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Original Research Paper

Environmental Heat Stress Mitigation in Livestock Farms Using Nature-Based Cooling Systems

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Key Words

Heat stress, Livestock welfare, Nature-based cooling systems, Microclimate modification, Vegetative shading, Evaporative cooling ponds, Windbreak tree belts, Thermal humidity index (THI), Climate-resilient agriculture, Sustainable livestock production.

Abstract

The escalating heat stress situations and global temperature increase is a significant problem to the livestock welfare, productivity and the sustainability of agro-ecosystems especially in the climatically sensitive areas. The research question that is examined in this study is how nature-based cooling systems, i.e., vegetative shading structures, evaporative cooling ponds, and windbreak tree belts, can alter the farm microclimates and reduce heat stress levels in cattle and small ruminant production units. The microenvironmental parameters, including ambient temperature, relative humidity, wind speed, solar radiation, and Thermal Humidity Index (THI) were recorded continuously over a period of 90 days in a summer in the southern hemisphere through a set of automated dataloggers, whereas physiological parameters of animal heat stress, including the respiration rate, panting score, and rectal temperature were measured under specific intervals. The cooling interventions were integrated with significant changes of the microclimatic conditions with a decrease in the ambient temperature by 2.846C, increase in the local humidity by 47% and moderate wind velocities and a significant reduction in THI values of extreme to moderate stress levels of the measurements. In line with this, livestock confined in treated areas had significant respiration rates and scores of panting reduced, and were more responsive in their behaviour, in terms of increased time in rest and continuous control feeding, suggesting better thermal comfort and welfare. In addition to microclimate regulation, vegetative systems had other ecological advantages, such as increased soil moisture availability by 12 -17 percent, greater ground vegetation cover, and biodiversity indices because of favourable habitat conditions along shelterbelts and pond margins. Such results reveal that nature based cooling systems provide a sustainable, low-cost and energy-efficient option to traditional types of mechanical cooling technology, which could enhance climate-resilient livestock production systems. The research highlights the importance of incorporating ecological design concepts in farm management initiatives to prevent heat stress, enhance animal welfare, and ensure the sustainability of the environment in the long term in changing climatic conditions.

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Introduction

Climate change in the world has been one of the contributing factors to increase the occurrence of cases of heat stress, the induction period and intensity, to which livestock production systems face noted dramatic challenges across the globe. Increments in ambient temperatures accompanied by an increment in the level of humidity hinder proper dissipation of heat by animals pushing them out of the thermoneutral range. This creates homeothermic imbalance and initiates physiological stress with an increase in respiration rates, a decrease in feed consumption, metabolic disturbance, and impaired immune activity. In the case of dairy and meat-producing species, thermal stress is directly translated into reduced yield of milk, reduced growth and development, reproductive loss and mortality, thus posing a threat to the economic stability and food security of areas susceptible to heat.

The most commonly used forms of heat stress management include traditional cooling methods (such as mechanical ventilation, high-pressure misting systems and air-conditioned housing) and yet adverse effects of energy use, the cost of installation and reliance upon power supply restrict their practicality in the long term, particularly when applied to small and resource-intensive farms. Moreover, these artificial systems are associated with the rise in the costs of operation and indirectly with the rise in greenhouse gas emissions, which are aimed at the opposite of sustainability. Subsequently, the livestock industry has taken interest in seeking more sustainable, low cost and ecologically friendly options that would not impair the ecological purity.

The cooling system based on nature can be a viable and sustainable option as it involves the use of natural ecological processes to control the microclimatic conditions. Shading at the vegetative level decreases direct sun radiation, evaporative cooling ponds enhance the moisture level of the air and reduce the temperatures of the surrounding areas with natural evaporation processes; tree belts of windbreaks optimise the airflow distributions and reduce the amount of heat load among animal enclosures. All of these interventions combined form a buffered microenvironment that allows improving thermal comfort and at the same time, stimulating soil stability, improving biodiversity, and resilience in the landscape. These multifunctional advantages can be in line with international attempts at creating livestock systems that are climate smart.

Due to the pressing necessity of adaptive mechanisms, this paper is a methodical review of the synergistic advantages of vegetative shading structures, evaporative cooling ponds, and windbreak trees belts in relieving heat stress on cattle and small ruminant farms. The research provides a detailed evaluation of the effect of nature-based solutions on the environmental conditions and the welfare of animals by combining the use of continuous microclimatic monitoring with physiological and behavioural signs of animal comfort. The research results will help to reinforce evidence-based principles of planning climate-resilient livestock farms to increase productivity without obstructing the ecological sustainability of the farms.

Literature Review

Heat Stress and Productivity of Livestock

Heat stress has been identified as one of the greatest limitations to the productivity or livestock particularly within the tropical and semi arid areas where livestock is subjected to temperatures that are well above their thermoneutral zone. Excessive exposure to high temperatures interferes with homeothermic processes that result in an increase in respiration rate, decrease in feed consumption, metabolic imbalance and weakening of immune responses. As many studies documented, milk yield, reproductive efficiency, and overall performance of dairy cows have been found to fall drastically in high THI environment with thresholds of 80, the conditions of which are to be regarded as the significant ones, signifying severe heat load and physiological discomfort in the cases of excessive heat (Becker et al., 2020; Berma, 2008). Specific breed differences in thermoregulations have also been reported and Holstein and Brown Swiss cows will have different responses towards heat load, based on color composition, water loss through evaporations and metabolism (Correa-Calderon et al., 2004; Foroushani & Amon, 2022). The seasonal tests also ratify that lactating cows exhibit higher cortisol, high rate of panting, and low rate of rumination activities during high summer months (Levit et al., 2021). The chronic effects of heat stress can also change placental development, foetal growth and postpartum productivity among dairy cows, which indicates the extended reproductive and developmental consequences of heat stress (Lazzari et al., 2024). All these studies present an urgent need to employ adaptive cooling measures to reduce the loss of animal welfare and productivity.

Nature Based Cooling Solutions

Vegetative Shading Systems

Vegetative shading has become a viable, sustainable microclimate alteration technique in the livestock set ups. Incident solar radiation cuts by 50 70, radiant heat load, and soil moisture retention are also increased by tree canopies increasing thermal comfort of grazing animals (Casarotto et al., 2025). It has also been found that shade-grown spaces encourage behavioural decisions that generate good behavioural responses in the form of raised resting activity and reduced respiration effort, which translates to lower energy expenditures when exposed to heat. Agro forestry buffers offer more ecological services as compared to the artificial shading structures i.e. the carbon sequestration, erosion cheques, and the increase of the biodiversity.

Evaporative Cooling Ponds

The evaporative cooling systems like shallow water ponds are also being proposed to be installed in smallholder and semi-intensive livestock farms. These ponds form a local evaporative cooling effect that lowers the temperature of the environment and enhances the humidity in the air by evaporation of water naturally. Experiments based on graphical and sensor-based modelling solutions prove that evaporative cooling is much more effective at increasing the efficiency of ventilation in barns and decreasing heat loads in peak temperature seasons (Zhou et al., 2023). Evaporative cooling has been used in experimental studies to demonstrate increased thermoregulatory behaviours like less sweating, slower rate of respiration, and a more consistent rectal temperature in high solar radiation-exposed dairy cows (Correa-Calderon et al., 2004; Mendonça et al., 2017; Brenu et al., 2013). Evaporative cooling is however effective depending on the location of ponds, depth of water, movement of air and the rate at which ponds were regularly maintained.

Windbreak Tree Belts

Another nature-based solution which is aimed at streamlining the movement of the air and the elimination of heat sources in open yards with livestock is windbreak tree belts. Thick vegetation strips reflect warm winds, lessen exposure to the sun and lower absorption of heat toward the ground, producing a cooler microclimate in the environment of animals in downwind location. Scientific researches have documented the ability of carefully positioned windbreaks to be able to reduce ambient temperatures by 1 -3 o C and maintain a constant wind speed without hindering natural ventilation (Casarotto et al., 2025; Santhakumar et al., 2015). Besides thermal advantages, windbreaks have structural protection, enhance conditions of beneficial species, and increase the general stability of farm sceneries.

Sustainability and Balance of Ecosystems

In addition to their cooling ability, there are numerous co-benefits of nature-based systems that lead to sustainability of the environment in the long run. A vegetative shading and windbreak structures increase carbon capacity, litter retention and soil organic matter structure, which also increases soil fertility (Casarotto et al., 2025; Sindhu, 2025). These systems would also sustain the population of pollinators, helpful insects, and ground vegetation, providing ecologically efficient boundaries to farms. Unlike the energy-consuming mechanical cooling systems, nature-based interventionsilled are affordable, low-maintenance interventions that are in line with the concept of climate-smart agriculture. The value added to livestock management systems can provide a sustainable solution of enhancing animal welfare and decreasing heat-related productivity losses and agro-ecosystem resilience to climatic changes pressure (Becker et al., 2020; Lazzari et al., 2024; Janaki Sathya & Geetha, 2011; Kalaivani et al., 2019).

Methodology

An extensive and field-based experimental approach was taken in order to quantitatively measure the cooling performance and ecological benefit of three nature-based interventions. The methodology is divided according to the three main parts: system installation and experimental design, memory of microclimate and animal physiological observation and memory of ecological and soil quality measurement.

Experimental Location, Systems Built and Design Framework

Site and Design Layout

The research was conducted in a small ruminant and mixed cattle farm in a semi-arid agro climatic area where the temperature is usually way above 40C during summer. A randomised block experimental design was also used to facilitate the ability of comparison of results of various treatments and further subdivide the study area into four separate zones with three nature-based cooling interventions and one control group with no microclimate changes. The area of each treatment zone was the same (20 x 20 m), which made it possible to provide homogeneous exposure to livestock and balance the environmental variation of the area to which the livestock was going to be exposed. The layout of the farms, soil profile, and wind patterns were evaluated before the installation to ensure that the different cooling systems were placed in the most favourable position and location. The animals rotated across the zones were randomly rotated at a given time so that there was no bias in behaviour to avoid any bias in behaviour; the rotating experimental animal was uniformly interacted with each intervention of the experimental period of 90 days.

Installation of Vegetative Shading and evaporative coolings pond

Native and fast-growing tree species such as Azadirachta indica, Dalbergiasissoo and Leucaenaleucocephala were introduced in the vegetative shade system that were in form of structured rows aimed at creating a continuous canopy. The density of the canopy was kept at 55-65 years old as that allowed it to give significant shade but at the same time allowed natural ventilation enough to prevent stagnation and stifling of the air. A shallow evaporative cooling pond with the size of 12 m2 and the depth of water equal to 0.6 m was built adjacent to the shaded area that could be natural cooled in a manner of evaporation-convection. The pond was located in strategic places close to areas where livestock rest to have maximum cooling effect on the local micro climate. The water levels were checked and topped up when necessary to achieve constant evaporative behaviour during the 90 days study period which made the cooling effects stable and to be repeated (Marpaung et al., 2025).

Windbreak Tree Belt Installation and Control Zone Installation

The mine was surrounded with a tree belt of the types of a double-row windbreak to block the high temperatures afternoon winds and minimise the thermal load on livestock at the south-western side of the study area. Casuarina equisetifolia and Eucalyptus tereticornis were chosen as tree species with dense foliage, and fast growth, and a high rate of transpiration, which can be effectively modified to modify the airflow and decrease exposure to sunlight. The plantings of trees were done at spacing intervals in an effort to balance the porosity and the effectiveness of wind-deflection and maintain structural continuity of the barrier. By contrast, the control region was completely open with no cooling structure, which was the baseline of measuring the microclimatic and physiological impacts of the interventions Figure 1. All the zones-maintained livestock movement, feeding times and water access the same to make the experiment valid and would isolate the effects of each of the nature-based cooling systems.

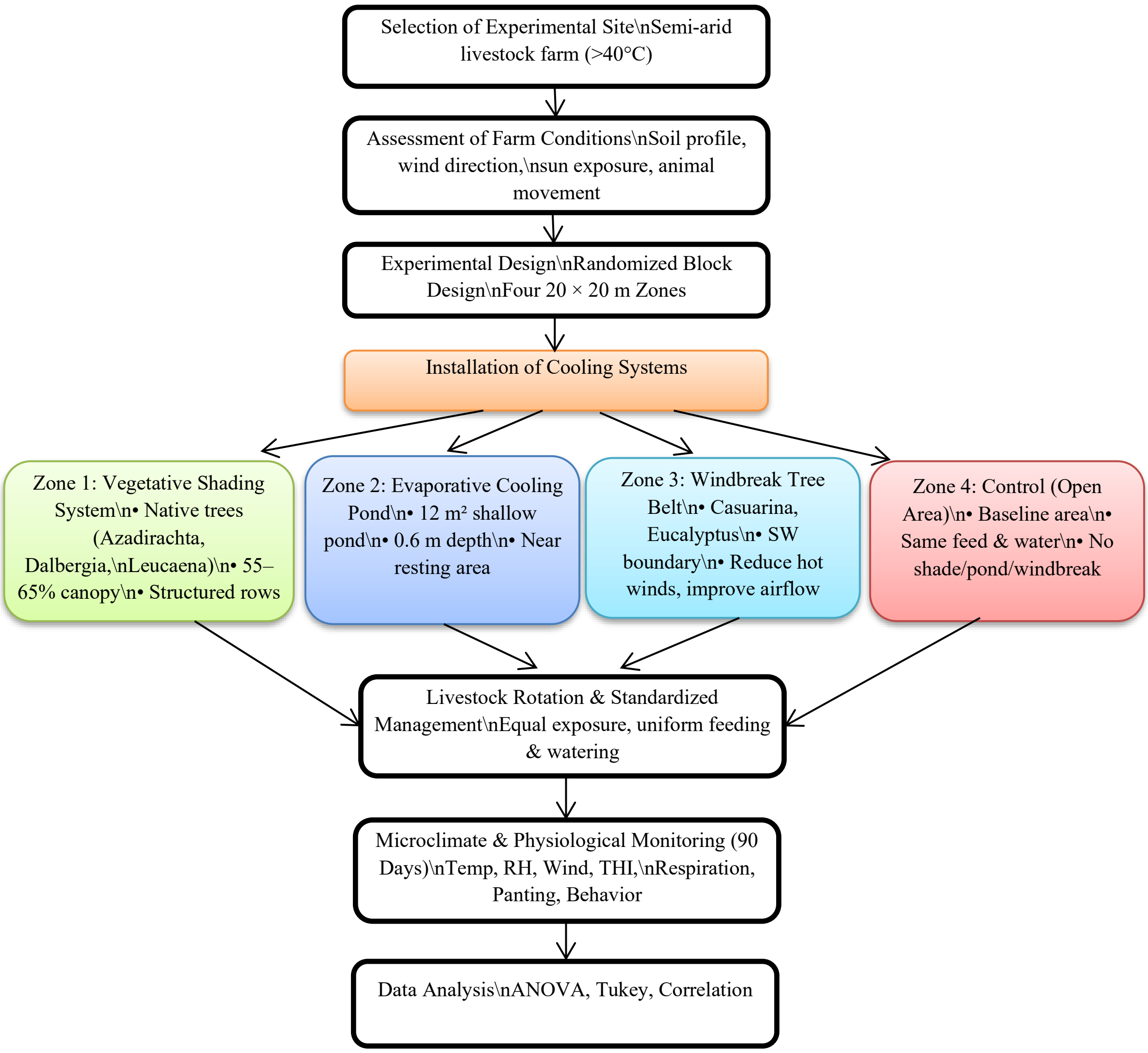

Figure 1: Flowchart of the Experimental Design and Installation of Nature-Based Cooling Systems in Livestock Farms

Microclimatic Parameter Monitoring and Heat Stress Assessment

The Microclimatic Data Collection and Instrumentation

Continuous microclimatic measurements were conducted to properly measure cooling performance of the nature-based interventions using a combination of calibrated environmental sensors to were linked to automated data loggers. Major parameters of microenvironment measured as ambient temperature (C) and relative humidity (percentage) was recorded with shielded thermistors at livestock body height (1.2 m) such that the true thermal exposure was determined; wind speed (m/s) which was measured using a high-quality portable anemometer to understand how the air modulated between treatment zones; and radiation load (W/m2) which was measured using pyranometers to determine the effect of solar heat gain. Also, the temperature and humidity measurements were combined to calculate Thermal Humidity Index (THI) that would assess gross heat stress severity. These parameters were recorded at 15-min and made it possible to prepare high-resolution data which were later aggregated to hourly and daily means to compare the statistics between interventions and control conditions.

Heat Stress Signalling Physiology and Behaviour in Livestock

The physiological reactions of livestock were closely followed to determine direct relationships between any change in microclimatic conditions and alleviation of the heat stress. The measurements were done at two instances per day, that is, in the morning and afternoon at the peak temperatures of heat to record the diurnal changes in heat stress indicators. The flank movements were counted as the respiratory rate (breaths/min), which is a sensitive measure of respiratory load during exposure to heat. A standardised 0-4 scale of panting intensity was used in the measurement of the severity of panting and rectal temperature (o C) was measured in calibrated digital thermometers to determine core body heat retention Figure 2.

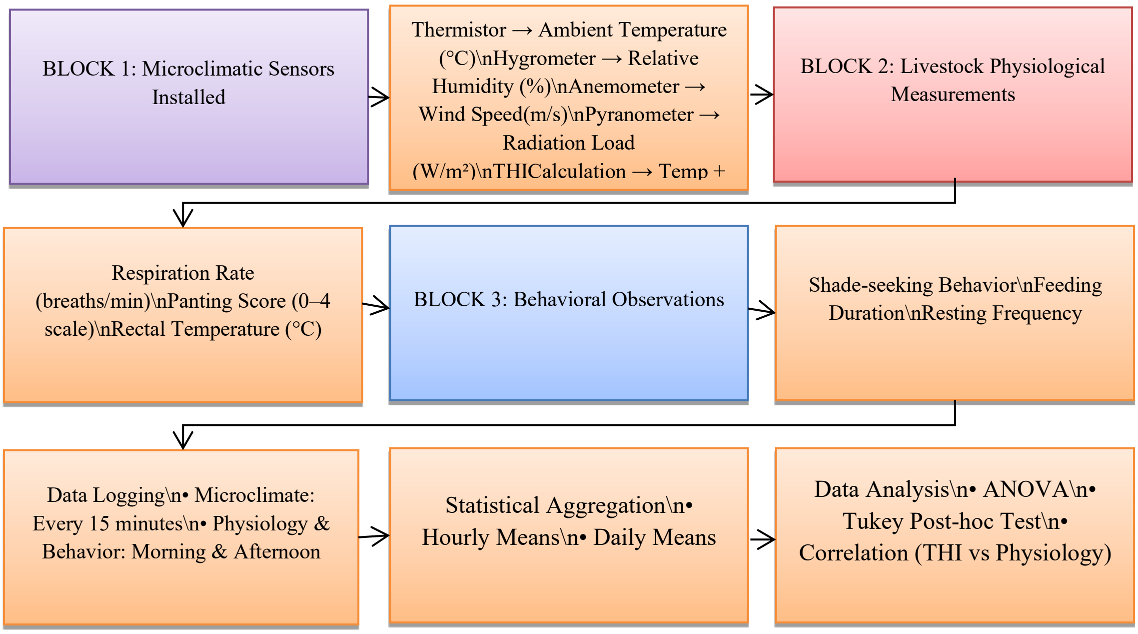

Figure 2: Workflow of Microclimatic Monitoring and Livestock Heat Stress Assessment

To measure shifts in the comfort and activation patterns across the changing microclimatic conditions, voluntary observations of complementary behaviours (such as shade-seeking tendencies, time at feeding, and frequency of resting) were recorded as assessments. Combined, these physiological and behavioural indicators provided a strong evaluation system to define the usefulness of every cooling intervention in the prevention of heat strain and enhancement of the overall welfare of animals.

Soil, Vegetation, and Biodiversity Assessments

Monitoring Moisture and Quality of Soil

The parameters to measure the ecological co-benefits of the nature-based cooling interventions were the soil moisture and soil quality, which were monitored systematically in all treatment areas and control areas. The effect of vegetative shading and evaporative cooling on the retention of soil water was determined by measuring the gravity content (REE) of soil moisture at a depth of 0-15 cm after every 2 weeks. To measure the effect of the interventions on thermal buffering in soil, the in-situ digital probes were used to measure the soil temperature complementarily. Moreover, the soil organic carbon content and micro-organism biomass were studied by applying the established laboratory procedures, which made it possible to measure the soil fertility and biological activity at altered microclimatic conditions. The metrics were used to offer a solid insight into how the existence of natural-based cooling systems affects soil health and nutrient cycling in livestock farming settings.

Biodiversity and Vegetation Surveys

To estimate the ecological enhancement brought about by the cooling systems that were put in place, vegetation structure and biodiversity dynamics were assessed. The abundance of plant species, ground cover, and canopy structure was evaluated by essentially locating 1 m 2 quadrats at a systematic location in every treatment zone, which enabled quantifying the diversity of vegetation as well as the formation of habitats. Insects beneficial to humans such as pollinators and natural predators were surveyed by using the sweep netting and pitfall trapping techniques to determine ecosystem services related to higher vegetation. Also, point-count surveys were undertaken with the avian diversity during the peak activity time under the aim of understanding which habitat was suitable and what attractions wildlife. These measurements allowed an adequate analysis of the increase in biodiversity in connexion with nature-based microclimate interventions.

Data Interpretation and Methodology of Analysis

All microclimatic, physiological, soil and biodiversity data collected was statistically looked into to establish the value of the cooling interventions and their relative efficacy. The one-way Analysis of Variance (ANOVA) was used to determine treatment-level differences with the post-hoc tests of Tukey to identify a particular difference between vegetative shading, evaporative cooling ponds, windbreak belts, and the control area Table 1. Correlation analysis was carried out to measure relationships between decreases in THI and livestock physiological responses to allow establishment of cause-and-effect relationships between enhancement of microclimate and animal welfare. This assimilating analytical framework predetermined the strict interpretation of the ecological and biological effects provided by the nature-based systems.

Results and Discussion

Changes in the Microclimate and Temperature

The implementation of the nature-based cooling systems bore great positive microclimatic impacts across all of the treatment areas, and the ambient temperatures in the treatment areas were lower (2.84.6 o C) by comparison to the ambient temperatures in the control area.

Table 1: Soil, Vegetation, and Biodiversity Parameters Measured Across Treatment and Control Zones

Assessment Category	Parameter Measured	Method / Instrument	Frequency	Purpose
Soil Moisture & Quality	Gravimetric soil moisture (%)	Soil sample oven-drying	Biweekly	Measure water retention improvement
	Soil temperature (°C)	In-situ digital soil probes	Biweekly	Assess thermal buffering
	Organic carbon (%)	Walkley–Black method	Monthly	Evaluate soil fertility changes
	Microbial biomass (mg/kg)	Chloroform fumigation–extraction	Monthly	Assess soil biological activity
Vegetation	Plant species richness	1 m² quadrat sampling	Monthly	Evaluate biodiversity
	Ground vegetation cover (%)	Quadrat + visual estimation	Monthly	Measure ecological enhancement
	Canopy density (%)	Densiometer / canopy analysis	Monthly	Assess shading ecosystem impacts
Biodiversity	Beneficial insects (count)	Sweep-net + pitfall traps	Biweekly	Evaluate ecosystem services
	Avian diversity	Point-count surveys	Biweekly	Wildlife habitat assessment
Statistical Analysis	ANOVA, Tukey HSD	Statistical software	End-of-study	Identify significant differences
	THI–Physiology correlation	Pearson correlation	End-of-study	Examine heat stress relationship

Peak heat hours (12:00 to 16:00 h) of cooling had the highest effect and it proves that the vegetative canopy cover, surface water evaporation and turf alteration due to the wind can absorb extreme temperature. To this effect, Thermal Humidity Index (THI) was modified on its range of extreme heat stress to those parameters that were considered moderate signifying a deep relaxation of the heat burden on the atmosphere. These data confirm the synerg Endowment of the nature-based interventions in the form of creating a thermally conducive environment to animals when they find themselves in the active solar radiation environment by availing shading, evaporative cooling, and airflow modulation.

Dynamics Effect to Relative Humidity and Wind Speed

Relative humidity and the wind movement also demonstrated the efficiency of cooling systems. The local humidity (4-7 percent) induced by evaporative cooling ponds increased heat loss to evaporation of extremely small scale of the microclimate. During the atmospheric profile Belt windbreak trees were also used with constant effort to capture the warm direction of the unsuitable winds and slow down the unreasonable speed brought about by the winds and ensure that the air moved at a reasonable speed needed to cool the convective heat. All this humidity, wind velocity variations enhanced the overall thermal comfort of livestock and hence vegetation and water bodies have a crucial role to play in ensuring that the microenvironment parameters do not alter even in the face of semi arid climatic conditions.

Physiological and Behavioural Enrichment of Livestock

Animals confined in nature-based cooling pads were highly reimbursed of heat stress physiologically. It slowed down to 101+8 breaths/min in the control areas to 78+6 breaths/minute in the treated areas and a decline in breathing work was observed at 23-percent.

The average of panting was reduced by 3.2 and 1.8 that manifested a tremendous alteration in thermal discomfort. The use of such physiological observations was complemented with the behavioural observations such as an increased period in resting areas, increased feeding action and general relaxed behaviour in animals in cooled areas. These integrated responses are also a result of microclimate amelioration and this demonstrates that the technology is a direct way of reducing the stress of animals by normalising thermoregulatory activity and minimising the heat-related behavioural stress.

Advantages of Soil Health and Ecological

Ecological advantages in the form of immense quantities of ecological values were produced in the scenery of the farms except the comfort of livestock. The shading by the vegetation increased moisture levels of the top soils 12-17 years as well as increasing large vegetation canopy on the ground, in addition to the difference in soil temperature. An increased number of useful insects including pollinators and natural predators was a sign of good quality of habitat and a diversified vegetation. Another way the tree belts were used was in controlling erosion, addition of organic matter as well as aesthetics in the landscapes set up. These environmental benefits show how biological cooling systems are multidimensional in a way that they can be used not only to stimulate the livestock production but to increase the stability of the whole ecosystem.

Internalisation Discussion and Implication on Climate-Resilient Livestock Farming

Overall, the combined results confirm the great potential of nature-based cooling interventions as cost-effective and sustainable measures that can be implemented to decrease the heat stress in the livestock farm. The vegetative shading had rapid benefits of microclimate, such as the cover of the canopy and transpiration, and the benefits of evaporative ponds had special cooling benefits of significant value to both small ruminants and dark resting areas. Figure 3 Windbreaks had been observed to have a better airflow and reduced the direct heat load in high afternoon period. The system has long-term ecological objectives, reduced energy dependency and reduced operational costs as compared to the conventional cooling technologies Table 2. Their integration makes it easier to have climate-sensitive livestock management, which is more productive and sustainable to climatic pressures with an increase in temperature around the world.

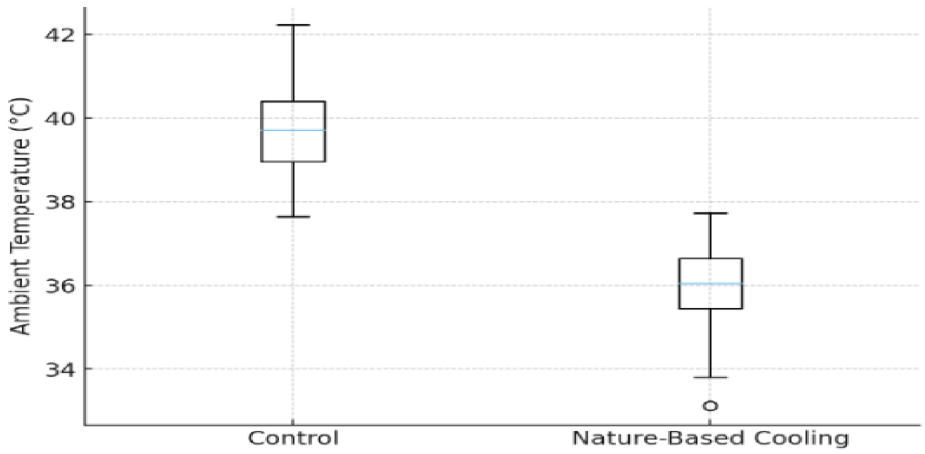

Figure 3: Box Plot of Ambient Temperature Differences between Control and Nature-Based Cooling Zones

Table 2: Summary of Microclimatic, Physiological, and Ecological Responses to Nature-Based Cooling Systems

Parameter Category	Control Zone	Nature-Based Cooling Zones	Observed Improvement / Effect
Ambient Temperature (°C)	39.5–40.8	35.2–37.0	↓ 2.8–4.6°C reduction in heat load
Peak Heat Stress (12:00–16:00 h)	Severe THI range	Moderate THI range	Significant THI decrease
Relative Humidity (%)	Baseline	+4–7% increase near pond	Enhanced evaporative cooling
Wind Speed (m/s)	Higher, unstable	Moderated, stable	Improved airflow regulation by windbreaks
Respiration Rate (breaths/min)	101 ± 8	78 ± 6	↓ 23% respiratory strain
Panting Score (0–4)	3.2	1.8	↓ 44% heat stress symptoms
Behavioral Responses	Reduced resting time	Increased resting & feeding	Better comfort, calmer behavior
Soil Moisture (%)	Lower	+12–17% higher	Improved water retention under shade
Biodiversity Indicators	Fewer insects & birds	More pollinators & birds	Enhanced ecological richness
Landscape Ecosystem	Minimal vegetation	Dense canopy, stable soil	Better erosion control & aesthetics
Overall Impact	High heat stress	Strong heat mitigation	Sustainable, low-cost cooling alternative

Conclusion

This paper reveals that nature-based cooling systems, which include vegetative shading constructions, evaporative cooling ponds, and windbreak tree belts represent a very effective and viable solution to addressing heat stress in the environment in livestock production systems. The combined interventions brought about great changes in the parameters of microclimate, including lowered ambient temperature and THI, and increased relative humidity and soil air stability, all of which made the environment livelier and more comfortable to the cattle and small ruminants. These microclimate adjustments directly incorporated into quantifiable physiological advantages, such as low levels of respiration, low levels of panting, and behavioural reaction that demonstrated low amounts of heat stress. Also, the ecological co-benefits of enhanced soil moisture content, augmented biodiversity and augmented landscape endurance signify the multifunctional worthiness of the nature-based solutions. On the whole, the results underline that the use of such low-cost and energy-efficient cooling methods can have a very high positive impact on the livestock welfare, productivity, and eco-sustainable livestock management because of the rising global temperature issues.

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