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Heat Stress Mitigation in Resource-Constrained Dairy Farming Systems: Practical Strategies for Sustainable Development

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Abstract

Heat stress poses a critical threat to dairy production, particularly in resource-constrained systems prevalent across tropical and subtropical regions. Elevated ambient temperatures, compounded by high humidity, directly impair feed intake, milk yield, reproductive efficiency, and overall animal welfare. In low-resource settings, conventional cooling technologies such as automated fans, sprinklers, and climate-controlled housing remain economically inaccessible. Therefore, cost-effective, locally adaptable, and sustainable solutions are essential for maintaining productivity and animal health. This review consolidates practical heat stress mitigation strategies applicable in economically challenged dairy systems, organized under ten core categories: housing design, shading techniques, water management, feeding practices, ventilation enhancement, bedding and flooring, grazing and animal movement, animal handling, behavioral support, and community-based interventions. The paper emphasizes the integration of passive cooling methods such as shade trees, natural ventilation, and strategic grazing management with behaviourally aligned handling and resource-sharing models. Each category is examined in terms of feasibility, affordability, and impact on animal performance and welfare. Special focus is given to region-specific practices and indigenous knowledge systems that enhance adaptability under climatic extremes. By adopting these tailored interventions, resource-poor dairy producers can significantly alleviate thermal stress, promote animal comfort, and foster sustainable livestock development with minimal financial input. The findings contribute to climate-resilient dairying under economic constraints.

Keywords: Dairy farming, heat stress, low-cost interventions, resource-limited systems, sustainable development

INTRODUCTION

Dairy farming in tropical and subtropical regions faces significant challenges due to escalating environmental temperatures [1]. Heat stress has emerged as one of the most critical factors affecting dairy cattle performance, particularly under conditions of high humidity, solar radiation, and limited air movement [2]. The physiological consequences of heat stress include reduced feed intake, lowered milk yield, impaired reproductive performance, altered metabolic profiles, and compromised immune function [3]. These impacts are more pronounced in resource-constrained dairy systems where both infrastructural and technological capacities are limited [4]. Unlike commercial farms equipped with climate control mechanisms, smallholder and low-resource operations often rely on basic, traditional practices to manage environmental stressors, making them highly vulnerable to climatic variability [5–8].

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Resource-limited dairy systems, which dominate in many developing countries, are typically characterized by inadequate housing, poor ventilation, limited access to clean water, and minimal investment in animal welfare infrastructure [9, 10]. Despite the availability of advanced cooling technologies, the cost, energy requirements, and maintenance constraints often hinder their adoption [1, 2, 11–13]. Consequently, there is an urgent need to identify and implement practical, economically viable, and environmentally sustainable heat abatement strategies tailored to these systems. Passive approaches such as shade provision, natural ventilation, optimized feeding schedules, and improved water accessibility hold promise for mitigating heat stress without incurring substantial financial burdens [1, 2, 11–13]. However, systematic documentation and categorization of these low-cost strategies remain limited.

This study presents a comprehensive and structured synthesis of practical heat stress mitigation strategies specifically designed for resource-constrained dairy systems. Unlike existing literature that often focuses on high-input technologies, this review highlights ten operational categories encompassing both conventional and indigenous approaches that are accessible and implementable within low-resource contexts. The novelty of this study lies in its integration of multidisciplinary interventions with a strong emphasis on economic feasibility, cultural acceptability, and sustainability. By bridging scientific insights with field-based practices, the review provides an actionable framework for enhancing climate resilience and productivity in vulnerable dairy farming systems.

HOUSING DESIGN

Roof Elevation

Increasing roof height enhances convective air movement, allowing hot air to rise and escape efficiently [13]. This modification reduces heat accumulation within animal shelters and improves thermal comfort without relying on mechanical ventilation. It is a cost-effective, passive solution especially suited for resource-limited farms operating in high-temperature regions with minimal infrastructure investment requirements.

Open-Sided Structures

Open-sided sheds with adjustable curtains enable flexible air exchange while providing protection from wind and rain [2]. Curtains can be raised during the hottest periods to enhance cross-ventilation and lowered during adverse weather. This adaptable design improves airflow, reduces humidity, and lowers indoor temperature, thereby helping to alleviate heat stress among dairy cattle in low-resource environments.

East-West Orientation

Aligning sheds along an east-west axis minimizes the duration and intensity of direct solar exposure on building surfaces [1]. This orientation ensures that longer walls receive less radiant heat throughout the day, thereby reducing overall heat gain within the shelter. It is a low-cost, design-level intervention that significantly enhances indoor thermal conditions for dairy animals.

Ridge Ventilation

Installing ridge vents at the roof peak facilitates natural upward movement of hot air, allowing heat to escape efficiently [12]. This passive ventilation method enhances airflow and reduces thermal buildup in enclosed or semi-enclosed structures. Ridge vents are simple to construct, require no energy input, and are highly effective in promoting heat relief in dairy shelters.

Extended Eaves

Wide eaves create shaded areas around the building perimeter and reduce solar heat gain on walls [11]. This architectural feature lowers the internal temperature by minimizing direct sunlight penetration, especially during midday hours. Eaves also protect feed and water stations from overheating. It is a cost-effective strategy that supports passive cooling in low-input dairy housing.

SHADING TECHNIQUES

Shade Trees

Planting trees such as neem or banyan provides long-term, natural shade that reduces solar radiation and ground heat [14, 15]. These trees lower ambient temperatures, improve microclimatic conditions, and enhance animal comfort. Once established, they require minimal maintenance and offer additional benefits like erosion control and biodiversity enhancement, making them ideal for sustainable dairy farming in resource-limited areas.

Palm Frond Covers

Utilizing locally available palm fronds for roofing or wall shading offers an affordable and biodegradable solution [2]. These materials provide immediate protection from direct sunlight, lower indoor temperatures, and can be easily replaced as needed. Palm frond structures are especially useful in rural regions where industrial materials are inaccessible, ensuring consistent thermal comfort for dairy cattle.

Shade Nets

Installing low-cost shade nets over open areas or above cattle resting zones significantly reduces solar exposure [2]. These nets are lightweight, reusable, and can lower ambient temperatures by blocking harmful UV rays. Their affordability and ease of installation make them suitable for smallholder farms aiming to protect animals during peak heat periods without high infrastructure costs.

Movable Panels

Portable shade panels placed in grazing areas offer flexible protection as cattle move. These panels can be constructed from bamboo, wood, or fabric, and relocated based on sun position or pasture rotation schedules [16]. This mobility ensures continuous shading while optimizing land use, making it a practical intervention for small-scale dairy producers.

Crop Residue Covers

Temporary shading using crop residues such as sugarcane leaves or maize stalks utilizes farm waste to create simple overhead shelters. These materials are readily available, cost-free, and can be tied to wooden frames or trellises [17, 18]. This approach provides quick, effective shading and promotes circular resource use, supporting both animal welfare and environmental sustainability.

WATER MANAGEMENT

Frequent Water Access

Ensuring cattle have frequent access to clean, cool water supports thermoregulation and maintains hydration under heat stress [1, 11, 15, 19]. Increased water availability encourages higher intake, which helps dissipate body heat. Regular access to water also supports feed intake and milk production. This simple yet vital practice is essential for maintaining health and performance during hot periods.

Shaded Troughs

Placing drinking troughs under shade prevents water from heating due to direct sunlight. Ground-level positioning allows easy access, while shading maintains water palatability and temperature [20–23]. This setup encourages frequent drinking, reduces thermal load, and minimizes water wastage from evaporation. Shaded troughs are a low-cost modification with direct impact on animal comfort.

Multiple Refills

Refilling water sources multiple times daily keeps the water temperature low and ensures freshness [24]. Frequent replenishment discourages algae growth and maintains oxygen levels, promoting consumption. This approach is particularly effective in open troughs where water heats rapidly. It is a labor-intensive but affordable practice that enhances animal hydration during extreme heat.

Targeted Wetting

Applying water directly to heat-sensitive body areas such as the udder and flanks helps reduce body temperature quickly [11–13, [25]. This method mimics evaporative cooling and is effective during peak heat hours. Though it requires manual effort, it is cost-effective and especially useful where mechanized cooling systems are unavailable.

Prevent Stagnation

Avoiding stagnant water around troughs and shelters prevents the breeding of mosquitoes and bacterial proliferation, which are aggravated by heat [26–28]. Regular cleaning and proper drainage are essential to reduce disease risk. This proactive hygiene measure not only protects animal health but also supports overall productivity during heat stress conditions.

FEEDING PRACTICES

Cooler Feeding Hours

Feeding during cooler periods, such as early morning and evening, minimizes the heat stress on cattle [22, 29]. These times avoid the peak temperatures of midday, when cattle's appetite and feed intake are generally reduced due to thermal discomfort. Feeding during cooler hours enhances nutrient absorption, supports milk production, and optimizes overall livestock performance during hot conditions.

Increased Water Content

Incorporating water-rich feeds, such as fresh green fodder, helps alleviate dehydration and provides cooling effects. These feeds enhance rumen function and reduce heat production during digestion [25, 30, 31]. Increased moisture content in the diet also encourages better intake, improves hydration, and supports digestion, especially during hot weather when water access might be limited or inadequate.

Low Heat Feeds

Avoiding high-heat increment feeds, such as grains and fibrous materials, during peak heat hours prevents excessive body heat production. These feeds require more energy for digestion and increase metabolic heat [23, 32, 33]. By adjusting feeding schedules and offering cooler, easily digestible feeds during the hottest parts of the day, dairy farmers can reduce stress and maintain animal comfort and productivity.

Shaded Feeding Areas

Providing feed in shaded areas ensures that cattle consume their meals in a cooler environment. By preventing feed from being exposed to direct sunlight, temperature increases are minimized, which aids in improving feed intake and digestion [34]. This practice, particularly in low-resource systems, is a simple yet effective strategy to reduce heat stress during feeding times.

Low-Heat Fermented Rations

Using energy-dense, low-heat fermentation rations minimizes metabolic heat production during digestion[35–38]. Fermented feeds, such as silage or haylage, are easier for cattle to digest and help reduce internal body temperature. These rations, which also support optimal rumen health, improve feed efficiency, offering a cost-effective strategy to maintain dairy productivity under heat stress.

VENTILATION ENHANCEMENT

Manual Fans

Installing low-cost manual fans in strategic locations enhances air circulation and provides localized cooling for dairy cattle [1]. These fans can be operated with minimal energy consumption, making them suitable for low-resource settings. By improving airflow, fans help reduce heat buildup in confined spaces, promoting animal comfort and encouraging better feed intake during hot weather.

Stack Ventilation

Utilizing stack ventilation with an open ridge enhances air movement by leveraging the natural upward flow of warm air [39]. The warm air rises and escapes through the ridge, while cooler air is drawn in from the sides, improving ventilation. This passive cooling method is energy-efficient and ideal for open-sided or semi-enclosed dairy shelters in hot climates.

Cross-Ventilation Windows

Creating cross-ventilation windows facilitates the exchange of air between opposite sides of the shelter [40]. This design encourages a continuous airflow, helping to expel hot, humid air and replace it with cooler outside air. Cross-ventilation windows are a simple yet effective way to enhance cooling in dairy buildings without significant financial investment.

Wet Gunny Bags

Hanging wet gunny bags on walls or inside the shelter helps cool the air through evaporative cooling [41]. As the water evaporates, it lowers the ambient temperature, creating a more comfortable environment for the cattle. This low-cost technique works best in dry conditions and provides immediate relief from heat stress, especially in low-resource dairy systems.

Reduced Wall Height

Reducing wall height improves natural airflow by preventing heat buildup in enclosed spaces. Shorter walls allow more effective air exchange, creating a more comfortable environment for cattle [22, 42, 43]. This modification enhances passive cooling by facilitating air movement, and it is an easy, low-cost adjustment to existing shelter designs, particularly in hot climates.

BEDDING AND FLOORING

Sand Bedding

Using sand as bedding material helps maintain cooler resting surfaces for dairy cattle. Sand has high thermal mass, which allows it to absorb heat during the day and remain cooler during the night [44]. This provides a more comfortable resting area for the cattle, reducing thermal stress and supporting better sleep, which in turn improves overall health and productivity.

Frequent Bedding Replacement

Replacing bedding regularly prevents the accumulation of heat from manure and body heat. Fresh bedding ensures that the cattle rest on cooler, more comfortable surfaces [44]. This practice reduces the risk of bacterial growth and odors, and it helps maintain a hygienic environment while preventing thermal buildup in confined spaces, particularly during hot periods.

Dry Flooring

Maintaining dry flooring is essential for reducing humidity levels, which can exacerbate heat stress [28]. Wet or damp floors increase heat retention, making the environment more uncomfortable for the cattle. Dry flooring also prevents the growth of harmful pathogens and supports better hoof health. By ensuring proper drainage and ventilation, farmers can keep floors dry and comfortable.

Perforated Flooring

Using perforated flooring enhances ventilation and dissipates body heat from resting cattle. The gaps in the floor allow for better airflow underneath the animal, reducing heat retention from the ground [44]. This simple modification ensures that hot air does not accumulate beneath the bedding, promoting thermal comfort and reducing the risk of heat-related stress in dairy cattle.

Slatted Flooring

Installing low-cost slatted floors in resting areas allows for efficient drainage and improved air circulation [28]. Slats help reduce heat buildup by allowing airflow underneath the cattle and promoting cooling through evaporative processes. This simple yet effective solution ensures that resting areas remain dry and comfortable, preventing excessive heat retention and improving cattle welfare.

GRAZING AND ANIMAL MOVEMENT

Morning/Evening Grazing

Grazing during early morning or late evening allows cattle to avoid the peak heat of midday. These cooler periods reduce thermal stress and promote higher forage intake. Grazing during these times also helps conserve energy, improve overall productivity, and maintain animal welfare, as cattle are more likely to remain comfortable and productive in milder temperatures.

Minimized Midday Movement

Reducing animal movement during the hottest part of the day helps minimize heat exposure and energy expenditure. Limiting physical activity during peak temperatures reduces the risk of heat exhaustion and supports cattle health. This strategy helps maintain milk production, reduces stress, and enhances overall animal welfare by encouraging rest and shade-seeking behaviors during midday heat.

Rotational Grazing

Implementing rotational grazing in shaded areas ensures that cattle can seek shelter from the sun while still grazing. This system also prevents overgrazing of specific areas, improves pasture health, and reduces heat stress by offering multiple cool resting zones. Shaded grazing areas optimize thermal comfort, enhance productivity, and protect the environment by allowing pasture regrowth.

Avoid Overstocking

Avoiding overstocking in open areas helps maintain comfortable spacing between animals, preventing overcrowding and excessive heat buildup. Overstocking leads to increased competition for shade and water, exacerbating heat stress. By managing stocking density, farmers can ensure that each animal has adequate access to resources and can rest in shaded areas, reducing stress and improving performance.

Rest Under Shade

Providing rest breaks under shade is essential for maintaining cattle comfort and preventing heat stress. By encouraging animals to rest in shaded areas during the hottest parts of the day, farmers can reduce thermal load, conserve energy, and support better feed intake. This practice promotes healthier and more productive cattle, particularly in resource-constrained grazing systems.

GRAZING AND ANIMAL MOVEMENT

Grazing Times

Grazing during early morning or late evening minimizes cattle exposure to high midday temperatures. These cooler periods reduce the strain of heat stress, encourage higher feed intake, and promote energy conservation [5]. Cattle are more likely to stay hydrated and productive during these hours, ultimately improving both welfare and performance in hot climates.

Restricted Daytime Movement

Limiting animal movement during the hottest part of the day reduces thermal load and energy loss. By encouraging cattle to rest during peak heat, the risk of heat exhaustion is minimized [45]. This also reduces the likelihood of reduced milk production and other heat-related issues, helping maintain overall animal health and comfort.

Rotational Grazing

Rotational grazing in shaded areas ensures that cattle are able to graze while avoiding direct sun exposure [46]. This method allows animals to move between different pasture areas, optimizing shade availability and reducing heat stress. Rotational grazing also promotes healthier, more sustainable pastures by preventing overgrazing and improving forage quality.

Avoid Overstocking

Overstocking in open areas exacerbates heat stress by increasing competition for limited shade, water, and space [47]. By maintaining proper stocking density, farmers can ensure sufficient resources for each animal, reducing stress levels and improving comfort. This strategy helps maintain animal health, supports pasture management, and ultimately leads to improved livestock productivity.

Shade Resting

Providing rest breaks under shade ensures that cattle can escape the heat during the hottest parts of the day [28, 48]. By offering shaded resting areas, farmers promote animal welfare and reduce the risk of heat stress. This practice also enhances feed intake and overall performance, as it encourages cows to rest and recover during periods of extreme heat.

ANIMAL HANDLING

Milking Timing

Scheduling milking during cooler hours, such as early morning or late evening, helps reduce the additional heat burden on cows [14]. This practice ensures that milking occurs when cattle are more comfortable and less stressed, improving milk yield and quality. Reducing heat exposure during milking supports overall animal health and enhances welfare during periods of high temperatures.

Avoid Heat Stress Activities

Avoiding vaccination or transport during hot periods prevents exacerbating heat stress. These activities increase metabolic heat production and elevate body temperature, which can lead to severe stress or health complications [30, 37]. By scheduling such procedures during cooler parts of the day or in cooler months, farmers reduce the risks of heat-related issues, supporting animal welfare.

Minimize Stress

Minimizing stress-inducing activities, such as rough handling or sudden changes in routine, is critical during hot weather [18, 43, 49, 50]. Stress can compound the effects of heat stress, leading to reduced feed intake, lower milk production, and overall decreased performance. By maintaining calm and consistent routines, farmers can help prevent further strain on the animals during extreme heat conditions.

Encourage Free Movement

Allowing cattle to move freely within a comfortable environment helps reduce stress levels. Restricting movement can lead to frustration, overheating, and poor circulation [22]. By providing adequate space for movement, farmers reduce the risk of heat buildup and ensure that cows can seek shade and water at their discretion, thus minimizing heat-related stress.

Calm Handling

Handling cattle calmly and gently minimizes stress and prevents the release of excess metabolic heat. Aggressive or sudden movements trigger stress responses, increasing body temperature and exacerbating heat stress [9, 25, 31, 51, 52]. By employing low-stress handling techniques, farmers can improve animal welfare, reduce the risk of heat-related disorders, and maintain better productivity and overall health during hot weather.

BEHAVIORAL MODIFICATION SUPPORT

Wallowing Encouragement

Encouraging wallowing, where feasible, helps cattle regulate body temperature by utilizing evaporative cooling [53]. Wallowing in mud or water provides relief from heat stress and serves as a natural cooling mechanism. This behavior also helps in reducing external parasites, further enhancing comfort and overall health during hot weather, ultimately promoting better productivity and welfare.

Community Shade Areas

Providing community shade areas for resting ensures that all animals have access to cooler spaces during the hottest parts of the day [14, 15]. This communal approach reduces competition for shade, encourages social behaviors, and supports overall well-being. By ensuring adequate shade coverage, farmers can minimize heat stress and maintain animal comfort throughout the day.

Adequate Resting Space

Ensuring group size allows sufficient space for each animal to rest comfortably reduces stress and prevents overheating [28, 54]. Overcrowding in resting areas can lead to aggression, limited access to shade, and heat buildup. By adjusting group sizes based on available space, farmers ensure that animals have room to lie down, rest, and cool off, thus promoting better health and productivity.

Comfortable Bedding for Lying

Promoting lying behavior using comfortable bedding materials, such as sand or soft organic matter, encourages cattle to rest during periods of heat stress [24, 27, 55–57]. Providing proper bedding helps animals relax, conserve energy, and regulate body temperature. Comfortable resting conditions improve sleep quality and reduce metabolic heat production, ultimately supporting animal welfare and milk production.

Maintaining Cleanliness

Maintaining animal cleanliness supports thermoregulation by reducing the accumulation of dirt and debris on the skin, which can impede heat loss [55]. Clean animals have better airflow around their bodies, which enhances cooling through evaporation. Regular cleaning also prevents bacterial infections and other health problems, promoting overall animal comfort and improving productivity in hot conditions.

COMMUNITY AND RESOURCE SHARING

Shared Water Tanks

Sharing water tanks for cooling helps ensure that all animals have access to sufficient water during hot periods [47]. By pooling resources, farmers can install larger water storage systems that allow for regular refilling, maintaining cool, clean water for hydration and cooling. This collective approach optimizes water use and reduces the stress of individual water sourcing, enhancing animal welfare.

Communal Shaded Areas

Building communal shaded resting areas offers a shared space for livestock to escape the heat. This collective infrastructure reduces the competition for shade, ensuring that all animals have access to cooling during peak temperatures [58]. By providing a communal area, farmers can manage shade resources more effectively, ensuring better heat stress management and improving overall animal welfare.

Co-operative Cooling Models

Using co-operative models for shared cooling infrastructure allows smallholder farmers to pool resources for energy-efficient cooling systems, such as misting or fan setups [5]. By sharing the costs of these systems, farmers can afford better technology, which benefits all parties. This cooperative approach not only reduces financial burdens but also increases cooling efficiency and promotes sustainable practices in resource-limited settings.

Shared Cooling Systems

Pooling funds for shared fan or mist systems enables farmers to invest in cooling solutions they may not be able to afford individually [35, [42, 58–61]. These systems can be used across multiple farms, providing a cost-effective method for mitigating heat stress. Shared systems promote collective responsibility and help ensure that all participating farms have access to efficient cooling technologies, improving overall livestock comfort.

Heat Mitigation Workshops

Conducting local workshops for heat mitigation awareness educates farmers on effective strategies to manage heat stress in livestock [26, 49]. These workshops foster community knowledge-sharing and help farmers implement practical, cost-effective solutions tailored to their specific needs. By enhancing awareness, farmers are better equipped to improve animal welfare and productivity while minimizing the adverse effects of heat stress on their herds.

CONCLUSION

Heat stress remains a formidable constraint to productivity, health, and welfare in resource-constrained dairy systems, particularly in regions experiencing prolonged climatic stress. This study underscores the viability of practical, low-cost mitigation strategies that align with local resources and management capacities. By organizing interventions under ten core categories, the review offers a comprehensive framework that supports informed decision-making and field-level implementation. Emphasizing passive cooling, behavioral adaptations, and community-based approaches, these strategies collectively enhance thermal comfort, sustain milk production, and promote animal welfare. The findings advocate for knowledge dissemination, farmer training, and policy support to mainstream these cost-effective interventions, thereby fostering climate-resilient and sustainable dairy farming practices across economically challenged regions.

Future directions

Future research should focus on validating the effectiveness of individual and combined low-cost heat mitigation strategies through on-farm trials across diverse agro-climatic zones. Emphasis should be placed on quantifying physiological, behavioral, and productive responses of dairy cattle to specific interventions under variable resource constraints. Integrating indigenous knowledge systems with modern scientific principles may further optimize strategy design for local adoption. The development of decision-support tools to guide farmers in selecting context-appropriate solutions based on farm type, climate, and economic conditions is essential. Moreover, participatory research involving farmers, extension agents, and policymakers can strengthen adoption pathways. Future studies should also assess long-term impacts on animal welfare, greenhouse gas emissions, and farm economics to ensure sustainability. Incorporating gender-sensitive approaches and community-driven innovations will further enhance inclusivity and resilience. Overall, an interdisciplinary and systems-based research framework is required to support scalable and climate-smart heat abatement solutions in low-resource dairy systems.

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