Nutritional Management of Heat-Stressed Pregnant Dairy Cows

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Abstract
Rising global temperatures present an increasing challenge to dairy production, with heat stress during the dry period posing significant risks to cow health and subsequent lactation performance. While the impacts of heat stress on lactating cows are well documented, comparatively less attention has been given to pregnant, non-lactating animals. Evidence suggests that heat stress during late gestation can disrupt endocrine function, impair energy balance, and promote systemic inflammation, thereby affecting the transition period, early lactation performance, and overall productivity. The aim of this review is to synthesise and critically evaluate current knowledge on the physiological and metabolic responses of pregnant dairy cows to heat stress during the dry period, with particular emphasis on placental function, fetal development, and maternal metabolic adaptation. Special attention is given to nutritional strategies that may mitigate these effects, including the use of rumen-protected fats, antioxidants, and essential trace minerals such as chromium, as well as dietary formulation and feeding management. These interventions may improve thermoregulation, reduce inflammatory responses, and support metabolic resilience in heat-stressed cows. A better understanding of effective nutritional and management strategies during the dry period is essential for safeguarding cow welfare, improving productive longevity, and supporting sustainable dairy production under increasingly warm climatic conditions.

Keywords: chromium, dry period, heat stress, mitigation, nutrition, protected fat

1. Introduction

Climate change has direct effects on livestock performance and welfare, mainly through increases in temperature and the frequency of extreme weather events. Furthermore, it affects animals indirectly through changes in the availability of fodder and pasture [1]. Moreover, climate projections suggest that global temperatures could increase by 3.3°C to 5.7°C by the year 2100, making it even more difficult for dairy farmers to maintain optimal conditions for their livestock [2].

Dairy cattle are subjected to significant stress during gestation and lactation when exposed to high ambient temperatures and humidity, a condition known as heat stress. This occurs when the temperature-humidity index (THI) surpasses 68 [3], triggering evaporative cooling processes like panting and sweating [4–6]. Effective management of environmental factors is therefore critical for both lactating and non-lactating (dry) cows to maintain health and productivity [7]. Heat stress elevates core body temperature by 0.4°C to 1.0°C and induces behavioral, physiological, and metabolic adaptations aimed at enhancing heat

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loss or reducing internal heat production [5, 8]. Lactating cows under heat stress exhibit increased standing time, bunching, and reduced activity, rumination, and altered feeding patterns [5, 9–11]. Similar adaptive responses are observed in dry cows during late gestation [7]. The dry period is a phase of accelerated fetal growth, and heat stress during this time can induce long-term negative effects on the offspring through *in utero* programming [12, 13]. These programming effects also impact the dam's mammary gland, as placental hormones like placental lactogen and estrogens are crucial for its development [14]. Maternal hyperthermia can impair placental development and function, with the severity dependent on the gestational stage [15]. Heat transfer from dam to fetus occurs via placental perfusion, and the placenta's diffusion capacity decreases as gestation advances [16]. Studies in ewes have demonstrated that heat stress reduces placental weight, placentome number, and cell division [17, 18]. In goats, heat stress led to prolonged placental retention, increased cotyledon number, and reduced placental efficiency [19]. Other research in small ruminants has linked environmental stressors to adverse effects on placental efficiency [20], binucleate cell number [21], cotyledon number, placental weight [22, 23], and surface area [24], though the specific responses in cows require further clarification. This underscores the need for nutritional management strategies to mitigate these detrimental impacts. The aim of this review is to synthesise and critically evaluate current knowledge on the physiological and metabolic effects of heat stress in pregnant dairy cows during the dry period, with particular emphasis on placental and fetal development, and to assess the effectiveness of nutritional strategies proposed to mitigate these adverse effects.

2. Impacts of maternal heat stress on embryonic placental, and fetal development

2.1. Effect on embryonic development

Maternal heat stress during the periconceptional period and early gestation disrupts embryogenesis due to the high heat sensitivity of preimplantation embryos. Substantial embryonic mortality occurs during the first week post-fertilization under heat stress conditions [25, 26]. Holstein heifers exposed to elevated temperatures during the initial seven days post-estrus demonstrated increased proportions of abnormally and slowly developing embryos [26], a finding corroborated by in vitro studies where bovine zygotes cultured at 40-40.5 °C exhibited reduced blastocyst formation rates [27].

The mechanisms underlying hyperthermia-induced embryonic abnormalities are multifaceted. Intracellular alterations include reduced mitochondrial membrane potential and calcium ion concentrations, both critical for developmental regulation [28]. Nuclear modifications encompass DNA fragmentation indicative of apoptotic processes [29]. Additional cellular damage arises from elevated reactive oxygen species production under heat stress [30]. Furthermore, paternal genomic imprinting may be particularly vulnerable during early embryonic stages due to active demethylation processes occurring post-fertilization [31], potentially creating heritable epigenetic modifications across generations [30], though this requires further validation in bovine models.

Embryonic thermotolerance increases with developmental progression, potentially attributable to enhanced cell numbers and upregulated protective mechanisms including heat shock protein expression [32]. The periconceptional heat challenge may function as a natural selection mechanism, favouring embryos with superior developmental competence [33], though this review necessitates additional investigation. However, several limitations apply to these findings. Most studies relied on vitro or nulliparous heifers, neither of which accurately represents late-gestation dry cows. Furthermore, the extreme temperatures used in some experimental protocols may not reflect in vivo conditions, and the proposed natural selection mechanism remains unvalidated in commercial dairy herds.

2.2. Effect on fetal development

Late-gestation heat stress significantly affects fetal development through multiple pathways. Fetal thermoregulation depends entirely on maternal systems, with placental circulation facilitating approximately 80-90% of heat exchange [34]. A key maternal adaptation to this challenge is a circulatory redistribution, where blood is shunted away from the uterus toward the skin to facilitate convective heat loss [35], which occurs

concurrently with reduced dry matter intake in pregnant dams [36]. However, the evidence for these mechanisms in dairy cows is less direct than often assumed. The heat exchange comes from computer modeling, and the blood shunting response has been primarily documented in sheep, warranting cautious prediction to late-gestation dry cows.

2.3. Effect on placental

Placental function becomes compromised during heat stress, evidenced by decreased circulating concentrations of key placental hormones including estrone sulfate, placental lactogen, and pregnancy-specific protein B [17, 37, 38]. Transcriptomic analyses in porcine models revealed 169 differentially expressed genes in heat-stressed placentae, primarily involved in nutrient transport and metabolic processes [39]. Initial compensatory mechanisms may include upregulated expression of insulin-like growth factors and vascular endothelial growth factors observed in ovine models [40], though placental mass reduction primarily results from decreased cell numbers rather than altered cell size [18].

Contrasting placental morphological responses have been documented in bovine studies. Some research indicates increased cotyledon numbers and surface area in heat-stressed dams [41], potentially representing compensatory adaptation. Conversely, other investigations report reduced cotyledon numbers and surface area [42]. These discrepancies may reflect methodological challenges in placental research, including variable expulsion intervals and high endogenous RNase activity complicating molecular analyses [43].

Collectively, maternal heat stress creates a nutrient-restricted hyperthermic intrauterine environment through combined effects of reduced placental efficiency, altered blood flow distribution, and diminished nutrient intake. These conditions ultimately restrict fetal growth and induce permanent developmental adaptations [44], with potential metabolic consequences extending into postnatal life independent of intrauterine growth restrictions [45]. The inconsistency in placental morphological findings point to an important research priority: prospective studies in heat-stressed dry cows that together measure cotyledon morphology, hormone concentrations, gene expression, and nutrient transfer efficiency. In the absence of such integrated studies, the relationship between placental structure and function under heat stress will remains insufficiently defined, limiting the precision of nutritional recommendations.

3. Nutritional strategies to mitigate heat stress in pregnant dry cows

3.1.1. Foundational nutritional adjustments

The transition from the dry period to lactation in dairy cows constitutes a crucial period demanding significant physiological adjustments to meet the demands of both fetal development and the initiation of milk synthesis in the new lactation cycle [46]. Furthermore, an inability to successfully adapt to these metabolic and hormonal shifts, particularly in the final three weeks of gestation, is associated with an increased risk of postpartum health disorders [46]. In addition to the considerable metabolic challenges faced by high-producing dairy cows during this transition, oxidative stress presents a further concern, as it has the potential to impair immune function [47].

Consequently, the nutritional and management strategies implemented for the periparturient cow are paramount, serving as the most critical factors affecting overall health and subsequent reproductive performance [48]. Specifically, the level of energy intake in the prepartum period is a key determinant for postpartum liver function and susceptibility to metabolic diseases [48]. Recent research has substantiated that over nutrition during the dry period can impair liver function and adversely affect the expression of genes associated with peroxisome proliferator-activated receptors (PPAR) in early lactation [48]. A major limitation is that the transition period studies come primarily from lactating cows in thermoneutral environments. Heat-stressed dry cows differ considerably, as they experience reduced feed intake rather than overnutrition. Therefore, direct application of these findings to heat-stressed dry cows requires validation.

3.1.1. Water

Ad libitum access to water is critical for dairy animals exposed to environmental heat stress, as water is essential for thermoregulation, helping to dissipate excess body heat through sweating and panting. Water intake is positively correlated with

milk production and DMI [49], and it increases with rising environmental temperatures due to greater water loss. Intake can rise by 50% when the Temperature-Humidity Index (THI) exceeds 80. Therefore, a constant supply of clean water within the shed is essential. During heat stress, adding ice cubes to drinking water can help lower water temperature [50]. Under severe heat conditions, a Holstein cow producing 28 kg of milk per day may consume between 121 to 135 L of water daily [51]. Providing chilled water (10°C) to lactating cows was more effective in reducing body temperature than warmer water (28°C), though it was only about 32% effective overall. Interestingly, strategic water restriction after feeding has been shown to improve nitrogen balance and nutrient digestibility in heat-stressed ewes without adverse immune effects [52]. A major drawback is that most water studies were conducted in lactating cows, not dry cows. The limited effectiveness of chilled water (32% reduction in body temperature) indicates that water management alone is insufficient. Moreover, the water restriction findings in ewes should not be directly applied to pregnant dairy cows experiencing heat stress.

3.1.2. Fiber level in the ration

Fiber and its digestibility are among the first nutrients to interact with hot weather conditions. Generally, fiber influences voluntary dry matter intake (DMI), chewing, and ruminating activity [53]. The level of crude fiber (CF) in the ration plays a significant role in heat stress amelioration. While sufficient fiber is essential for normal rumen function and maintaining feed intake through high-quality forage, the digestion and metabolism of fiber generate more heat than concentrates. Research indicates that feeding lactating cows a ration low in crude fiber (12.50% on a dry matter basis) significantly decreased rectal temperature, pulse rate, and respiration rate. Consequently, fiber levels must be carefully considered when formulating rations for ruminants in hot humid tropical regions. West et al. [5] found that cows fed a low-fiber diet during a hot period had higher daily milk output and lower body temperature and respiration rate than those fed a high-fiber diet. Supporting this, Miron et al. [55] evidenced that decreasing the Neutral Detergent Fiber (NDF) level in the diet helped lower respiration rate and rectal temperature while increasing DMI and milk production. Similarly, Adin et al. [56] reported a significant decrease in rectal temperature when dietary NDF was reduced. Conte et al. [54] reviewed that diet with low metabolic heat increment can enhance feed intake and performance under heat stress. Therefore, fiber intake significantly impacts heat generation and must be accounted for in developing efficient nutritional and environmental management strategies. Nevertheless, the fiber research cited were conducted in lactating cows, not dry cows. Reducing NDF too much (below 28%) poses a risk of rumen acidosis, yet no studies have determined the safe lower limit for dry cows under heat stress. Until such research is conducted, fiber modifications should be made cautiously while monitoring rumen health.

3.1.3. Sodium, potassium, and magnesium

Electrolyte minerals like sodium (Na) and potassium (K) are necessary for maintaining water balance, ion balance, and acid-base status in heat-stressed animals. Potassium is the main osmotic regulator in sweat gland production. Heat-stressed cows require more sodium to replace sweat losses. While sodium chloride is a low-cost supplement that may enhance milk output, excessive levels can disrupt digestion and mineral status. The dietary requirement for potassium increases from 1.4 to 1.6% of DM during hotter periods. Because sodium and magnesium compete with potassium for absorption, their concentrations should also be increased; magnesium should be provided at 0.35-0.4% DM to help minimize metabolic diseases. Sanchez et al. [57] reported that sodium bicarbonate, potassium carbonate, and potassium bicarbonate improve feed intake, milk production, and fat content in dairy cows during hot weather by enhancing ruminal buffering and maintaining acid-base homeostasis. It is worth noting that the primary source for electrolyte recommendations was published over three decades ago. While the physiological principles remain valid, modern high-producing dairy cows may have different electrolyte requirements due to genetic selection for increased milk yield. Re-evaluation of electrolyte needs in contemporary Holstein cows under heat stress conditions is strongly recommended. The foundational nutritional adjustments for heat-stressed pregnant dry cows, including water, fiber, and electrolyte recommendations, are summarized in Table 1.

Table 1. Foundational nutritional adjustments for heat-stressed pregnant dry cows.

Nutrients	Dosage	Timing
Cooled water	>120 L/cow/day	Ad libitum
Crude Fiber	12.50% of DM	During hot period
Electrolytes	K-1.4 to 1.6% of DM, Mg-0.35-0.4% of DM	During hotter period

3.2. Energy density enhancement

3.2.1. Rumen-protected fats

Incorporating higher dietary fat is a common method to reduce metabolic heat production, as fat has a lower heat increment (up to 50%) compared to forages. The inclusion of fat in diets may reduce the heat load due to its high energy density and lower metabolic heat compared to fiber and carbohydrates. Melo et al. [58] reported that supplementing cows with palm oil lowered rectal temperature and respiratory frequency while increasing milk output and feed efficiency. Similarly, supplementing Murrah buffaloes with the calcium salt of palm oil fatty acids significantly maintained body condition [58], and feeding 4% Ca salts of fatty acids led to a 12.4% improvement in milk yield [59].

Bypass fat supplementation is particularly valuable for early lactating animals as it increases the energy density of the ration, thereby preventing acute negative energy balance during heat stress [60]. One such product is 'Prill Fat,' a non-hydrogenated vegetable oil with over 85% palmitic acid that bypasses rumen fermentation due to its high melting point (>57°C) [61]. This inert fat can be added up to 9% of dry matter intake. Rumen-protected fats increase caloric density without negatively affecting dietary fiber content or digestion [62]. In Indian conditions, 75g of prilled fat per day can be supplemented to lactating cows [63]. Studies have shown that pre- and post-partum fat supplementation significantly increases milk yield, milk fat content, body condition score (BCS), and energy balance in Murrah buffaloes [64]. Moreover, the combination of dietary fat (Prill fat) with the antioxidant astaxanthin was more effective in ameliorating the adverse effects of heat stress [65]. In summary, bypass fat supplementation is crucial for alleviating negative energy balance during heat stress without adversely affecting DMI or rumen fermentation, while also providing benefits for milk yield, nutrient utilization efficiency, and postpartum recovery. A clear research gap is the absence of dose-response studies examining fat supplementation in dry, pregnant cows under heat stress. Unresolved questions include the optimal dosage (g/day), optimal duration (last 3 weeks vs. entire dry period), and potential interactions with other dietary components such as fibre, protein, chromium. Additionally, the promising combination of fat with astaxanthin requires validation in Holstein dairy cows before practical recommendations can be made.

3.2.2. Protein and amino acids

Dairy animals experiencing heat stress often enter a negative energy balance (NEBAL) due to reduced feed intake. To compensate, dietary crude protein (CP) levels should be increased during heat stress. Specifically, increasing the proportion of Rumen Undegradable Protein (RUDP), or bypass protein, is often recommended because the net passage rate of microbial protein from the rumen declines with reduced DMI. However, the literature shows conflicting results regarding the benefits of increased protein and altered protein solubilities [66, 67]. For example, Arieli et al. [68] suggested that adding more dietary CP, particularly RUDP, is not beneficial during heat stress, with Linn et al. [69] positing that low rumen motility and declined passage rate from highly degradable protein diets may be detrimental. Conversely, methionine supplementation has been shown to boost milk production, enhance antioxidant capacity, and reduce lymphocyte apoptosis [70]. Given the lower DMI during heat stress, Conte et al. [54] emphasized the importance of increasing dietary protein, either through rumen undegradable proteins or by improving protein quality with key amino acids like methionine and lysine. Lakhani et al. [71] found that a ration containing 34.5% NDF and 8.4% metabolizable protein (MP) had a beneficial effect on heat stress amelioration in lactating Murrah buffaloes. Protein supplementation studies show conflicting results, offering no clear guidance for dry cows All available data were conducted in lactating cows or buffalo, and dry cows having no milk production likely have different protein requirements. Until

dry cow-specific dose-response studies are conducted, protein recommendations should be made cautiously, with methionine supplementation should be considered promising but unconfirmed for dry cows. Energy density enhancement strategies, particularly the use of rumen-protected fats and amino acid supplementation, are presented in Table 2.

Table 2. Energy density enhancement strategies for heat-stressed dry cows.

Nutrients	Dosage
Prilled fat	75g/cow/day
Calcium salts of fatty acids	4% of DM
Methionine + lysine	Balance to requirement

3.3. Vitamin and mineral supplementation

3.3.1. Vitamins C, E, and niacin

Supplementation with Vitamins A, C, E, and zinc has shown positive effects in ameliorating environmental heat stress [72], with Vitamins C and E possessing strong antioxidant properties.

Vitamin C: Heat stress reduces plasma vitamin C levels in lactating cows [73], as ascorbate functions as a scavenger of reactive oxygen species (ROS); supplementing vitamin C and electrolytes showed ameliorating effects in buffaloes [74], and ascorbic acid helped normalize immune status and physiological responses in pregnant buffalo heifers [75], while rumen-protected capsules containing vitamin C have also been shown to ameliorate heat stress and improve production [76].

Vitamin E: Vitamin E protects biological membranes from ROS damage and acts as a chain-blocking inhibitor of lipid peroxidation [77], and adequate levels of antioxidants like selenium and vitamin E are crucial for ruminant health and milk quality [78].

Niacin (Vitamin B3): Niacin has been evaluated for its role in vasodilation and lipid metabolism; it increases peripheral vasodilation, which enhances sweat gland activity, thereby promoting evaporative heat loss [79], an adaptive mechanism which helps prevent reductions in DMI and improves milk yield. Studies have shown that encapsulated niacin can reduce skin temperature and increase milk yield in heat-stressed cows [80], improve lipid metabolism [81], and lower core body temperature during acute heat stress [82]. A critical gap exists in the vitamin literature, the lack of specific dosage recommendations for dry cows. While the text describes beneficial effects of vitamin C, vitamin E, and niacin, no quantitative guidelines (e.g., IU/day for vitamin E, g/day for vitamin C or niacin) are provided. Practitioners cannot implement evidence-based vitamin protocols without such dosages. Future research should establish dry cow-specific vitamin requirements, including potential interactions between vitamins.

3.3.2. Zinc and selenium

Zinc acts as an enzyme activator and is crucial for pH regulation, immunological competence, and cellular processes [83]. A suitable daily supply is essential as there is no specific zinc storage system in the body. Zinc supplementation has been proven to support the antioxidant defence system and reduce oxidative damage [84, 85]. It aids in reducing heat stress and improving immunity in transition dairy cattle [85]. Furthermore, dietary zinc supplementation at 80 and 120 ppm enhanced the reproductive efficiency of Karan Fries cattle [86], and resulted in lower cortisol levels, better immunity, and increased productivity [87].

Selenium is a component of the glutathione peroxidase (GPX) enzyme, which helps protect tissues from oxidative stress by eliminating free radicals. Supplementing dairy animals with selenium and vitamin E improves feed consumption, physiological responses, acid-base balance, and oxidative status under heat stress [88]. Thatcher et al. [89] found that feeding selenium-yeast to transition cows during hotter months increased immune competence and improved uterine health and pregnancy rates. Calamari et al. [90] also reported enhanced antioxidative defence and immunity in heat-stressed cows supplemented with selenium. Similarly, selenium improved feed intake and growth while maintaining oxidative balance in heat-stressed lambs [91]. A significant gap in the literature is the lack of studies investigating the combined effects of zinc and selenium supplementation in dry cows. Although the individual benefits of zinc and selenium are well documented, potential interactive effects between

them remain unexplored. Given that both minerals play roles in antioxidant defense (zinc in superoxide dismutase and selenium in glutathione peroxidase), their combined effect may be superior to either mineral alone. Future research should employ factorial designs (Zn × Se) to establish optimal ratios for dry cows under heat stress.

3.3.3. Chromium

Chromium plays a vital role in energy metabolism by improving tissue sensitivity to insulin and acting as a glucose tolerance factor. Insulin-resistant animals are more susceptible to stress, and chromium helps insulin function more efficiently in glucose, lipid, and protein metabolism [92]. Spears et al. [93] reported that heifers fed higher chromium doses showed improved insulin sensitivity. However, these findings are primarily derived from studies in buffalo, and direct extrapolation to Holstein dairy cows requires confirmation due to known species differences in thermotolerance and insulin sensitivity. Chromium supplementation also boosts immune function by increasing immunoglobulin synthesis and modulating inflammatory responses [94]. It has been shown to reduce weight loss, enhance milk output, decrease plasma NEFA, and increase pregnancy rates in heat-stressed dairy cows [95]. Combining microenvironment modification with chromium supplementation is an effective management practice, as it increases DMI and average daily gain (ADG), reduces stress indicators, and enhances immunity in growing calves [96]. Ribeiro et al. [97] found that chromium supplementation improved glucose metabolism and maintained vaginal temperature in heat-stressed dairy cows.

3.3.4. Mineral Supplementation

Minerals are vital for metabolic processes, development, milk synthesis, reproduction, and health. Since animals cannot synthesize minerals, they must be provided through feed. However, feed and fodder are often poor sources, necessitating the inclusion of high-quality mineral combinations in rations. In hot climates, mineral supplementation should be viewed not only as a means to meet nutrient requirements but also as a strategy to mitigate the effects of heat stress [90]. For instance, micronutrient supplementation (Vitamin A, E, and Zinc) during the prepartum period can enhance dairy cow health and improve calf well-being [98]. Similarly, adding antioxidant micronutrients (Cu, Zn, and vitamins A and E) to buffalo rations improved udder health, milk yield, and milk composition [99]. However, the mineral supplementation studies cited focus primarily on lactating cows or buffalo, not on dry, pregnant cows. The claim that 'feed and fodder are often poor sources' of minerals lacks a supporting citation. Until dry cow-specific research is conducted, mineral supplementation should follow standard dry cow recommendations with caution against excessive copper and selenium. The key vitamin and mineral supplementation options discussed in Sections 3.3.1 through 3.3.4 are summarized in Table 3.

Table 3. Vitamin and mineral supplementation for heat-stressed dry cows.

Nutrients	Dosage
Vitamins C, E, and niacin	Supplemented
Zinc	80 and 120 ppm
Selenium	Hotter months
Chromium	Higher doses

3.4. Feed additives

3.4.1. Astaxanthin

This xanthophyll carotenoid has anti-inflammatory, antioxidant, and immunomodulatory properties. It enhances immune response by reducing DNA oxidative damage and inflammation [100] and improves T-cell proliferation and IgG production [101]. It is a key feed additive for helping animals cope with climate change and stress [102]. Supplementation reduces pro-inflammatory cytokine [103, 104] and hinders ROS-induced production of NF-κβ [105]. In dairy animals, it has been shown to improve milk quality and yield [106, 107]. Dietary inclusion of astaxanthin has heat stress ameliorative actions in heifers, promoting growth and allowing earlier puberty attainment [108]. It also reduces HSP70 expression, implying boosted immunity [104], and is more effective when combined with dietary fat [66]. Evidence for astaxanthin in dairy cattle is limited. Most studies are from non-ruminant species or in vitro, and the

few bovine studies focused on lactating cows or heifers, not dry cows. Until dry cow-specific, dose-response studies are conducted, astaxanthin should be considered an emerging additive with unproven efficacy for dry pregnant cows.

3.4.2. Betaine

Betaine is a natural osmolyte and methyl group donor [109]. It has been recommended to improve gut integrity under heat stress [110]. Dietary betaine supplementation improves DMI and growth rate in beef cattle and sheep. It decelerates ruminal starch fermentation, reducing the heat increment of feeding. In Karan Fries cows, betaine improved reproductive performance [111], reduced physiological responses, and increased antioxidant enzyme activity [112]. Similarly, in lactating Holstein cows, betaine increased milk production, milk protein, and milk fat concentration [113]. Other benefits include higher DMI, improved volatile fatty acid (VFA) concentrations, enhanced serum antioxidant capacity, and better metabolic profiles [114]. In buffalo heifers, betaine acted as a growth promoter by lowering cortisol and NEFA while increasing growth hormone [115], and in lactating buffaloes, it increased DMI and milk fat while reducing physiological responses [116]. The betaine literature shows several research needs for dry cows: dose-response studies (0–75 g/day) measuring temperature, DMI, cortisol, NEFA, and antioxidants; comparisons of betaine alone vs. with other osmoprotectants; effects on rumen fermentation; and 60-day safety trials. Until these data are available, the 25–50 g/day recommendation remains extrapolated and should be used cautiously.

3.4.3. Melatonin:

Melatonin is a powerful antioxidant and free radical scavenger that regulates seasonal reproduction. It acts synergistically with other antioxidants [117–119]. Exogenous melatonin protects against oxidative stress, improves total antioxidant capacity, and enhances germ cell viability [120]. It helps maintain reproductive efficiency in buffaloes during heat stress by reducing oxidative stress [121]. Supplementation has been shown to lower HSP expression, reduce rectal temperature, alter antioxidant profiles, and improve sperm quality in buffalo [121, 122]. It also enhanced estrus behaviour in heat-stressed postpartum anestrous buffaloes. A major weakness of the melatonin section is the inclusion of studies reporting sperm quality and estrus behavior in postpartum anestrous buffaloes. These outcomes are entirely irrelevant to dry, pregnant cows, which are already pregnant and not attempting to conceive. Such findings should not be used to justify melatonin supplementation in the target population of this review. Future revisions should focus exclusively on outcomes relevant to dry cows, such as body temperature, antioxidant status, and fetal development.

3.4.4. Chlorophytum borivilianum

Also known as 'Safed Musli,' this herb is recognized for boosting immunity [123]. Its roots are rich in various compounds and possess therapeutic properties, acting as a rejuvenator, antioxidant, and immune modulator [124, 125]. Its antistress properties have been evidenced in animal models [126]. Dietary inclusion of its root powder has been beneficial in enhancing immunity, reducing stress hormones, optimizing plasma metabolites, lowering pro-inflammatory cytokines, and improving milk yield and quality in Karan Fries cows [127, 128]. The feed additives reviewed, including astaxanthin, betaine, melatonin, and *Chlorophytum borivilianum*, are listed with their recommended dosages in Table 4.

Table 4. Feed additives for mitigating heat stress in pregnant dry cows.

Nutrients	Recommended dosage
Astaxanthin	Supplemented
Astaxanthin + dietary fat	More effective
Betaine	Supplemented
Melatonin	Supplemented
Chlorophytum borivilianum	Dietary inclusion

4. Knowledge gaps and future research directions

Despite the growing body of evidence, several critical knowledge gaps remain: (1) Most studies have been conducted in lactating cows rather than dry, pregnant cows; (2) The long-term effects of prenatal heat stress on second-generation offspring are unknown; (3) Optimal dosages of emerging

supplements (e.g., astaxanthin, betaine) for dry cows specifically have not been established; (4) Interactions between multiple nutritional interventions are rarely studied.

Conclusion

In the face of rising global temperatures, managing pregnant, non-lactating dairy cows has become a critical frontier for sustaining herd health and productivity. Heat stress during the dry period inflicts lasting damage on the dam's metabolic health and milk yield and compromises fetal development through impaired placental function and in utero programming. Addressing this challenge requires nutritional strategies that go beyond basic sustenance toward active mitigation. Diets should minimize internal heat production while maximizing nutrient density and resilience, achieved through reduced fermentable fibre, inclusion of rumen-protected fats, and high-quality protein sources. Electrolyte replenishment remains essential for thermoregulation, while supplements such as chromium, selenium, vitamin E, betaine, and astaxanthin strengthen metabolic and cellular defences. The dry period must be recognized not as a time of rest but as a crucial window of opportunity. Implementing these evidence-based nutritional interventions will help build a more thermotolerant, healthy, and productive herd, ensuring the sustainability of dairy production in an increasingly warm world.

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