role in supporting the metabolic demands of the mammary gland during lactation, contributing to increased basal energy metabolism that helps meet the substrate requirements for milk synthesis and secretion in dairy cows (Fazio et al., 2022). Monitoring changes in circulating T_3 and T_4 throughout lactation provides insight into the cow's metabolic adaptation to lactation, where concentrations often decrease during early lactation, reflecting negative energy balance (NEB) and high nutrient demands of the mammary gland (Fazio et al., 2022). However, the relationship between thyroid hormones and milk production is complex and multifactorial: while some studies suggest negative correlations between circulating T_3/T_4 and milk yield particularly in early lactation or under severe NEB this relationship is influenced by physiological stage, energy balance, and endocrine adjustments (Duru et al., 2021). Thus, tracking thyroid hormones alongside other metabolic indicators such as insulin, NEFA, and glucose provides a more comprehensive assessment of metabolic status and adaptive capacity in dairy cows, especially during the stressful transition period when cows shift from pregnancy to peak lactation and are at increased risk for metabolic disorders.

2.3.3. Insulin

Insulin's known functions include glucose delivery to cells, and fat and protein sparing. During the last three weeks of gestation, insulin levels typically rise significantly, and research suggests variable prepartum insulin levels, with some studies noting a peak of around 16 mUl^{-1} at calving (Grum et al., 1996). However, after calving, insulin levels drop to about 5 mUl^{-1} before gradually increasing to approximately 10 mUl^{-1} by 100 days into lactation (Grum et al., 1996). As lactation progresses, plasma insulin concentrations reflect changes in energy metabolism and nutrient partitioning, and this dynamic is influenced by interactions with the insulin-like growth factor-1 (IGF-1) axis that is responsive to growth hormone signalling in dairy cows (Rhoads, 2013). Insulin plays a central role in ruminant metabolism, acting as an anabolic hormone that promotes protein synthesis and reduces proteolytic breakdown, particularly during lactation when nutrient demands are high (Hocquette et al., 2007). In ruminants, insulin regulates energy balance by suppressing gluconeogenesis and promoting glucose utilization, thereby conserving gluconeogenic amino acids and reducing the need for their catabolism (Hocquette et al., 2007). Additionally, insulin contributes to inhibition of cellular protein degradation by targeting the proteasome pathway, a key proteolytic system within cells (Hamel et al., 1997), which helps preserve body protein during the elevated metabolic demand of lactation. Consequently, monitoring changes in insulin and IGF-1 alongside other metabolic indicators offers valuable insight into the metabolic status and adaptive capacity of dairy cows throughout lactation and the transition period.

Cows on restricted diets lose body weight and body reserves, leading to lower plasma glucose and thus low insulin levels compared to those on maintenance diets (Ferraretto et al., 2014) and recent findings suggest a link between leptin and insulin, indicating that leptin may help regulate insulin during early lactation (Wang et al., 2020). Wankhade et al. (2017) noted a decline in plasma insulin postpartum in primiparous cows, which persisted until week 4 and then gradually increased until the 20th week. This decline coincides with an increase in liver triacylglyceride accumulation due to adipose tissue mobilization, supporting lactation demands (Ingvartsenand Andersen, 2000).

2.3.4. Alkaline phosphatase

Alkaline phosphatase (ALP) is an enzyme predominantly produced in the liver, bone, and placenta and is released into the bloodstream during tissue injury and physiological processes such as bone growth and pregnancy. The primary role of alkaline phosphatase (ALP) involves the hydrolysis of phosphate esters, thereby supporting skeletal mineralization and bone growth, regulating cellular growth and differentiation, and contributing to membrane-associated transport and signaling processes (Millan, 2013). Research has demonstrated that serum alkaline phosphatase (ALP) concentrations can vary under different physiological and stress conditions, and elevated ALP activity is commonly associated with bone disorders, hepatobiliary diseases such as bile duct obstruction, and stress-related metabolic alterations, including those induced by heat stress (Millan, 2013; Ongbo et al., 2026). Heat stress markedly alters physiological and biochemical responses in calves and heifers, including changes in blood enzyme profiles associated with metabolic and hepatic function (Collier et al., 2017; Bernabucci et al., 2010). Evidence suggests that prolonged exposure to heat stress can exert lasting effects on enzyme regulation, including alkaline phosphatase (ALP), reflecting adaptive and pathological alterations in liver and bone metabolism (Bernabucci et al., 2010). In contrast, feed restriction under thermoneutral conditions has been shown to increase circulating ALP activity, likely due to enhanced hepatic metabolic adaptation associated with reduced dry matter intake and altered energy balance (Ferraretto et al., 2014; Roche et al., 2009). Seasonal variations in ALP activity have also been reported under field conditions; for example, in Sahiwal cows, plasma ALP activity decreased by 19.7% and 12.8% on the 30th and 15th days postpartum, respectively, during winter, while corresponding reductions of 13.9% and 9.75% were observed in Karan Fries cows, indicating breed-specific metabolic responses to seasonal stress (Vaidyaand Singh, 2019).

3. CONCLUSION

Different stressors and multi-stressors impacted animal homeostasis and production, making stress assessment more important under global climate change. Although advanced molecular techniques provided insights into stress adaptation, they remained costly and time-consuming. Simple physiological changes such as respiration rate, heart rate and body temperature gave a fair indication of thermoregulatory adaptation during heat stress. Stress severity was further confirmed by plasma metabolites, hormones and enzymes like NEFA, glucose, cortisol, thyroid hormones, insulin and ALP, enabling timely ameliorative measures.

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