Towards Heat-Resilient Dairy Cattle: From Environmental Challenges to Climate-Smart Solutions

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Introduction: -

Heat stress is brought about by any combination of high levels of temperature, humidity and solar radiation with little wind, so that temperatures are higher than the animal's comfort zone **(West JW, 2003).** Hot environment affects the performance of dairy cattle both directly and indirectly. To exploit the fullest genetic potential of a dairy cattle, environmental conditions and diets should be modified.

Heat stress is a form of hyperthermia (elevated body temperature) in which, the physiological systems of the body fail to regulate the body temperature within a normal range. Heat stress in animals is considered to be a violation of animal welfare and rights. Stress is a reflex reaction of animals in harsh environments and causes unfavorable consequences to range from discomfort to death. Climate change is one of the major threats to the survival of various species, ecosystems and the sustainability of livestock production systems across the world, especially in tropical and temperate countries.

The thermoneutral zone (TNZ) of dairy animals ranges from 16°C to 25°C, within which they maintained a physiological body temperature of 38.4-39.1°C. However, air temperatures above 20-25°C in the temperate climate and 25-37°C in a tropical climate like in India, enhance heat gain beyond that lost from the body and induces heat stress. As a result, body surface temperature, respiration rate (RR), heart rate and rectal temperature (RT) increase which in turn affects feed intake, production and reproductive efficiency of animals **(Berman, 2005).** Rectal Temperature >39.0°C and Respiration Rate >60/ min indicate that cows are undergoing heat stress and this is sufficient to affect milk yield and fertility. However, the animal being homeotherms can resist heat stress to some extent depending on species, breed and productivity

Environmental Factors Contributing to Heat Stress: - (Hahn, 1999)

1. **High Temperature**:

Constant exposure of cattle to high temperature causes a rise in its rectal temperature, a decline in feed intake, an increase in water intake, a decrease in production of milk, changes in milk composition, reduction in growth and even a loss in body weight. This is the reason for deterioration in the performance of temperate dairy cattle when introduced into tropical countries. Animals graze and eat less during daytime and tend to eat more during the night.

2. **High Humidity:**

Evaporative heat loss is the most important channel of heat loss possessed by animals, which, in turn, depends on air temperature, air humidity and area of evaporating surface, available water in the body and air movement. High absolute humidity depresses evaporative heat loss greatly and thus, adds to the heat load of the animal. However, humidity does not have undesirable effect on the performance of farm animal at low ambient temperature because they do not have to depend on evaporative channel for heat dissipation under such conditions.

3. **Solar Radiation:**

Solar radiation has direct and indirect effect on animals. It may directly affect skin causing sunburns, skin cancer and other photosensitive disorders. Intense solar radiation increases heat load on animals.

Skin color and length, density and condition of hair determine the amount of heat absorbed by the body from solar radiation. Animals having light coat with glossy texture are less affected by solar radiation than those with dark, sparse and coarse hair coat. Standing animals absorb less solar radiation than those lying down.

4. **Length of Day-Light (photoperiod):**

During summer, the longer photoperiod increases the duration of solar radiation exposure, which elevates the heat load on dairy cattle. When prolonged daylight is accompanied by high ambient temperature and relative humidity, the animals' ability to dissipate body heat is further reduced, thereby increasing the risk and severity of heat stress.

Effects of Heat Stress on the Health of cattle:

1. **Water intake:**

Water is the most important and critical nutrient needed by the animals. A loss of only one- fifth of body water is fatal. Cow bodies normally contain 55-65% of water **(Murphy *et al.*, 1983)**. Lactating dairy cows need more water than other livestock, because 87% of milk is water. Drinking water satisfies 80-90% of dairy cow's total water needs. water consumption is variable, and depends on ambient temperature, DMI, milk yield, sodium intake, physiological stage and other factors. Heat Stress increases the water requirements to rehydrate the body and replenish water lost by excessive sweating. Providing insufficient water to dairy cattle can hamper milk production, growth, metabolism, and health. High-milk-producing cows are more susceptible to heat stress compared to less-producing cows because of their increased heat emissions, higher feed consumption, and greater water requirements for maintaining hydration.

2. Growth performance:

Exposure to high temperatures leads to a deterioration in growth performance in cattle. Both total weight gain and average daily gain are notably lower in the summer compared to the winter season. **(Kadzere CT et al., 2002).** Heat Stress negatively impacts the performance of heifers and calves as well. In dairy cows, it results in decreased metabolic rates and vasodilation along with behavioral changes, leading to blood hormone concentrations and body temperature alterations, ultimately impacting growth performance.

3. Milk Production:

Reduced milk production is the first perceived consequence of heat stress. Heat stress affects the productive performance of dairy animals. Reduced feed intake during heat stress is the major reason for reduced milk production in dairy cows. The optimum environmental temperature for lactation depends on species, breed and degree of tolerance to heat or cold. The milk yield of Holstein cattle declines at temperature above 21 °C and in Brown Swiss and Jersey cattle, it declines at about 24 to 27 °C whereas milk yield of Zebu cattle declines at only above 34°C. **(Wheelock JB et al., 2010).** Heat regulations made by cow includes heat dissipation to the environment and reduced production of metabolic heat. In non-cooled farms heat stress can cause 40-50% decline in milk yield while in cooled farms it can go up to 10-15%.

4. Reproductive Performance and Fertility: -

The patterns of reproductive behavior of farm animals vary with the variation in climatic conditions. Pronounced variations observed in the signs of estrus, rates of conception and frequency of calving are generally attributed to climatic factors. Heat stress resulted in decreased estrus frequency, estrus duration and calving rate. It increases ACTH and cortisol secretion and blocks estradiol-induced sexual behavior, that developed follicles damage and become non-viable when the body temperature exceeds 40°C.

The increased body temperature caused by heat stress leads to a significant reduction in fertility and reproductive capabilities, making it difficult for cows to conceive. HS affects various aspects of reproductive physiology and lowers conception rates in dairy cows globally. The reduced ability of lactating cows to regulate their body temperature during the summer is attributed to decreased thermoregulatory competence, which is linked to lower reproductive success, primarily due to the intensive genetic selection for high milk production.

5. Mortality:

Prolonged exposure to heat wave-induced Heat Stress can lead to increased mortality in dairy cows. When dairy cows are exposed to 32°C for at least three consecutive days, their chance of dying increases because a high Temperature–Humidity Index (THI) reduces the animal's ability to dissipate body heat **(Ravagnolo *et al*., 2000).** Generally, THI values above 72 indicate heat stress, while THI above 88 indicates severe heat stress. Under such conditions, cows develop hyperthermia, dehydration, metabolic disturbances and heat stroke, which can ultimately lead to organ failure and death.

Heat Stress Mitigation Strategies:

Careful management, which can alleviate heat stress, is the best way to maintain high production levels in lactating cows in a hot environment. Good management includes the modification of the surrounding environment to reduce the impact of the environment or to promote heat loss from the animals.

Preventing an increase in body temperature in hot environment can be approached in three ways:

a. Lowering the environmental temperature by modifying the structure of the shed where the cattle are kept or by introducing zero energy cooling facilities.
b. Increasing heat loss from animals by sprinkling them with water or using fans.
c. Increasing the efficiency of feed energy utilization and reducing the heat increment of animals from feeding.

Different methods for keeping a check on heat stress of livestock

1. **Shade - a natural cooling system: -**

Providing shade is one of the most important and cheapest ways to modify the cow's environment during hot weather. The most effective sources of shade are trees and other plants. They provide not only protection from sunlight, but also create a cooling effect through the evaporation of moisture from their leaves.

It was estimated that total heat load could be reduced from 30% to 50% with a well – designed shade, and shading is one of the more easily implemented and economical methods to minimize heat from solar radiation. Cows in a shaded versus no shade environment had lower rectal temperature (38.9 *vs* 39.4°C) and reduced respiratory rate (54 *vs* 82 breath/ min) along with yielding 10% more milk when shaded. Cattle with no shade had reduced ruminal contractions, higher rectal temperature and reduced milk yield compared to shaded cows.

2. **Artificial cooling system for dairy cows: -**

- **Evaporative cooling pads and fan system: -** this method is effective in areas of low or high humidity and cools the air, while raising relative humidity. This system requires fans, evaporative cooling pads and pumps to circulate water to the pads.

- **Fog system: -** a fog system sprays small water droplets into the air and cools the air as the droplets evaporate. When an animal inhales the cooled air, it can exchange heat with the air and remove heat from its body. High –pressure foggers disperse very fine water droplets, which quickly evaporate and cools air while raising the relative humidity.
- **Cooling ponds/Wallowing tanks: -** the cooling ponds have been found to effectively reduce body temperature with no apparent adverse effect on udder health or other disease.

3. **Night grazing/ Zero-hour grazing: -** Although air temperature and the level of solar radiation begin to fall after about 2 pm, the temperature of the roof remains high. As a result, the body temperature and respiration rates of animal rise. Cattle kept in a shed maintain a rapid heartbeat during the night. However, when the cattle are allowed out into a pasture at night, these physiological responses decrease immediately. This is result of both of the reduction in radiating heat from the surrounding cattle and the rise in heat loss from the cattle.

4. **Selection of heat-resistant breeds: -** It is well established that *Bos indicus* breeds and their crosses show better resistance as compared to *Bos Taurus* breeds to indirect negative effects of heat stress on production and reproduction performance because of appropriate thermoregulating mechanisms.

5. **Feeding of high energy diet and feed supplements: -** It includes use of fatty feeds or the calcium salts of fatty acids as a way of improving the energy supply for cows in summer. Cows fed such a diet in hot weather had a higher milk yield and a lower body temperature and respiration rate.
   Timed AI in combination with Beta-carotene supplementation improved pregnancy rates during periods of heat stress in dairy cows. Supplementation with selenium and vitamin E was found to have a beneficial effect on fertility of cows in hot environment.

6. **Time of feeding and feeding frequency:**

   The feeding behavior of animal changes when it is hot. Animals consume more feed during cooler evening hours. The quantity of feed and the feeding schedule should be adjusted to accommodate this behavior. Having fresh feed in the mangers after milking is a good way to encourage DMI. When the weather is very hot, at least 70% of daily feed should be given fresh at night.

Emerging innovative strategies: -

1. **Gene editing and heat stress adaptation**: -

Gene editing technologies like clustered regularly interspaced short palindromic repeats (CRISPR) and tools from synthetic biology offer novel ways to boost heat resilience in livestock by targeting traits such as thermotolerance and feed efficiency. CRISPR/Cas9, preferred for its precision and ease over older methods such as transcription activator-like effector nucleases, is supported by genome-wide studies identifying markers linked to heat tolerance for selective breeding. Gene editing of HSPs and sweat gland traits also shows promise. HSP70 protects cells during heat stress, lowers body temperature and enhances immunity **(Collier and Collier, 2012).** Similarly, genetic selection targeting sweat gland function and associated quantitative trait loci may support breeding of heat-tolerant animals.

2. **Cloned or Lab-grown heat-tolerant livestock: -**
   a) **Somatic cell nuclear transfer**: - Somatic Cell Nuclear Transfer (SCNT) combined with stress-resistance gene integration allows precise genome editing with minimal mosaicism. Transgenic calves generated via SCNT exhibit stable gene expression and improved stress resilience. However, low efficiency and embryonic stress-related gene overexpression remain as challenges. The technique demands advanced technical expertise but remains promising for both production and conservation.

   b) **Selective propagation via epigenetic resilience**: - Breeding for epigenetic heat resilience offers a promising route to improve animal welfare and productivity under intensifying heat stress. This approach integrates genetic and epigenetic mechanisms - including DNA methylation and gene regulation to enhance thermotolerance in species such as dairy cattle. Early heat exposure can also shape long-term resilience by altering stress-related genes such as corticotropin-releasing hormone (CRH). In dairy cattle, adding heat tolerance markers to breeding has improved how well we can predict resilience. However, heat-tolerance traits must be balanced against other production traits to avoid breeding trade-offs.

5. **Wearable thermoregulation devices**: -

Wearable and animal-borne technologies should be understood primarily as detection and decision-support tools rather than direct heat stress mitigation devices. In dairy cattle, ear tags, rumen boluses, accelerometers and multi-sensor collars can continuously monitor body temperature, rumination, activity, drinking behavior and other physiological indicators associated with heat load. These technologies mitigate heat stress indirectly by triggering management responses, such as activating fans or sprinklers, altering feeding time, moving animals to shade or identifying individuals requiring intervention. **(Neethirajan, 2023).** Adaptive cooling devices and sensor-linked sprinkler systems have been evaluated mainly in dairy cattle, where timely cooling can reduce stress duration and support milk yield.

6. Digital twin models for livestock:

Digital twin models simulate real-time physiological and behavioral data from wearable sensors to create virtual animal replicas, enabling proactive heat stress management. **(Verdouw et al. 2021)**. The Intelligent Unified Management and Energy Tracking Architecture framework utilizes energy balance metrics for intervention planning. Predictive models based on machine learning algorithms support early stress detection and reproductive efficiency improvements.

7. Climate-responsive livestock systems: -

Integrating livestock into cyber-physical systems (CPS) is transforming agriculture by connecting animals, environments and digital technologies for real-time monitoring and AI-driven management, enhancing animal welfare and operational efficiency. CPS enables automated adjustments such as optimized feeding and micro-climate control while Precision Livestock Farming (PLF) promotes individualized care with reduced resource use and environmental impact **(Berckmans, 2017).** Sustainable practices are supported by recycling crop residues as feed and using manure to improve soil fertility. In arid regions, robotics and drones offer innovative heat stress mitigation through behavioral monitoring, targeted cooling and environmental modifications like shade and sprinklers. Smart sensor-based cooling systems further enhance energy-efficient thermal regulation. Despite these advances, challenges including cost, infrastructure, data privacy and regional adaptability persist.

Hence, it's evident that heat stress is a significant issue affecting farm animals worldwide. By employing effective management strategies, such as providing shade and ventilation, using cooling systems, and selecting heat-tolerant breeds, farmers and animal caregivers can help reduce the impact of heat stress on farm animals. Future priorities include developing cost-effective cooling solutions for tropical farms, advancing genetic and molecular tools for heat tolerance and expanding precision monitoring technologies to detect early physiological stress. Strengthening research, innovation, and technology transfer will be essential to enhance resilience and sustain animal production under accelerating climate change.

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