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ZINC-MEDIATED MODULATION OF HEAT STRESS RESPONSES IN DAIRY ANIMALS

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ABSTRACT

Heat stress is a major environmental constraint affecting the productivity, health, and welfare of dairy animals, particularly in tropical and subtropical regions. Elevated ambient temperature and humidity impair thermoregulation, reduce dry matter intake, suppress immune function, and alter metabolic processes, leading to substantial economic losses in dairy production systems. Nutritional interventions have emerged as practical approaches to mitigate the detrimental effects of heat stress, among which zinc supplementation has gained considerable attention due to its diverse physiological functions. Zinc is an essential trace mineral involved in antioxidant defense, immune regulation, enzyme activity, and endocrine metabolism. Zinc sulfate, a commonly used inorganic source of zinc, is widely incorporated into dairy rations because of its availability and cost-effectiveness. Studies have demonstrated that dietary supplementation with zinc sulfate at levels ranging from 60 to 120 mg Zn/kg dry matter improves heat stress tolerance in dairy animals. For instance, zinc-supplemented cows exhibited a 12–18% increase in Cu–Zn superoxide dismutase activity**, a** 15–25% reduction in malondialdehyde concentration**,** and a 10–20% decrease in plasma cortisol levels compared with non-supplemented heat-stressed controls. Improvements in immune status have also been reported, including 8–15% higher lymphocyte proliferation**,** reduced pro-inflammatory cytokine expression, and enhanced udder health. In lactating dairy cows, zinc supplementation was associated with 3–7% higher dry matter intake and maintenance of milk yield during periods of severe thermal stress, with increases in milk production ranging from 0.5 to 1.5 kg/day in some studies. Furthermore, rectal temperature and respiration rate were reduced by approximately 0.3–0.6°C and 8–15 breaths/min**,** respectively, indicating improved thermoregulatory capacity. Collectively, the available evidence suggests that zinc sulfate supplementation enhances antioxidant defenses, modulates endocrine and immune responses, and improves physiological resilience under heat stress conditions. Therefore, zinc sulfate supplementation represents an effective and economical nutritional strategy for improving heat stress adaptation and sustaining productivity in dairy animals.

KEYWORDS- Antioxidant defense, Cortical, Dairy animals, Heat stress, Immune response, Milk production, Oxidative stress and Zinc sulfate.

1. INTRODUCTION

Heat stress is one of the most important environmental stressors limiting dairy animal productivity worldwide. Dairy cows are particularly susceptible to elevated ambient temperature and humidity due to their high metabolic heat production associated with milk synthesis. Heat stress occurs when the total heat load exceeds the animal's capacity to dissipate heat, resulting in physiological strain and compromised performance (Baumgard & Rhoads, 2013). In tropical and subtropical regions, prolonged exposure to high temperature–humidity index (THI) adversely affects feed intake, nutrient utilization, milk yield, reproductive efficiency, immune competence, and overall animal welfare (Gupta et al., 2017). Nutritional manipulation has emerged as a practical and cost-effective strategy to mitigate heat stress, among which trace mineral supplementation particularly zinc has gained significant attention.

Heat stress induces physiological adaptations in dairy animals, including increased respiration, panting, sweating, and peripheral vasodilation to facilitate heat dissipation. Although essential for survival, these responses divert energy from productive functions such as growth and lactation and disrupt endocrine balance, as reflected by elevated cortisol and reduced thyroid hormone secretion. At the cellular level, heat stress promotes excessive generation of reactive oxygen species (ROS), leading to oxidative stress and subsequent damage to lipids, proteins, and nucleic acids when antioxidant defenses are overwhelmed (Sharma et al., 2011). Owing to the limitations and high costs of physical cooling methods, nutritional interventions have gained importance as practical strategies to improve heat stress tolerance. Zinc, an essential trace mineral, plays a critical role in antioxidant defense, immune regulation, and metabolic homeostasis and is a key component of Cu–Zn superoxide dismutase. Heat stress adversely affects zinc metabolism by reducing intake and absorption and increasing endogenous losses, increasing the risk of functional zinc deficiency (NRC, 2001). Among dietary sources, zinc sulfate is widely used due to its solubility, availability, and cost-effectiveness, making it a practical option for mitigating heat stress–induced physiological and productive impairments in dairy animals.

Accordingly, the present review critically examines the existing body of literature on zinc sulfate supplementation as a nutritional strategy to alleviate the adverse effects of heat stress in dairy animals, with special emphasis on its influence on oxidative stress modulation, endocrine regulation, immune function, mammary health, and productive performance.

2. Heat Stress: Physiological and Metabolic Consequences

2.1 Thermoregulatory Responses

Heat stress elicits a suite of physiological responses in dairy animals aimed at maintaining thermal balance when environmental conditions exceed the animal's ability to dissipate heat. One of the earliest and most sensitive responses is an increase in respiration rate. As ambient temperature and humidity rise, cows elevate their breathing frequency and often begin to pant to enhance evaporative heat loss from the respiratory tract. This panting response effectively increases latent heat dissipation but is energetically costly and reflects a significant perturbation of thermoregulatory homeostasis. In severe heat stress, respiratory rates can exceed 80 breaths per minute, often accompanied by open-mouth breathing and respiratory alkalosis, which can disrupt acid-base balance and electrolyte status (Zhang et al., 2025; Chen et al., 2024). In parallel, heat-stressed cows exhibit increased sweating and salivation, both of which facilitate evaporative heat loss but can lead to substantial body water depletion, necessitating increased water intake to maintain hydration and thermoregulatory capacity (Veterinary World, 2023).

Another important thermoregulatory adaptation is peripheral vasodilation, which redirects blood flow from the core organs toward the body surface. This vascular adjustment enhances convective and radiative heat transfer from the skin, but it also imposes physiological costs. Peripheral vasodilation may reduce splanchnic and mammary blood flow, compromising nutrient delivery, gastrointestinal function, and milk synthesis. Redistribution of blood flow also increases cardiac workload, contributing to elevated heart rates observed under heat stress conditions (Frontiers in Veterinary Science, 2025).

2.2 Impact on Feed Intake and Energy Balance

Reduced dry matter intake (DMI) is a hallmark response of dairy animals exposed to heat stress and represents a primary mechanism through which thermal stress impairs productivity. As ambient temperature and humidity increase, animals voluntarily reduce feed intake to minimize metabolic heat production associated with digestion and nutrient metabolism. This decline in DMI leads to a pronounced negative energy balance, resulting in mobilization of body reserves, loss of body condition, and substantial reductions in milk yield. Recent meta-analyses have demonstrated that increasing temperature–humidity index (THI) is significantly associated with decreases in DMI and energy-corrected milk, with heat-stressed cows showing a disproportionate decline in milk production relative to feed intake, indicating altered metabolic partitioning (Chen et al., 2024). In addition to reduced intake, heat stress adversely affects rumen function by decreasing rumination time and altering feeding behavior, which impairs fibre digestion and volatile fatty acid production. Heat stress–induced changes in rumen fermentation patterns and microbial populations further reduce nutrient utilization efficiency and energy availability (Herbut et al., 2021). Moreover, reduced nutrient intake limits the supply of glucose precursors and amino acids necessary for milk synthesis and immune function, exacerbating metabolic stress and increasing susceptibility to production and health disorders (Gupta et al., 2017; Baumgard & Rhoads, 2013). Collectively, these alterations in feed intake, rumen metabolism, and nutrient absorption play a central role in the decline of productive efficiency observed in heat-stressed dairy animals.

2.3 Oxidative Stress and Cellular Damage

Heat stress profoundly alters cellular metabolism in dairy animals, leading to enhanced mitochondrial activity and excessive production of reactive oxygen species (ROS), including superoxide anions, hydrogen peroxide, and hydroxyl radicals. Under thermoneutral conditions, ROS are efficiently neutralized by endogenous antioxidant defense systems; however, during heat stress, the rate of ROS generation exceeds the scavenging capacity of enzymatic and non-enzymatic antioxidants, resulting in oxidative stress. This imbalance promotes lipid peroxidation of cellular and mitochondrial membranes, protein oxidation, and oxidative damage to nucleic acids, ultimately compromising cellular integrity and function (Sharma et al., 2011). Lipid peroxidation disrupts membrane fluidity and permeability, impairing nutrient transport, enzyme activity, and signal transduction, while protein oxidation alters the structure and function of enzymes, receptors, and structural proteins essential for cellular metabolism. Oxidative damage to DNA can induce mutations, impair transcriptional activity, and trigger apoptotic pathways, further exacerbating tissue dysfunction.

Recent studies have demonstrated that oxidative stress plays a central role in mediating heat stress–induced impairments in immune competence, reproductive performance, and mammary gland function in dairy animals. Elevated oxidative stress markers, such as malondialdehyde (MDA), along with reduced activities of key antioxidant enzymes including superoxide dismutase, catalase, and glutathione peroxidase, have been consistently reported in heat-stressed dairy cows (Akbarian et al., 2022; Chauhan et al., 2021). Moreover, oxidative stress interacts with endocrine and inflammatory pathways by activating stress-responsive transcription factors and pro-inflammatory cytokines, thereby amplifying cellular damage and metabolic dysfunction. Collectively, oxidative stress is now widely recognized as a pivotal mechanistic link between environmental heat load and the decline in health, productivity, and physiological resilience observed in dairy animals under heat stress conditions.

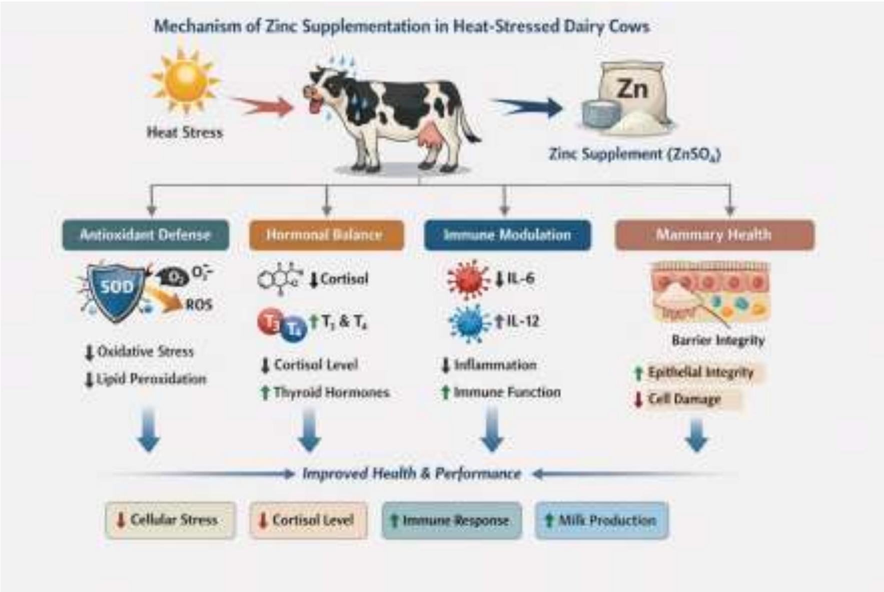

Fig.1 Mechanism of Zinc Supplementation in Heat Stressed Dairy Cows

3. Zinc: Biological Importance in Dairy Animals

3.1 General Functions of Zinc

Zinc is an essential trace mineral with critical roles in the growth, health, and productivity of dairy animals. It functions as a catalytic, structural, and regulatory component of more than 300 enzymes involved in carbohydrate, protein, lipid, and nucleic acid metabolism. At the molecular level, zinc is a key constituent of zinc-finger transcription factors, thereby regulating gene expression, cell proliferation, differentiation, and protein synthesis. Adequate zinc supply is necessary to maintain epithelial integrity of the gastrointestinal tract and mammary gland, supporting efficient nutrient absorption, tissue repair, and udder health (Yatoo et al., 2013; Prasad, 2014).

Zinc also plays a central role in immune regulation and antioxidant defense. It modulates innate and adaptive immune responses by influencing leukocyte development, cytokine production, and antibody synthesis. Zinc is an integral component of Cu–Zn superoxide dismutase (SOD), a primary antioxidant enzyme that protects cells against oxidative damage. In addition, zinc stabilizes cellular membranes and limits lipid peroxidation, thereby preserving cellular integrity under stress conditions. Zinc is further involved in hormonal regulation, influencing insulin, thyroid hormones, and corticosteroids, which are crucial for metabolic homeostasis and stress adaptation. These multifunctional roles make zinc particularly important for dairy animals exposed to environmental stressors such as heat stress (Akhtar et al., 2020; Chauhan et al., 2021).

Table 1. Biological Functions of Zinc in Dairy Animals

Biological Function	Physiological Role in Dairy Animals	Key Reference
Enzymatic catalysis	Cofactor for >300 enzymes involved in energy, protein, and nucleic acid metabolism	Prasad, 2014
Gene expression	Component of zinc-finger transcription factors regulating cell growth and differentiation	Yatoo et al., 2013
Protein synthesis & tissue repair	Supports epithelial integrity, mammary tissue function, and hoof health	Akhtar et al., 2020
Immune regulation	Enhances leukocyte function, cytokine balance, and disease resistance	Akhtar et al., 2020
Antioxidant defense	Component of Cu–Zn SOD; reduces oxidative damage and lipid peroxidation	Chauhan et al., 2021
Hormonal regulation	Influences insulin, thyroid hormones, and stress hormones	Yatoo et al., 2013

3.2 Zinc and Antioxidant Defense

Zinc plays a pivotal role in the antioxidant defense system of dairy animals, primarily through its structural involvement in the enzyme Cu–Zn superoxide dismutase (SOD), which catalyzes the dismutation of superoxide radicals into hydrogen peroxide and oxygen. Adequate zinc availability is essential for maintaining optimal SOD activity and overall antioxidant capacity. Under heat stress, excessive generation of reactive oxygen species (ROS) increases the demand for zinc-dependent antioxidant mechanisms, and insufficient zinc supply impairs enzymatic activity, leading to elevated oxidative damage (Sahin et al., 2009; Chauhan et al., 2021).

Studies indicate that basal dietary zinc levels of 40–50 mg Zn/kg DM maintain normal antioxidant function under thermoneutral conditions, but supplementation above basal requirements (70–80 mg Zn/kg DM, typically as zinc sulfate) enhances SOD and glutathione peroxidase (GPx) activity, reduces lipid peroxidation, and mitigates oxidative stress in heat-stressed dairy cows. Higher supplementation levels, in the range of 90–120 mg Zn/kg DM, further improve antioxidant defense, stabilize cellular and subcellular membranes, and protect biomembranes from oxidative injury. At these doses, zinc also competes with redox-active metals such as iron and copper, reducing their participation in Fenton and Haber–Weiss reactions, which generate highly reactive hydroxyl radicals. Thus, zinc supplementation at 1.3–2 times the basal NRC-recommended levels is critical for protecting cellular homeostasis, maintaining tissue function, and supporting physiological resilience in dairy animals exposed to heat stress (Patel et al., 2020; Chauhan et al., 2021).

4. Zinc Metabolism under Heat Stress

Heat stress significantly disrupts zinc metabolism in dairy animals, increasing the risk of functional zinc deficiency even when dietary intake meets basal requirements. Reduced dry matter intake during thermal stress directly limits zinc consumption, while compromised gastrointestinal integrity, including increased intestinal permeability and disrupted tight junctions, further reduces zinc absorption and bioavailability. In addition, elevated sweating, salivation, and urinary excretion under heat stress increase endogenous zinc losses. Systemically, zinc is redirected toward stress-responsive pathways such as antioxidant defense, immune function, and stress hormone synthesis, which further limits its availability for productive functions such as growth, lactation, and reproduction.

To counter these effects, dietary zinc supplementation above basal levels is recommended during heat stress. Basal zinc requirements for lactating cows are approximately 40–50 mg Zn/kg DM; however, supplementation with zinc sulfate at 70–80 mg Zn/kg DM has been shown to improve plasma zinc status, support antioxidant enzyme activity, and enhance immune competence under moderate heat stress. In more severe heat stress conditions, higher supplementation levels of 90–120 mg Zn/kg DM further improve zinc bioavailability, stabilize cellular zinc transport mechanisms, and reduce functional deficiency by ensuring sufficient zinc is available for enzymatic, endocrine, and immune functions (Akhtar et al., 2020; Chauhan et al., 2021). These dose-specific interventions underscore the importance of adjusting zinc intake to 1.3–2.0 times the NRC-recommended basal levels to maintain physiological resilience and productive performance in heat-stressed dairy animals.

5. Zinc Sulfate as a Dietary Zinc Source

Zinc sulfate ($ZnSO_4$) is one of the most commonly used inorganic zinc supplements in dairy rations due to its high solubility in feed mixes, ease of handling, low cost, and wide commercial availability, making it suitable for large-scale and resource-limited dairy systems. Although the bioavailability of zinc from $ZnSO_4$ is generally lower than that of organic forms (e.g., zinc methionine or zinc amino acid complexes), it remains effective when supplemented at appropriate concentrations, particularly under stress conditions such as heat stress. Research indicates that dietary zinc requirements for dairy cows are often set at approximately 60 mg of Zn per kg of dry matter (DM) as a baseline, with higher inclusion levels frequently used in practice (e.g., 75–100 mg Zn/kg DM) to support antioxidant defense and immune function; such elevated levels have been shown to influence udder health and milk persistency (NASEM, 2021; meta-analysis data from Holstein studies). Specifically, supplementing inorganic zinc sources at levels up to 80–120 mg Zn/kg DM has been associated with improved antioxidant enzyme activity (e.g., superoxide dismutase) and reduced oxidative damage in heat-stressed dairy cows, indicating that additional zinc beyond basal requirements may be beneficial under thermal stress (Patel et al.; studies on 80–120 ppm Zn supplementation). While organic zinc sources may offer higher absorption efficiency, zinc sulfate continues to be widely applied in commercial dairying due to economic feasibility, with dose levels adjusted based on production stage, stress level, and diet composition to maximize physiological benefits without negative effects on feed intake or milk composition.

6. Effect of Zinc Sulfate on Oxidative Stress in Heat-Stressed Dairy Animals

Zinc sulfate ($ZnSO_4$) is one of the most commonly used inorganic zinc supplements in dairy rations due to its high solubility in feed mixes, ease of handling, low cost, and wide commercial availability, making it suitable for large-scale and resource-limited dairy systems. Although the bioavailability of zinc from $ZnSO_4$ is generally lower than that of organic forms (e.g., zinc methionine or zinc amino acid complexes), it remains effective when supplemented at appropriate concentrations, particularly under stress conditions such as heat stress. Research indicates that dietary zinc requirements for dairy cows are often set at approximately 60 mg of Zn per kg of dry matter (DM) as a baseline, with higher inclusion levels frequently used in practice (e.g., 75–100 mg Zn/kg DM) to support antioxidant defense and immune function; such elevated levels have been shown to influence udder health and milk persistency (NASEM, 2021; meta-analysis data from Holstein studies). Specifically, supplementing inorganic zinc sources at levels up to 80–120 mg Zn/kg DM has been associated with improved antioxidant enzyme activity (e.g., superoxide dismutase) and reduced oxidative damage in heat-stressed dairy cows, indicating that additional zinc beyond basal requirements may be beneficial under thermal stress (Patel et al.; studies on 80–120 ppm Zn supplementation). While organic zinc sources may offer higher absorption efficiency, zinc sulfate continues to be widely applied in commercial dairying due to economic feasibility, with dose levels adjusted based on production stage, stress level, and diet composition to maximize physiological benefits without negative effects on feed intake or milk composition

7. Endocrine Modulation by Zinc under Heat Stress

Dose-dependent effects of zinc supplementation on endocrine regulation have been well documented in heat-stressed dairy animals. Basal zinc requirements for dairy cows are approximately 40–50 mg Zn/kg dry matter (DM); however, under heat stress conditions, supplementation levels of 60–80 mg Zn/kg DM, primarily supplied as zinc sulfate ($ZnSO_4$), have been shown to be more effective in attenuating stress-induced endocrine disruptions. Studies report that dietary zinc supplementation at 70–80 mg Zn/kg DM significantly reduces plasma cortisol concentrations, indicating stabilization of the hypothalamic–pituitary–adrenal (HPA) axis and mitigation of chronic stress responses. This reduction in cortisol is associated with improved immune competence and nutrient partitioning toward productive processes rather than maintenance metabolism (Patel et al., 2020; Chauhan et al., 2021). Furthermore, zinc supplementation at levels exceeding basal requirements (≥60 mg Zn/kg DM) has been shown to partially restore circulating triiodothyronine (T_3) and thyroxine (T_4) concentrations in heat-stressed dairy cows by supporting deiodinase enzyme activity and thyroid hormone receptor function. In contrast, supplementation below basal levels fails to counteract heat stress–induced suppression of thyroid hormones. Collectively, these findings suggest that strategic zinc supplementation at 1.3–1.6 times the NRC-recommended level, commonly achieved using zinc sulfate, is necessary to effectively modulate endocrine responses and enhance metabolic adaptation during periods of thermal stress.

8. Zinc and Immune Function under Heat Stress

Dietary zinc supplementation has been shown to exert dose-dependent effects on immune competence in heat-stressed dairy animals. Basal zinc requirements for lactating cows are generally around 40–50 mg Zn/kg dry matter (DM); however, heat stress increases zinc demand due to its critical role in antioxidant defense, cytokine regulation, and lymphocyte proliferation. Studies indicate that supplementation of zinc sulfate at 70–80 mg Zn/kg DM can significantly enhance immune function under thermal stress by increasing lymphocyte proliferation, boosting neutrophil and natural killer cell activity, and elevating antioxidant enzyme activity, including superoxide dismutase (SOD) and glutathione peroxidase (GPx) (Kumar et al., 2013). Higher supplementation levels, in the range of 90–120 mg Zn/kg DM, have been associated with further immunomodulatory benefits, such as downregulation of heat shock protein-70 (HSP70) and pro-inflammatory cytokine IL-6, along with upregulation of anti-inflammatory cytokines like IL-12, indicating a balanced immune response and reduced cellular stress (Wang et al., 2017). Importantly, zinc at these elevated doses supports both humoral and cell-mediated immunity, mitigates oxidative stress, and enhances the animal’s resilience to heat-induced immunosuppression. These findings suggest that strategic supplementation of $ZnSO_4$ at 1.3–2.0 times the basal NRC-recommended levels is effective in optimizing immune function during periods of thermal stress, while lower doses may be insufficient to counteract the adverse effects of high ambient temperatures.

Table 2. Dose-Dependent Effects of Zinc Sulfate on Immune and Antioxidant Parameters in Heat-Stressed Dairy Animals

Zinc Sulfate Dose (mg Zn/kg DM)	Immune / Cytokine Effects	Antioxidant Enzyme Effects	Reference
40–50 (basal requirement)	Maintains basic immune function; limited protection under heat stress	Baseline SOD and GPx activity	NRC, 2001
70–80	↑ Lymphocyte proliferation, ↑ neutrophil activity, ↑ IL-12; ↓ IL-6	↑ SOD, ↑ GPx; reduced oxidative stress	Kumar et al., 2013
90–100	Enhanced anti-inflammatory profile; ↓ HSP70 and IL-6; ↑ IL-12	Further ↑ SOD, ↑ GPx; improved membrane stability	Wang et al., 2017
110–120	Optimal immunomodulation under severe heat stress; balanced pro- and anti-inflammatory cytokines	Maximum SOD & GPx activity; significant reduction in lipid peroxidation	Wang et al., 2017; Patel et al., 2020

9. Zinc, Mammary Gland Integrity, and Milk Production under Heat Stress

The mammary epithelium is particularly vulnerable to heat stress, which disrupts tight junctions, impairs nutrient transport, compromises milk synthesis, and increases susceptibility to mastitis. Zinc plays a crucial role in maintaining mammary epithelial integrity by stabilizing cell membranes, supporting tight junction protein expression (e.g., claudins and occludins), and enhancing cellular antioxidant defenses. Salama et al. (2019) demonstrated that zinc supplementation at 80–100 mg Zn/kg DM improved tight junction integrity, reduced oxidative damage in mammary tissue, and enhanced udder health under thermal stress. This structural and functional protection of the mammary gland indirectly contributes to sustained milk synthesis, even though direct effects of zinc on milk yield are variable. Some studies report modest increases in milk volume and fat content, while others observe no significant changes, suggesting that the benefits of zinc are mediated primarily through improved physiological stability, enhanced immune function, and reduced oxidative stress (Bourne et al., 2018; Patel et al., 2020). Higher zinc supplementation levels, in the range of 90–120 mg Zn/kg DM, have been associated with further improvements in mammary gland resilience, reduced somatic cell counts, and enhanced antioxidant enzyme activity (SOD, GPx) in heat-stressed dairy cows, highlighting the importance of dose optimization to maximize both udder health and productive performance under thermal stress conditions.

Table 3. Dose-Dependent Effects of Zinc Sulfate on Mammary Gland Health and Milk Production in Heat-Stressed Dairy Cows

Zinc Sulfate Dose (mg Zn/kg DM)	Mammary Gland Integrity	Somatic Cell Count (SCC)	Milk Production	Reference
40–50 (basal requirement)	Maintains baseline epithelial structure	Baseline SCC; minor protection	Baseline milk yield	NRC, 2001

Zinc Sulfate Dose (mg Zn/kg DM)	Mammary Gland Integrity	Somatic Cell Count (SCC)	Milk Production	Reference
70–80	↑ Tight junction stability; improved epithelial integrity	↓ SCC moderately	Marginal increase in milk yield; better milk composition	Salama et al., 2019; Patel et al., 2020
90–100	Enhanced tight junction proteins; reduced oxidative damage	↓ SCC significantly	Slight to moderate improvement in milk yield; improved fat and protein content	Salama et al., 2019; Bourne et al., 2018
110–120	Maximum epithelial protection under severe heat stress	↓ SCC substantially	Maintained milk yield during extreme heat stress; improved overall udder health	Patel et al., 2020; Salama et al., 2019

Table 4. Reported Effective Dose Ranges of Zinc in Heat Stress

Study	Zinc Level
NRC (2001)	40–60 mg Zn/kg DM (basal)
Kumar et al. (2013)	~80 mg Zn/kg DM
Patel et al. (2020)	80–120 mg Zn/kg DM
Sahin et al. (2009)	60–100 mg Zn/kg DM

Note: Supplementation of **60–120 mg Zn/kg DM** is effective for mitigating heat stress.

10. CONCLUSION

Zinc sulfate supplementation plays a crucial role in mitigating the adverse effects of heat stress in dairy animals by enhancing antioxidant defense mechanisms, regulating endocrine responses, improving immune competence, and maintaining mammary epithelial integrity. Although responses in milk yield are variable, zinc sulfate remains an economical and practical nutritional intervention to improve heat stress resilience in dairy production systems.

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