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High-speed Air Flow Alleviates Circadian Heat Load and Stabilizes Peripheral Thermoregulation in Heifers

Neha Rajawat[1], Ajay Kumar Dang[1], Babita Kumari[1], Anil[1], Ashutosh[1]

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ABSTRACT

Background: Heat stress represents a major challenge to livestock health and welfare under intensive housing systems in tropical and subtropical regions. Especially during the hottest periods of the day, when high temperatures and humidity intensify the physiological burden on dairy cows. This pilot study investigates the influence of varying high-speed airflow within the dairy barn on both the barn microclimate and the animals' circadian heat load.

Methods: This pilot study investigated the short-term effects of varying high airspeed airflow on the barn microclimate and animal physiology to optimize maximum effectiveness. Airflow-based treatments were applied along the barn axis at targeted airflow speeds of ASc (control), AS1 (1.8 m/s), AS2 (3.6 m/s) and AS3 (4.8 m/s). At each airspeed treatment level, observations were recorded to evaluate diurnal physiological responses, specifically rectal temperature and respiration rate. The study involved six heifers (12-18 months) and both environmental and physiological measurements were taken three times daily during the hot-dry (HD) and hot-humid (HH) seasons.

Result: THI ranged from 74-85 under hot-dry conditions and increased to 76-89 under hot-humid conditions, with relative humidity rising from 48-95%. Within each season, THI showed a slight decline with increasing air speed (ASc-AS3), indicating localized improvement in the shed microclimate. CO_2 concurrently decreased from 720-760 to 610-640 ppm ($p<0.001$). Rectal temperature peaked at 39.59°C and 39.98°C and respiration rate at 33.50 and 37.33 breaths/min, respectively, both significantly reduced at higher air speeds ($p<0.001$). Peripheral surface temperatures (forehead, head, eye, flank) were higher under humid heat but declined markedly with increasing airflow (3.6-4.8 m/s), with eye temperature decreasing from 39.79 to 39.20°C and 40.18 to 38.78°C. The skin temperature gradient increased from 2.76 to 3.34°C and from 2.36 to 3.25°C, reflecting enhanced heat dissipation. Overall, increasing air speed improved microclimate quality and effectively mitigated thermal and physiological stress.

Key words: Heat stress, Heifers, Hot dry (HD), Hot humid (HH), Microclimate cooling, Welfare.

INTRODUCTION

Heat stress remains a significant constraint in intensive dairy production systems, particularly in tropical and subtropical regions, where rising global temperatures have exacerbated thermal load challenges (Chen *et al*., 2021; Resende *et al*., 2025; Sesay *et al*., 2023). Cattle experiencing high heat stress exhibit elevated rectal temperature, increased respiration rate, altered skin heat dissipation and disrupted circadian rhythmicity, leading to measurable declines in productivity, welfare and immune competence (Bhalakiya *et al*., 2025; Slayi *et al*., 2025; Zhang *et al*., 2025). Maintaining diurnal thermoregulatory stability has therefore become central to modern livestock management as climate extremes increase in frequency and duration (Islam *et al*., 2023). Specio-thermal variability, Ventilation and airflow management represent core strategies for reducing thermal strain by enhancing convective heat transfer from the animal surface (Vieira *et al*., 2021). Computational simulations confirmed that increasing airflow velocity enhances convective heat transfer (Wang *et al*., 2018). However, emerging evidence highlights that airflow direction not only speed is a critical yet under-recognized determinant of cooling effectiveness, as the orientation of airflow relative to the animal's body governs the extent of surface exposure and turbulence intensity (Bah *et al*., 2021). Cross-flow ventilation, where air moves perpendicular to the animal's long axis, exposes a greater body surface area and yields higher convective heat transfer coefficients than front-flow or top-down airflow, thereby improving cooling efficiency (Wang *et al*., 2018; Tomasello *et al.*, 2021; Zhang *et al*., 2024). In addition to reducing sensible heat load, well-designed airflow systems also enhance barn microclimate quality by diluting and removing airborne contaminants, including $PM_{2.5}$, CO_2 and VOCs, which significantly affect respiratory health, oxidative stress and animal comfort (Liao *et al*., 2021; Lou *et al*., 2022; Li *et al*., 2024). Elevated $PM_{2.5}$ impairs pulmonary function and promotes oxidative stress, while high CO_2

[1]Division of Animal Physiology, ICAR-National Dairy Research Institute, Karnal-132 001, Haryana, India.

Corresponding Author: Ajay Kumar Dang, Division of Animal Physiology, ICAR-National Dairy Research Institute, Karnal-132 001, Haryana, India. Email: rajadang@gmail.com

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and VOC concentrations disrupt mucosal integrity and reduce overall air quality (Kayalar *et al*., 2024). Thus, targeted airflow optimized in both speed and direction has re-emerged as a powerful, scalable and underutilized tool for improving thermoregulation and microclimate quality in animal housing. recently Computational Fluid Dynamics (CFD) modeling has advanced understanding of airflow dynamics around livestock (Chen *et al*., 2021; Tomasello *et al*., 2021).

However, fewer studies have validated airflow effects under real barn conditions, where animal posture, barn geometry and fluctuating environmental parameters interact to shape cooling efficiency. Moreover, research integrating airflow engineering with physiological variables such as rectal temperature kinetics, respiration rhythm and skin temperature gradients (STG) remains limited despite increasing recognition that these variables provide sensitive indicators of heat stress dynamics (Cheng *et al*., 2024). Skin temperature gradient, in particular, has emerged as an important index reflecting the balance between core heat removal and peripheral cooling capacity under variable airflow speeds (Xu *et al*., 2025). Barn-axis pedestal coolers are used to target airflow toward the resting zone to provide uniformity of microenvironment as suggested by computer-based modals (Jung *et al*., 2023). However, the optimal airflow speed required to maximize convective cooling in the intensive housing remains undefined for contrasting climatic phases such as hot-dry (HD) and hot-humid (HH) seasons.

Fewer studies have validated airflow effects under real barn conditions, where animal posture, barn geometry and fluctuating environmental parameters interact to shape cooling efficiency (Mihalcin *et al.,* 2025; Tomasello *et al.,* 2021). Moreover, research integrating airflow engineering with physiological variables such as rectal temperature kinetics, respiration rhythm and skin temperature gradients (STG) remains limited despite increasing recognition that these variables provide sensitive indicators of heat stress dynamics. Barn-axis pedestal coolers, can be used to target airflow toward the resting zone, to remove heat stagnant zone in intensive housing system. However, the optimal airflow speed required to maximize convective cooling in barn axis direction remains undefined for contrasting climatic phases such as hot-dry (HD) and hot-humid (HH) seasons. Hot-dry climates Favor convection-driven cooling, whereas hot-humid conditions restrict evaporative heat loss due to high ambient moisture, making airflow optimization especially crucial.

To address these gaps, the present study employed a short-term pilot experimental framework focused on optimizing airflow speed delivered via barn axis orientation in support to natural ventilation and evaluating its impact on diurnal physiological responses. Integrating airflow with physiological and peripheral temperature provides a snapshot for understanding how barn-axis cooling influences thermoregulation and biological rhythm stability in heifers.

MATERIALS AND METHODS

Study location and climatic conditions

The experiment was conducted at the Climate Resilient Livestock Research Centre (CRLRC), ICAR-National Dairy Research Institute (NDRI), Karnal, India (29°42′3″N latitude, 76°59′6″E longitude; elevation 240 m above mean sea level). The climate is characterized by a hot and dry summer (April-May) and a hot and humid monsoon season (June-August). During spring, maximum ambient temperatures range from 19.6 to 32.3°C, with minimum temperatures between 4.4 and 17.0°C and relative humidity (RH) varying from 38 to 98%. In the hot-dry season, maximum temperatures range from 20.8 to 42.7°C and minimum temperatures from 12.1 to 28.8°C. The hot-humid season is characterized by persistently high temperatures, with maximum values of 27.4-36.6°C and minimum values of 20.8-28.9°C.

Experimental animals and breed profile

The study was conducted on Karan Fries heifers (12-18 months of age), a crossbred (Holstein-Friesian × indigenous dams) developed at ICAR-NDRI. The breed is characterized by a piebald coat pattern, larger body frame and moderate heat tolerance, exhibiting adaptive traits intermediate between exotic and indigenous cattle.

Experimental design and animal grouping

The experiment was conducted during both hot-dry (HD) and hot-humid (HH) seasons to identify optimal airflow levels for alleviating acute heat stress. Animals were randomly allocated to four air-speed treatments (ASc-AS3): a control group with no additional airflow (ASc) and three active airflow levels of 1.8, 3.6 and 4.8 m s^{-1} (AS1-AS3). Each treatment included six animals and animals were exposed to each air-speed level for 7 days. The total duration of the study was 88 days across both seasons, including 14 days for seasonal stabilization during the transition between seasons. Airflow was delivered along the longitudinal axis of the barn within the resting area of the animals. Physiological and microclimatic responses were recorded at predefined operational hours, with measurements taken twice during each exposure period to assess short-term thermoregulatory effectiveness.

Feeding and general management

All animals were maintained under uniform feeding and management practices as per ICAR-NDRI standards (ICAR, 2013). The diet consisted of a concentrate mixture (CP 20%, TDN 75%) comprising mustard/groundnut cake, maize, wheat bran, rice bran, 2% mineral mixture and 1% common salt. Animals received ad libitum green fodder (Trifolium alexandrinum, oats fodder) and wheat straw as roughage. Fresh drinking water was provided ad libitum throughout the experimental period.

Cooling system description

A custom-built barn-axis dual-nozzle cooling system was installed in the resting area to deliver directed high-velocity airflow along the animal line. The system comprised two identical blowers mounted on a welded frame, each enclosed in an aerodynamic casing and connected to two rectangular discharge nozzles (total outlet area = 2 ft^2). The blowers were driven by a single electric motor *via* a belt-and-pulley system, ensuring smooth operation with minimal vibration. A variable speed panel enabled precise regulation of airspeed up to 40 km/h. Air velocity was recorded using a digital anemometer at four distances from the nozzle (2.5, 5.5, 7.5 and 10.5 m), positioned at animal resting height (1.0-1.5 m).

Data collection and measurements

Microclimate and physiological parameters

Microclimatic variables, dry-bulb temperature (DBT), relative humidity (RH) and CO_2 concentration were recorded at 0, 1, 3 and 6 h of airflow operation. Ambient temperature was measured using a Zeal thermometer, RH was derived accordingly and CO_2 concentration was measured using a portable CO_2 monitor (Labwan India) calibrated before each session. The Temperature-Humidity Index (THI) was calculated using the equation proposed by Thom (1959).

$$THI = (0.8 \times T) + [(RH/100) \times (T - 14.4)] + 46.4$$

Where,
T= The dry-bulb air temperature (°C).
RH= The relative humidity (%).

Physiological responses were recorded at three-day intervals during the morning, afternoon and evening periods. Measurements included rectal temperature (RT), determined using a digital veterinary thermometer; respiration rate (RR), assessed by counting flank movements per minute; and peripheral surface temperature, which were specifically recorded during the peak heat-load hours in the afternoon to capture maximal thermal stress using a Testo IR camera (Model 868) featuring high-quality thermal images (160×120, up to 320×240 with super resolution).

Statistical analysis

Data were analysed using a general linear model. Within each season, the effects of airflow were assessed using one-way ANOVA, with the animal considered as a random effect to account for repeated measurements. Post-hoc comparisons were performed using Tukey's test for multiple comparisons. Results are reported as mean±SEM, along with 95% confidence intervals. Differences were considered statistically significant at $p<0.05$.

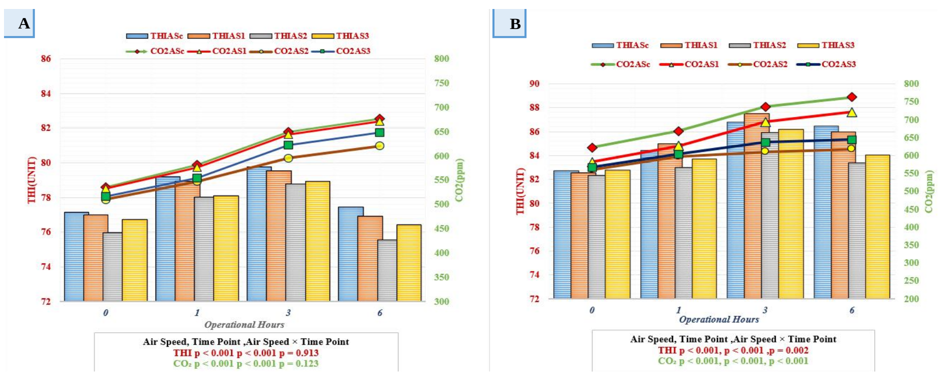
RESULTS AND DISCUSSION

Microclimate variables

Variation of microclimatic to varying air speed treatments during the hot dry (HD) and hot humid (HH) season are presented in Fig 1A and 1B, with the corresponding physiological responses (RT and RR) summarized in Table 1 and the peripheral surface temperature measurements and representative thermogram of hot dry cooling, control, hot humid cooling, hot humid control detailed in Table 2 and Fig 2 respectively, providing a comprehensive overview of the immediate thermal and physiological adjustments under the different airflow treatments. THI values showed clear seasonal and airflow dependent differences, ranging from approximately 74-85 in the hot dry period and increasing to 76-89 under hot humid conditions, indicating a greater thermal load during humid conditions, especially in the afternoon. CO_2 concentrations similarly varied with airflow, declining from 720-760 ppm at 0 h to 610-640 ppm at 6 h as air speed increased (ASc-AS3), reflecting improved ventilation efficiency. Statistical analysis showed that air speed and time point significantly affect both THI and CO_2, ($p<0.001$) in each season.

Rectal temperature (RT) and respiration rate (RR) responses to air-speed treatments

Rectal temperature and respiration rate exhibited a clear diurnal pattern across seasons and air-speed treatments



(A: Hot-dry (HD); B: Hot-humid (HH). THI is shown as line plots with markers and CO_2 as bar plots. Note: ASC= Control (no forced air); AS1= 1.8/ m/s; AS2= 3.6/ m/s; AS3= 4.8 m/s. Statistical significance given for time point, air speed and air speed × time interaction was determined at 95% confidence interval.

Fig 1: THI and CO_2 values recorded at four time points (0, 1, 3 and 6 h) under four air speed levels.

Table 1: Temporal variation in rectal temperature and respiration rate of animals exposed to varying air speeds under hot-dry and hot-humid conditions.

Variable	Season	ASc (Control)	AS1 (1.8m/s)	AS2 (3.6 m/s)	AS3 (4.8 m/s)	Season (p)	Air speed (p)	Season × air speed (p)
Rectal temperature (°C)								
Morning (RT-M)	HD	38.52^{ab}±0.03	38.47^{a}±0.02	38.45^{a}±0.02	38.57^{b}±0.02	*p<0.001*	*p<0.001*	*p<0.001*
	HH	38.87^{b}±0.03	38.93^{c}±0.03	38.83^{bc}±0.03	38.81^{a}±0.03			
Afternoon (RT-A)	HD	39.59^{c}±0.03	39.51^{bc}±0.03	39.30^{a}±0.02	39.45^{b}±0.02	*p<0.001*	*p<0.001*	*p=0.025*
	HH	39.98^{c}±0.03	39.98^{c}±0.03	39.63^{a}±0.03	39.76^{b}±0.03			
Evening (RT-E)	HD	39.09^{d}±0.05	38.93^{c}±0.01	38.63^{a}±0.03	38.73^{b}±0.03	*p<0.001*	*p<0.001*	*p=0.030*
	HH	39.57^{d}±0.03	39.38^{c}±0.05	38.96^{a}±0.02	39.05^{b}±0.03			
Respiration rate (Breath/min)								
Morning (RR-M)	HD	23.58^{b}±0.15	23.58^{b}±0.23	23.00^{a}±0.21	22.83^{a}±0.24	*p<0.001*	*p=0.002*	*p=0.712 (ns)*
	HH	25.58^{c}±0.29	25.58^{c}±0.23	25.42^{b}±0.15	24.83^{a}±0.21			
Afternoon (RR-A)	HD	33.50^{d}±0.47	29.83^{c}±0.30	27.42^{b}±0.28	24.25^{b}±0.28	*p<0.001*	*p<0.001*	*p<0.001*
	HH	37.33^{c}±0.38	30.25^{b}±0.13	26.00^{a}±0.34	25.58^{a}±0.15			
Evening (RR-E)	HD	30.25^{d}±0.35	25.50^{c}±0.44	22.33^{b}±0.19	21.50^{a}±0.31	*p<0.001*	*p<0.001*	*p<0.001*
	HH	34.17^{d}±0.39	24.83^{b}±0.24	22.08^{b}±0.31	22.50^{a}±0.15			

Note: ASC= Control (no forced air); AS1= 1.8/m/s; AS2= 3.6/m/s; AS3= 4.8 m/s. Different superscripts indicate significant differences (p<0.001) among air speed treatments within each season and body region. Two way ANOVA results for the main effects of season, air speed and their interaction (Season × air speed) are presented.

Table 2: Mean (±SD) peripheral surface temperatures (°C) across body regions exposed to different air speed treatments during hot dry (HD) and hot humid (HH) conditions.

Region	Season	ASc (Control)	AS1 (1.8m/s)	AS2 (3.6 m/s)	AS3 (4.8 m/s)	Season (p)	Air speed (p)	Season × air speed (p)
Peripheral surface temperature (°C)								
Forehead	HD	35.90^{bc}±0.08	35.71^{b}±0.08	35.49^{a}±0.06	36.00^{c}±0.06	*p<0.001*	*p<0.001*	*p<0.001*
	HH	37.73^{c}±0.09	37.57^{c}±0.08	35.60$^{a\pm}$0.08	36.44^{b}±0.06			
Head	HD	37.75^{b}±0.05	37.58^{ba}±0.06	37.49^{a}±0.05	37.75^{b}±0.05	*p<0.001*	*p<0.001*	*p<0.001*
	HH	38.85^{d}±0.05	38.68^{b}±0.06	37.45^{a}±0.05	38.48^{b}±0.04			
Eye	HD	39.79^{b}±0.03	39.68^{c}±0.04	39.20^{a}±0.02	39.35^{b}±0.02	*p<0.001*	*p<0.001*	*p<0.001*
	HH	40.18^{c}±0.03	39.38^{b}±0.04	38.78^{a}±0.04	38.94^{b}±0.13			
Flank	HD	36.83^{b}±0.03	36.71^{b}±0.06	36.01^{a}±0.03	36.11^{a}±0.07	*p<0.001*	*p<0.001*	*p<0.001*
	HH	37.63^{c}±0.03	37.13^{b}±0.07	36.41^{b}±0.03	36.51^{a}±0.07			
Leg	HD	39.00G"±0.09	38.82G"±0.07	38.26C"±0.07	38.17C"±0.06	*p=0.001*	*p<0.001*	*p=0.683 (ns)*
	HH	39.09^{b}±0.09	39.04^{b}±0.09	38.54^{a}±0.11	38.40^{a}±0.05			
ST gradient	HD	2.76^{a}±0.05	2.80^{a}±0.07	3.29^{b}±0.04	3.34^{b}±0.06	*p=0.002*	*p<0.001*	*p=0.003*
	HH	2.36^{a}±0.05	2.84^{b}±0.07	3.22^{c}±0.05	3.25^{c}±0.07			

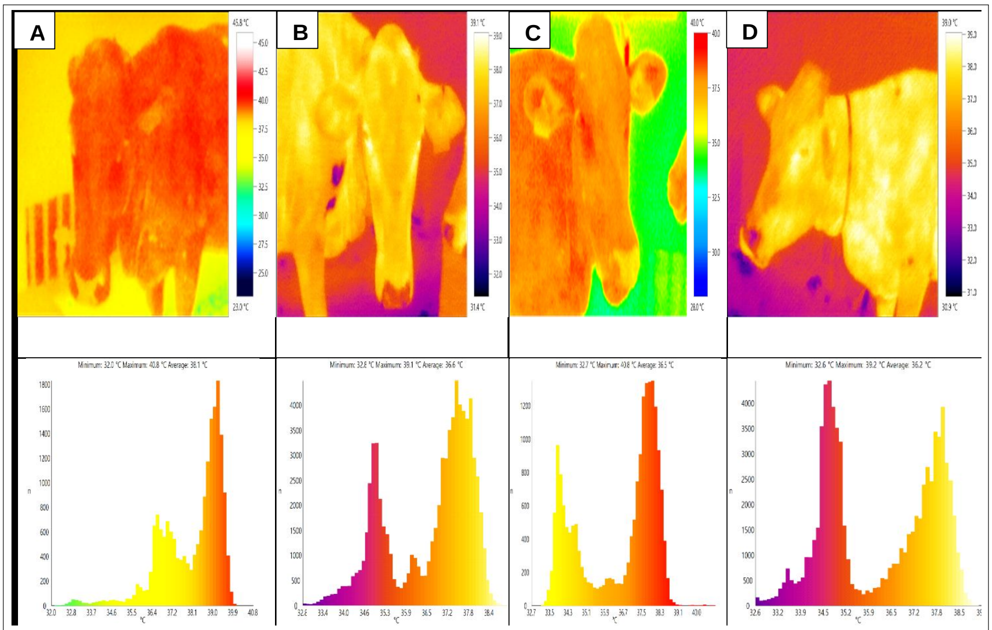
Note: ASC= Control (no forced air); AS1= 1.8/m/s; AS2= 3.6/m/s; AS3= 4.8 m/s. Different superscripts indicate significant differences (p<0.001) among air speed treatments within each season and body region. Two way ANOVA results for the main effects of season, air speed and their interaction (Season × air speed) are presented.

(Table 1), with lower values in the morning, a pronounced increase during the afternoon and partial recovery during the evening. In the hot-dry season, morning rectal temperature ranged from 38.45-38.57°C, whereas under hot-humid conditions it was consistently higher (38.81-38.93°C, p<0.001). Rectal temperature peaked during the afternoon, reaching 39.59°C in hot-dry control animals and 39.98°C in hot-humid control animals, before declining in the evening to 39.09°C and 39.57°C, respectively. Increasing air speed significantly reduced rectal temperature across all times of day (p<0.001), with the lowest afternoon values observed at 3.6 m/s (*e.g.*, 39.30°C vs 39.59°C in hot-dry conditions and 39.63°C vs 39.98°C in hot-humid conditions). Respiration rate showed a similar diurnal pattern, increasing from morning to afternoon and declining during the evening. Morning respiration rate was higher under hot-humid conditions (25.58 breaths/min) compared with hot-dry conditions (23.58 breaths/min). Afternoon respiration rate reached 33.50 and 37.33 breaths/min in hot-dry and hot-humid control animals, respectively and was markedly reduced with increasing air speed, declining to 27.42-26.00 breaths/min at 3.6 m/s (p<0.001). Evening respiration rate also decreased progressively with increasing air speed, from 30.25 to 22.33 breaths/min in hot-dry conditions and from 34.17 to 22.08 breaths/min in hot-humid conditions.

Peripheral surface temperature responses to air-speed treatments

Peripheral surface temperature at different body regions was significantly influenced by season, air speed and their interaction (Table 2). Across all regions, surface temperatures were consistently higher under hot-humid conditions than hot-dry conditions, indicating greater peripheral heat load during humid heat stress. At the forehead, surface temperature under hot-dry conditions ranged from 35.49 to 36.00°C, whereas under hot-humid conditions it increased markedly to 35.60-37.73°C, of season (p<0.001), air speed (p<0.001). Increasing air speed, particularly 3.6-4.8 m/s, significantly reduced forehead temperature in both seasons, with the lowest values observed at 3.6 m/s.

A similar response pattern was observed at the head region, where hot-humid animals exhibited higher surface temperatures (38.4838.85°C) compared with hot-dry animals (37.49-37.75°C). Both season (p<0.001) and air speed (p<0.001) exerted strong effects, indicated enhanced cooling efficiency of higher air speeds under humid conditions. At the eye region, surface temperature showed pronounced sensitivity to air movement, declining from 39.79 to 39.20°C in hot-dry conditions and from 40.18 to 38.78°C in hot-humid conditions as air speed increased, with highly significant effects of season (p<0.001), air speed (p<0.001), similarly surface temperature at the flank followed comparable trends, with hot-humid values (36.41-37.63°C) remaining higher than hot-dry values (36.01-36.83°C). Increasing air speed significantly reduced flank temperature in both seasons (p<0.001), In contrast, leg surface temperature was less sensitive to seasonal differences, showing a modest season effect (p = 0.001) and a significant air speed effect (p<0.001). Skin temperature gradient (ST gradient) also increased significantly with



(Note: Panels depict (A) Hot-dry control (no cooling), (B) Hot-dry cooling at optimum air speed, (C) Hot-humid control (no cooling) and (D) Hot-humid cooling at optimum air speed.

Fig 2: Infrared thermographic images and corresponding surface temperature histograms.

rising air speed in both seasons, reflecting enhanced peripheral heat dissipation. Under hot-dry conditions, the ST gradient increased from 2.76 to 3.34°C, while under hot-humid conditions it increased from 2.36 to 3.25°C, with significant effects of season ($p = 0.002$), air speed ($p<0.001$). Overall, higher air speeds, particularly 3.6-4.8 m/s, effectively reduced peripheral surface temperatures and increased thermal gradients, with more pronounced benefits observed under hot-humid conditions.

The present study reveals that air speed is a decisive factor in moderating heat stress responses and our findings clearly show that targeted airflow within the resting area can substantially improve both thermal and respiratory stability in animals exposed to tropical summer conditions. The observed diurnal variation from our findings in rectal temperature and respiration rate highlights the influence of circadian rhythm on thermoregulatory responses under heat stress. Afternoon and evening values were consistently higher, with rectal temperature peaking at 39.98±0.03°C and respiration rate reaching 37.33±0.39 breaths/min under hot-humid control conditions, reflecting the cumulative thermal load during peak ambient exposure. Increasing air speed significantly attenuated these responses, with reductions of up to 0.68°C in rectal temperature and 11 breaths/min in respiration rate at 3.6 m/s, indicating effective cooling even during circadian peaks. These findings suggest that optimized air speed delivery, particularly during afternoon and evening hours can modulate physiological rhythms and maintain core temperature and respiratory stability within acceptable thresholds, despite elevated external temperatures. Recent studies support that mechanical airflow interventions aligned with circadian heat stress profiles enhance animal comfort, reduce metabolic strain and mitigate heat stress behaviour in young bulls (Magrin *et al*., 2017; Slayi and Jaja *et al*., 2025). In addition to thermal benefits, targeted airflow in the resting area also contributed to lower THI and CO_2 accumulation, improving air quality within the animal microclimate. Such microclimate enrichment is known to reduce respiratory irritation and support healthier breathing patterns under heat stress (Jeppsson *et al*., 2021; Jannat *et al*., 2025). These combined effects indicate that airflow can buffer both thermal and respiratory load during circadian heat stress peaks. Increasing air speed produced a clear and consistent cooling response across all peripheral regions, with surface temperatures declining steadily as airflow intensified. Under hot humid conditions, Forehead temperature dropped from 37.73±0.09°C in the control to 35.60±0.08°C at 3.6 m/s, while eye temperature decreased from 40.18±0.03°C to 38.78±0.04°C, demonstrating strong convective heat removal. Comparable reductions were evident in the Flank (37.63±0.03°C to 36.41±0.03°C) and leg (39.09±0.09°C to 38.40±0.05°C). The corresponding rise in ST gradient from 2.36±0.05 to 3.34±0.06 at 3.6 m/s further confirms enhanced heat dissipation under increased airflow. However, at the highest air speed (4.8 m/s), animals exhibited a slight rebound in physiological responses and greater peripheral temperature variability, particularly during dry summer conditions (Sinha *et al*., 2018; Ahirwar *et al*., 2019), which may reflect the added thermal load associated with excessive dry heat exposure. These findings align with recent reports showing that higher air velocity improves boundary layer disruption, increases skin heat transfer and reduces peripheral thermal load in cattle (Kleinjan-Elazary *et al*., 2020; Bah *et al*., 2021). Studies using forced ventilation systems similarly demonstrate that air speeds above 2-3 m/s substantially enhance convective cooling efficiency, particularly under humid conditions where evaporative heat loss is limited (Reuscher *et al*., 2023). Overall, the present results confirm that elevated air movement is an effective strategy for reducing peripheral heat stress, especially in environments with high humidity. A distinctive strength of the present study is its focused evaluation of targeted cooling within the animal resting area, a micro zone often overlooked in conventional heat stress mitigation research. Unlike whole barn ventilation approaches, directing optimized air speed (3.6 m/s) specifically over the animal-occupied resting zone enriched the microclimate by reducing CO_2 accumulation and particulate concentration, thereby improving both thermal and respiratory comfort. This is particularly relevant because animals spend prolonged periods in the resting area, where stagnant air pockets and elevated humidity typically intensify heat load and respiratory irritation. Recent studies emphasize that microclimate level interventions can substantially improve welfare and physiological stability under tropical conditions (Andrade *et al*., 2022). Our finding shows that targeted airflow in the resting area provides both immediate circadian stabilization and sustained physiological resilience, integrating thermal relief, respiratory comfort.

CONCLUSION AND FUTURE SCOPE

Optimized airflow targeted at barn-axis cooling significantly enhanced microclimate quality by increasing air movement, reducing THI and eliminating concentrated heat pockets in the animal-occupied zone. This enhanced microclimate prevented heifers from crossing thermal-stress thresholds and yielded stable thermal comfort throughout the day. These results corroborate that strategically directed airflow is a simple, efficient and reliable method for enhancing barn microclimate quality and mitigating heat stress in cattle. Future uses for this system may encompass the integration of automated airflow controls, coupling targeted cooling with real-time THI sensors and scaling up this technology over a range of different livestock species or a prolonged exposure and housing designs toward adaptive, climate-smart cooling systems for precision livestock management. Further long-term studies are needed to evaluate the sustained effects of targeted airflow on animal welfare and performance.

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Ethics approval

Experimental approval for the present investigations was obtained from the Institutional Animal Ethics Committee, in accordance with the Committee for Control and Supervision of Experiments on Animals rules laid down by the Government of India, No. 50-IAEC-23-09 dated 28.11.2023.

Conflict of interest

The authors have declared no conflict of interest.

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