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Impact on anatomical and physiological integrity of milk producing organs due to environmental stress

Elizabeth VL Hmangaihzuali, Vanlalngilneii Ralte and Malsawmsangi

ICAR-Indian Veterinary Research Institute, izatnagar, Bareilly-243122
ICAR-Central Sheep and Wool Research Institute, Avikanagar, Malpura-304501
CAU-Coleege of Veterinary Science and Animal Husbandry, Selesih- 796014

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As global temperatures rise due to climate change, dairy livestock face increasing thermal challenges that disrupt metabolic homeostasis, reduce feed intake, alter hormonal balances, and compromise mammary gland function. The mammary gland, undergoes structural and functional alterations in response to thermal challenges affecting epithelial cell viability, blood flow and secretory capacity. This results in the alteration of cellular composition and health of milk with 10% increase in mammary epithelial cell concentration and reduction in viable immune cells like granulocytes.

The temperature-humidity index (THI) an integration of ambient temperature and relative humidity is widely used to quantify heat stress, and it correlates with reductions in milk yield and quality. Even moderate increases in THI above critical thresholds lead to significant declines in milk output in high producing animals. A study in Sweden show that 7-day average maximum temperatures rise to 20°C result in sharply decline of milk production. Similarly, large-scale analyses of Holstein herds in Korea confirm that rising THI values are associated with reductions in daily milk yield, fat, and protein content. Experimental simulations of air and radiant temperatures above 25°C leads to decline in milk production from stable levels of around 50–60 kg/day to near zero at 35°C under controlled conditions while chronic heat exposure leads to sustained suppression of lactation performance.

The physiological mechanisms include reduced dry matter intake (DMI) and increased energy demands for thermoregulation which limits energy availability for milk synthesis. Hormonal disruptions like sustained increased in prolactin and supressed production of luteinizing hormone (LH) further impair milk production. Elevated body temperatures also directly affect rumen function and gut integrity, contributing to systemic inflammation and oxidative stress that negatively impact udder health and increase somatic cell counts.

Heat stress influenced morphological changes in the bovine mammary gland through reduced perfusion and oxidative damage. Increased core body temperature leads to compromised mammary epithelial cell turnover and tight junction integrity. Studies show that when THI exceeds 72–74, cows experience a decline in mammary blood flow by up to 50%, limiting nutrient delivery essential for milk synthesis. This hypoperfusion triggers apoptosis in alveolar cells, reduces the number of active secretory units, and disrupts paracellular transport mechanisms, resulting in altered milk composition and increased somatic cell count. Histological analyses reveal vacuolization and desquamation of epithelial lining in ductal systems during prolonged heat exposure, further impairing milk ejection efficiency. Ultrastructural changes such as mitochondrial swelling and endoplasmic reticulum dilation in mammary epithelial cells, indicative of cellular stress and impaired protein folding capacity. In goats, similar patterns have been observed; water scarcity exacerbated by heat stress leads to dehydration and reduced mammary metabolic activity, with studies reporting up to a 32% loss in body weight correlating with atrophy of secretory tissue.

Conversely, cold stress presents different but equally impactful anatomical consequences, particularly in poorly insulated or high-producing breeds. s

While less studied than heat stress, extreme cold can induce vasoconstriction in peripheral tissues, including the udder, reducing local circulation and increasing susceptibility to frostbite, especially in cattle with large teat surface areas. Prolonged exposure to subzero temperatures may lead to ischemic injury, epithelial necrosis, and fibrotic remodeling of the teat canal, predisposing animals to bacterial invasion and chronic mastitis. In dairy goats and sheep raised in alpine climates, seasonal histopathological evaluations have shown thickening of the teat sphincter muscle and keratin layer as adaptive responses to minimize heat loss and pathogen entry, though these changes can also hinder milking efficiency.

Mammary epithelial cells are highly sensitive to cold stress, and acute cold stress can alter metabolism which reduce milk components synthesis adversely affecting lactation performance. While milk production drops in cold stess there is often higher protein, fat percentage and somatic cell count which are indicator of stress. There is overall reduction in immunity in cold stress, making the mammary gland more susceptible to pathogen.

Different species exhibit varying degrees of thermotolerance. Extreme heat events in regions like northern India have led to measurable drops in milk yield particularly when combined with water scarcity and poor shade availability. Goats, known for their adaptability to arid environments, also experience reduced milk output under prolonged heat stress, though breeds native to desert climates maintain better physiological stability.

Management interventions such as tunnel ventilation have demonstrated protective effects on mammary anatomy by mitigating rectal temperature rise and stabilizing physiological homeostasis. Nutritional strategies such as supplementation with rumen-protected amino acids or antioxidants help sustain DMI and milk production during summer months, although these approaches require cost-benefit evaluation at scale. Implementation of effective management strategy like using teat dip powder to prevent or reduce frostbite, proper shelter with adequate bedding and appropriate ventilation and health management by adjusting nutrition and health care during winter months to maintain the health and productivity

In conclusion, both heat and cold stress induce measurable anatomical alterations in the milk-producing organs of domestic animals, with heat stress causing widespread epithelial dysfunction and vascular compromise, while cold stress promotes ischemic and fibrotic changes. These structural impacts underscore the need for integrated management approaches—including genetic selection for thermotolerance, improved housing, and targeted nutrition—to safeguard mammary health and shift towards more resilient species offer sustain dairy productivity under changing climatic conditions.