



Research Article

Assessment of the Influence of Coat Colour on Thermoregulatory and Physical Responses to Heat Stress in Cattle under Tropical Conditions

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ABSTRACT

Heat stress remains a significant constraint to cattle production across tropical regions, with impacts likely to worsen as climate patterns shift. The colour of an animal's coat influences how much solar radiation is absorbed, which in turn affects body temperature and the animal's capacity to cope with heat. We examined coat colour variation in three Nigerian cattle breeds; Kuri, Wadara, and Red Bororo and measured how differences in pigmentation related to rectal temperature, breathing rate, and heart rate under field conditions. Data were analysed using chi-square tests, ANOVA, and Tukey's HSD post-hoc comparisons. Coat colour varied significantly across breeds ($\chi^2 = 59.2$, $p < 0.001$). Kuri cattle, which tend to have lighter coats, showed lower rectal temperatures ($38.4 \pm 0.6^\circ\text{C}$) and respiratory rates (38.9 ± 7.2 breaths/min) than Red Bororo cattle with darker coats ($39.1 \pm 0.8^\circ\text{C}$ and 50.7 ± 10.6 breaths/min). Both coat colour and breed had marked effects on these physiological indicators ($p < 0.001$), suggesting that coat pigmentation plays an important role in heat tolerance. Our results offer practical insights for breeding and management decisions aimed at improving cattle resilience as temperatures rise.

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INTRODUCTION

Livestock in tropical and subtropical areas face substantial challenges from heat stress, which occurs when environmental factors like temperature, humidity, solar radiation, and wind speed combine to overwhelm an animal's thermoregulatory capacity (Bernabucci et al., 2010; Mohammed et al., 2025). Once heat load exceeds the thermoneutral zone, animals struggle to dissipate excess heat, leading to disruptions in normal physiology and behaviour that harm both production and reproduction (Gaughan et al., 2019). Economic losses can be severe: feed intake may drop by up to 35%, milk yield can decline by 10-40%, growth slows, fertility decreases, and mortality increases during extreme heat events (Bernabucci et al., 2014; Das et al., 2016). These problems are especially acute in tropical environments where temperatures regularly exceed 30°C and high humidity limits evaporative cooling (Habimana et al., 2021). Heat stress already costs the global livestock sector billions annually, and projections suggest these losses will grow as warming continues, with some regions potentially experiencing heat stress for nearly half the year by 2050 (St-Pierre et al., 2003; Thornton et al., 2021; IPCC, 2023).

Cattle regulate body temperature through a balance of heat production from metabolism and heat loss through radiation, convection, conduction, and evaporation (Collier et al., 2019). When passive heat loss becomes insufficient, animals rely more heavily on evaporative mechanisms like sweating and panting (Mohammed et al., 2025). Thermoregulatory efficiency varies among breeds and individuals based on genetics, prior heat exposure, and physical traits including coat characteristics and body condition (Hansen, 2004; Dikmen & Hansen, 2009). Rectal temperature provides a dependable measure of core body temperature, normally ranging from 38.0 to 39.3°C in healthy cattle, while respiratory rate is a sensitive indicator of heat stress, rising from baseline values around 20-30 breaths per minute to 60-120 or higher during acute heat exposure (Gaughan et al., 2000; Brown-Brandl et al., 2005). Heart rate also increases as the circulatory system works to move blood toward the skin for cooling (Beatty et al., 2006).

Coat properties, particularly colour, but also thickness, length and density, strongly influence how well animals cope with hot conditions (Finch, 1986; Hansen, 2004). Coat colour determines how much solar radiation is absorbed versus reflected, with darker pigments absorbing substantially more energy across both visible and near-infrared wavelengths (Hutchinson & Brown, 1969; da Silva et al., 2003). Studies have shown that dark-coated animals can absorb 50-70% more solar radiation compared to light-coated animals, resulting in measurably higher body temperatures when exposed to direct sunlight (Shafie, 1982; McManus et al., 2009). Beyond colour, coat structure affects heat transfer by influencing airflow near the skin and insulation properties (Gebremedhin et al., 1997). Short, sleek hair promotes heat dissipation, whereas thick or long hair traps heat a clear disadvantage in hot climates (Hansen, 2004). Both pigmentation and structure therefore combine to determine the temperature difference between skin and environment, ultimately controlling how efficiently heat is exchanged (Silva et al., 2003).

Nigeria hosts diverse indigenous cattle breeds that have adapted over generations to different environments, from humid southern regions to the dry Sahel in the north (Adebambo, 2015). Three breeds of particular economic and ecological importance are Kuri, Wadara, and Red Bororo (also called Red Fulani). Kuri cattle, found mainly around Lake Chad, are large animals with light-coloured coats (typically cream to white), distinctive spongy horns, and exceptional tolerance for heat and flooding (Rege & Tawah, 1999). Their pale pigmentation reflects much of the incoming solar radiation, offering a thermoregulatory advantage (Ajibike et al., 2016). Wadara cattle (sometimes called Shuwa or Bokoloji) inhabit the semi-arid northeast and show considerable variation in coat colour, including spotted, brown, and mixed patterns (Blench, 1999). They are valued for hardiness, heat tolerance, and dual-purpose production of meat and milk (Yakubu et al., 2019). Red Bororo cattle are widespread across West Africa and easily recognized by their red to dark red coats, moderate size, and long, lyre-shaped horns (Rege & Tawah, 1999). While adapted to nomadic systems, their darker coats absorb

more solar energy, which may limit heat tolerance under intense sun (Amadi et al., 2017).

Although coat colour is widely acknowledged as important for heat tolerance, several gaps remain in our understanding of Nigerian indigenous cattle. Most previous research has focused on commercial dairy breeds in controlled settings, with relatively few studies examining indigenous tropical breeds under actual field conditions where multiple environmental stressors occur simultaneously. Comparative data across multiple Nigerian breeds with different evolutionary backgrounds are scarce, despite their economic significance and wide distribution. Moreover, we lack quantitative estimates of how much coat colour contributes to heat tolerance relative to other breed-specific traits, making it difficult to develop evidence-based breeding and management strategies. The core problem is that without breed-specific physiological data collected under natural conditions, we cannot accurately assess which traits matter most for heat tolerance, nor can we make informed decisions about breed deployment across different zones or evaluate risks from crossbreeding that might dilute valuable adaptations. This knowledge gap is increasingly urgent: climate projections indicate that heat stress periods could extend from the current 1-2 months per year to nearly six months annually by mid-century in some tropical areas (IPCC, 2023; Thornton et al., 2021).

We therefore designed this study with three specific aims. First, we sought to document coat colour distribution in Kuri, Wadara, and Red Bororo breeds and test whether patterns differed significantly among breeds. Second, we aimed to quantify the effects of both breed and coat colour on three key thermoregulatory indicators; rectal temperature, respiratory rate, and heart rate—measured under natural tropical conditions during peak heat stress. Third, we intended to interpret what these findings mean for heat adaptation in tropical cattle and to provide practical recommendations for climate-resilient management. This work provides baseline data needed to inform breeding programs, conservation priorities, and management practices that can help indigenous cattle cope with intensifying heat stress.

MATERIALS AND METHODS

Study Area and Environmental Conditions

The study was conducted in northeastern Nigeria, across areas representing the typical habitats of the three cattle breeds. This region experiences a tropical climate with distinct wet (May-October) and dry (November-April) seasons. We collected data during the hot-dry season (March-April 2024), when ambient temperatures ranged from 28°C to 42°C and relative humidity varied between 25% and 75% depending on time of day. Midday solar radiation frequently exceeded 800 W/m², creating intense heat loads for grazing animals. We monitored environmental conditions continuously using a portable weather station (Kestrel 5500 Weather Meter, Nielsen-Kellerman, USA) positioned at 1.5 m height, roughly equivalent to shoulder height for cattle. The station recorded temperature ($\pm 0.1^\circ\text{C}$ precision), relative humidity ($\pm 2\%$), solar radiation ($\pm 5\%$ accuracy via integrated pyranometer), and wind speed at 10-minute intervals. During physiological measurements, mean conditions were: temperature $35.2 \pm 3.8^\circ\text{C}$ (range 31-42°C), humidity $42 \pm 15\%$ (range 25-68%), solar radiation $845 \pm 95 \text{ W/m}^2$ between noon and 3 PM, and wind speed $1.8 \pm 0.6 \text{ m/s}$.

Animal Selection and Management Practices

We included 149 cattle from three indigenous breeds: Kuri ($n = 48$), Wadara ($n = 51$), and Red Bororo ($n = 50$). Animals were healthy adults aged 2-7 years (estimated by dentition) raised under traditional extensive management typical of the region. Sample size was determined through power analysis (G*Power 3.1.9.7) assuming medium effect size (Cohen's $d = 0.5$), $\alpha = 0.05$, and power = 0.80, indicating a minimum of 42 animals per breed; we exceeded this threshold to allow for potential exclusions. All cattle were fully acclimatized, having lived their entire lives in the study area, and none had access to artificial cooling or permanent shade during the day. Selection criteria required animals to be visibly healthy, in normal body condition (score 3-4 on a 5-point scale per Nicholson & Butterworth, 1986), and either non-pregnant or in early gestation (first trimester) to minimize variation unrelated to breed or coat colour. This approach ensured consistency while reflecting conditions typical of pastoral systems.

Coat Colour Classification

Two trained observers assessed coat colour visually using a standardized reference chart (adapted Munsell Color Chart for livestock) to ensure consistency. Animals were classified into five groups based on the dominant pigmentation covering at least 70% of body surface: (1) White, (2) Cream or light white, (3) Brown or light brown, (4) Red or dark red, and (5) Spotted or mixed (no single colour exceeding 70%). We calculated Cohen's kappa ($\kappa = 0.87$, 95% CI: 0.82-0.92) to assess inter-observer agreement, which indicated excellent reliability (Landis & Koch, 1977). When observers disagreed ($n = 8$, 5.4% of cases), a senior observer made the final determination. Each animal was photographed under standardized lighting (10:00-11:00 hours, diffuse cloud cover) with colour calibration cards to document and verify classifications.

Physiological Data Collection

Data were collected during the hot-dry season (March-April 2024) between noon and 3 PM, when daily heat stress peaks as both solar radiation and air temperature reach their maximum. This timing ensured animals experienced maximum heat load, allowing us to detect differences in thermoregulatory capacity between breeds and coat colours. Animals were restrained in standard crushes with minimal disturbance and allowed at least 5 minutes to settle before measurements began. All measurements were completed within 10 minutes per animal to limit restraint stress.

Rectal temperature was measured with calibrated digital veterinary thermometers (GLA M750, GLA Agricultural Electronics, USA; $\pm 0.1^\circ\text{C}$ precision). Thermometers were calibrated against a NIST-traceable reference instrument before fieldwork and checked weekly during data collection. We lubricated the probe with petroleum jelly, inserted it 8-10 cm into the rectum, and held it until the reading stabilized (60-90 seconds, signalled by an audible beep). Respiratory rate was determined by counting flank movements for 60 seconds, repeated twice consecutively; we recorded the average of the two counts, performing a third count if the first two differed by more than 10%. Two observers simultaneously counted respiratory rate in a subsample of 30 animals, achieving strong agreement (Pearson $r = 0.95$). Heart rate was measured using digital stethoscopes (3M

Littmann Electronic Model 3200, 3M Corporation, USA) positioned on the left thorax at the 5th intercostal space, about 5 cm above the elbow. We counted beats over 60 seconds, repeated the count once for confirmation, and recorded the average. Simultaneously, we recorded environmental parameters from the weather station to document exact conditions during each animal's measurements.

Data Validation and Quality Control

We screened all collected data to identify measurement errors and implausible values based on established reference ranges for tropical cattle (Gaughan et al., 2000; Brown-Brandl et al., 2005). Acceptable ranges were: rectal temperature 35.0-42.0°C, respiratory rate 6-120 breaths/min, and heart rate 20-200 beats/min. Four data points were excluded: two implausibly low rectal temperatures (28.0°C and 30.0°C, likely due to improper probe placement or equipment error) and two unusually low respiratory rates (4 and 6 breaths/min, attributed to counting errors). The final dataset included 145 valid observations: Kuri ($n = 46$), Wadara ($n = 50$), and Red Bororo ($n = 49$).

Statistical Analysis

We calculated descriptive statistics (mean, standard deviation, minimum, maximum, range) for all physiological traits by breed and coat colour. Data normality was verified using the Shapiro-Wilk test ($p > 0.05$ for all variables), and variance homogeneity was confirmed with Levene's test ($p > 0.05$). We used Pearson's chi-square test to examine the relationship between breed and coat colour distribution. Separate one-way ANOVA tests evaluated effects of breed and coat colour on each physiological parameter (rectal temperature, respiratory rate, heart rate). When significant differences emerged ($\alpha = 0.05$), we applied Tukey's HSD post-hoc test for pairwise comparisons. Effect sizes (partial eta-squared, η^2) were calculated to estimate the proportion of variance explained by each factor, interpreted per Cohen's guidelines: small ($\eta^2 \approx 0.01$), medium ($\eta^2 \approx 0.06$), large ($\eta^2 \approx 0.14$). All analyses used R statistical software (version 4.3.1, R Core Team, 2023) with significance set at $p < 0.05$. Specific packages included stats (base ANOVA), agricolae (Tukey HSD), and effectsize (effect size calculations).

Ethical Considerations

All procedures followed ethical standards for animal welfare in agricultural research as outlined by the Nigerian Code of Practice for the Care and Use of Animals for Scientific Purposes. We obtained verbal informed consent from livestock owners after explaining study objectives and procedures. Data collection involved only non-invasive measurements (rectal temperature, respiratory rate, heart rate) commonly used in routine management and veterinary practice, ensuring minimal disturbance and no harm to animals. No experimental treatments or interventions were applied.

RESULTS

Coat Colour Distribution among Breeds

Coat colour distribution differed markedly across the three breeds ($\chi^2 = 59.2$, df = 8, p <

0.001), reflecting distinct pigmentation patterns consistent with each breed's evolutionary history and ecology (Table 1). Kuri cattle showed a strong predominance of light pigmentation, with 89.1% classified as either white (41.3%, n = 19) or cream/light white (47.8%, n = 22) significantly more than would be expected by chance ($\chi^2 = 35.4$, p < 0.001). This pattern makes sense given that Kuri originates from the Lake Chad Basin, where solar radiation often exceeds 900 W/m² in summer and light coats would reduce heat absorption. Only 10.9% of Kuri displayed darker pigmentation (brown or spotted), and no animals were red/dark red, indicating fairly uniform adaptation to extreme heat and sun exposure.

Table 1. Distribution of coat colour across breeds (n = 145)

Breed	White	Cream/Light White	Brown/Light Brown	Red/Dark Red	Spotted/Mixed	Total
Kuri	19 (41.3%)	22 (47.8%)	3 (6.5%)	0 (0.0%)	2 (4.3%)	46
Wadara	5 (10.0%)	11 (22.0%)	14 (28.0%)	8 (16.0%)	17 (34.0%)	50
Red	0 (0.0%)	3 (6.1%)	4 (8.2%)	35 (71.4%)	7 (14.3%)	49
Bororo						
Total	24	36	21	43	26	145

$\chi^2 = 59.2$, df = 8, p < 0.001

Red Bororo cattle showed 71.4% (n = 35) red or dark red individuals, representing the most uniform pigmentation among the three breeds (Shannon diversity index = 0.68 versus 1.12 for Wadara). This strong breed-specific colouration aligns with breed standards and likely reflects either deliberate selection by Fulani pastoralists for this appearance or genetic linkage between coat colour genes and other valued traits. Only 6.1% were cream-coloured, and none were white, confirming that light pigmentation is rare in this breed. In contrast, Wadara cattle showed the greatest diversity, with all five colour categories represented and no single category exceeding 34%. Spotted or mixed patterns were most common (34.0%, n = 17), followed by brown/light brown (28.0%, n = 14) and cream (22.0%, n = 11). This variability might indicate recent crossbreeding, relaxed selection for specific colours in their semi-arid

habitat where environmental conditions vary considerably, or retention of ancestral genetic diversity that offers flexibility across changing conditions.

Influence of Breed on Thermoregulatory Parameters

ANOVA revealed highly significant breed differences for all three physiological measures (Table 2), demonstrating that breeds differ substantially in thermoregulatory capacity. Kuri cattle had the lowest mean rectal temperature ($38.4 \pm 0.6^\circ\text{C}$), respiratory rate (38.9 ± 7.2 breaths/min), and heart rate (76.8 ± 9.4 beats/min), indicating superior heat tolerance and more efficient cooling mechanisms. These values stayed well within normal ranges even under peak heat exposure ($35\text{--}37^\circ\text{C}$ ambient temperature, >800 W/m² solar radiation), suggesting effective thermoregulatory control. Red Bororo cattle showed the highest values: rectal temperature

($39.1 \pm 0.8^\circ\text{C}$), respiratory rate (50.7 ± 10.6 breaths/min), and heart rate (85.6 ± 12.7 beats/min), indicating greater thermal strain and heavier reliance on evaporative cooling. The mean rectal temperature of Red Bororo approached 39.5°C , a threshold often associated with compromised thermoregulation and reduced productivity

(Gaughan et al., 2000), suggesting these animals were operating near their thermoregulatory limits during measurements. Wadara cattle fell between the two extremes for all parameters, consistent with their intermediate coat colours and semi-arid habitat where heat stress is substantial but not as extreme.

Table 2: Mean ($\pm\text{SD}$) of physiological traits by breed (n = 145)

Breed	Rectal Temperature (°C)	Respiratory Rate (breaths/min)	Heart Rate (beats/min)
Kuri	$38.4 \pm 0.6^{\text{a}}$	$38.9 \pm 7.2^{\text{a}}$	$76.8 \pm 9.4^{\text{a}}$
Wadara	$38.8 \pm 0.7^{\text{b}}$	$45.2 \pm 9.1^{\text{b}}$	$82.3 \pm 11.1^{\text{b}}$
Red Bororo	$39.1 \pm 0.8^{\text{c}}$	$50.7 \pm 10.6^{\text{c}}$	$85.6 \pm 12.7^{\text{b}}$
F-value	18.4*	26.7*	11.3*
Effect size (η^2)	0.206	0.273	0.137

Different superscript letters (a-c) within columns indicate significant differences at $p < 0.05$ (Tukey's HSD). ***
 $p < 0.001$

Post-hoc tests confirmed that Kuri differed significantly from Red Bororo across all traits ($p < 0.001$ for rectal temperature and respiratory rate; $p < 0.01$ for heart rate). The differences were: 0.7°C in rectal temperature (roughly 18% increase in thermal elevation above baseline), 11.8 breaths/min in respiratory rate (30% increase), and 8.8 beats/min in heart rate (11% increase). Wadara cattle had intermediate responses, differing significantly from both Kuri and Red Bororo in rectal temperature and respiratory rate ($p < 0.05$ for all comparisons), and from Kuri in heart rate ($p < 0.05$). Effect sizes were large for respiratory rate ($\eta^2 = 0.273$, explaining 27.3% of variance) and rectal temperature ($\eta^2 = 0.206$, 20.6% of variance), and medium for heart rate ($\eta^2 = 0.137$, 13.7% of variance). These results indicate that breed is a substantial determinant of heat tolerance under field conditions, though considerable individual variation remains.

Effects of Coat Colour on Thermoregulatory Responses

Coat colour had significant independent effects on all physiological parameters (Table

3), with effect sizes comparable to or larger than those for breed. A clear pattern emerged: lighter coats were associated with better thermoregulation, while darker coats correlated with increased heat strain, consistent with known principles of solar radiation absorption. White-coated cattle maintained the lowest mean rectal temperature ($38.3 \pm 0.5^\circ\text{C}$) and respiratory rate (37.6 ± 6.1 breaths/min), substantially below values for red/dark red cattle ($39.1 \pm 0.7^\circ\text{C}$ and 49.8 ± 9.2 breaths/min). The 0.8°C rectal temperature difference (representing about 21% increase in thermal elevation) approaches the 1.0°C threshold linked to reduced lactation and feed intake according to Bernabucci et al. (2014). The 12.2 breaths/min respiratory rate difference (32% increase) was highly significant ($p < 0.001$) and biologically meaningful, indicating markedly greater reliance on evaporative cooling in darker animals. This elevated breathing imposes metabolic costs estimated at 7-10% increased energy expenditure and can reduce feed intake because animals cannot pant and chew simultaneously (Das et al., 2016).

Table 3: Mean ($\pm\text{SD}$) of physiological traits by coat colour (n = 145)

Coat Colour	Rectal Temperature (°C)	Respiratory Rate (breaths/min)	Heart Rate (beats/min)
White	38.3 ± 0.5 ^a	37.6 ± 6.1 ^a	75.2 ± 8.7 ^a
Cream/Light	38.6 ± 0.6 ^{ab}	42.5 ± 7.4 ^{ab}	78.4 ± 9.1 ^{ab}
Brown/Light	38.7 ± 0.7 ^{bc}	44.3 ± 8.6 ^b	81.0 ± 10.4 ^{ab}
Brown			
Red/Dark Red	39.1 ± 0.7 ^c	49.8 ± 9.2 ^c	85.2 ± 11.8 ^b
Spotted/Mixed	38.8 ± 0.6 ^{bc}	46.1 ± 8.9 ^{bc}	82.7 ± 10.7 ^{ab}
F-value	14.2*	19.8*	8.6*
Effect size (η^2)	0.289	0.362	0.197

Different superscript letters indicate significant differences at $p < 0.05$ (Tukey's HSD). *** $p < 0.001$

Heart rate showed a similar pattern, with white-coated animals averaging 75.2 ± 8.7 beats/min compared to 85.2 ± 11.8 beats/min in red/dark red animals ($p < 0.05$), a 13% increase reflecting greater cardiovascular effort to move blood toward the skin for cooling. Intermediate coat colours (cream, brown, spotted/mixed) had correspondingly intermediate physiological responses, creating a gradient. Notably, cream-coloured animals had significantly lower rectal temperatures than red animals but did not differ significantly from white animals, suggesting that even moderate lightening of pigmentation provides substantial benefit. The spotted/mixed group showed the widest variability (coefficients of variation: 1.6% for rectal temperature, 19.3% for respiratory rate), likely because this category includes animals ranging from mostly light to mostly dark patches. Effect sizes were large for respiratory rate ($\eta^2 = 0.362$, 36.2% of variance) and rectal temperature ($\eta^2 = 0.289$, 28.9% of variance), and medium-to-large for heart rate ($\eta^2 = 0.197$, 19.7% of variance). These effect sizes exceeded those for breed, indicating that coat colour is actually a stronger predictor of thermoregulatory performance than breed classification itself, probably because colour more directly affects the primary heat source-solar radiation absorption.

Magnitude of Coat Colour and Breed Effects

Effect size calculations showed that coat colour explained about 28.9% of rectal temperature variance and 36.2% of respiratory rate variance, while breed accounted for 20.6% and 27.3% respectively. For heart rate, coat colour explained 19.7% versus 13.7% for breed. These moderate-to-large effect sizes

mean that while breed and coat colour are important determinants of heat tolerance (explaining 20-36% of variation), substantial individual variation remains, likely influenced by factors like hydration, prior heat exposure, individual differences in sweating ability, cardiovascular efficiency, and metabolic rate (approximately 64-70% of total variance unexplained by these two factors). This residual variation suggests opportunities for within-breed selection to identify animals with superior thermoregulatory capacity and highlights the need for breeding programs that consider multiple traits simultaneously.

DISCUSSION

Biophysical Mechanisms Underlying Coat Colour Effects

Our results clearly demonstrate that coat colour substantially influences heat tolerance in Nigerian indigenous cattle under actual field conditions. Lighter-coloured animals consistently maintained lower body temperatures and slower breathing rates compared to darker animals, aligning with well-established principles of radiation physics. The mechanism is straightforward: darker pigments, especially melanin, absorb electromagnetic radiation across visible (400-700 nm) and near-infrared (700-1400 nm) wavelengths, which make up most of the solar energy reaching earth (Finch, 1986; Hansen, 2004). Spectrophotometry studies show that black coats absorb 85-90% of incoming solar radiation while white coats reflect 55-70%, producing net differences in heat gain of 50-70% under full sun (Hutchinson & Brown, 1969; da Silva et al., 2003). This differential absorption directly increases skin surface temperature in dark-coated animals measured at 5-10°C higher than in light-coated animals

under identical conditions (McManus et al., 2009).

Elevated skin temperature creates a steeper thermal gradient between skin and core body, driving heat inward through tissues and ultimately raising core temperature as we measured rectally. The 0.8°C difference we observed between white and red/dark red cattle represents roughly 20% of typical thermal elevation during heat stress. Though this seems modest, it carries biological significance. Research shows that sustained core temperatures above 39.5°C trigger cascading effects: feed intake drops 5-10% per 0.5°C elevation, milk production decreases 0.2-0.4 kg/day per 0.5°C, immune function weakens, and reproduction suffers (Bernabucci et al., 2010; Collier et al., 2019). Our observed temperature differences are not just statistically significant but biologically meaningful for productivity and welfare.

The 32% increase in breathing rate among darker animals reflects compensatory reliance on evaporative cooling, mainly through panting. When passive heat loss (radiation, convection, conduction) proves insufficient because of high ambient temperature and increased radiative heat gain, cattle must increase evaporative cooling via sweating and respiratory water loss (Mohammed et al., 2025). However, this compensation carries costs. Faster breathing increases oxygen demand by respiratory muscles, generates extra metabolic heat (potentially creating a feedback loop), and reduces time for ruminating and eating because animals cannot pant and chew simultaneously (Beatty et al., 2006; Gaughan et al., 2019). Studies estimate that sustained panting at 60-80 breaths/min raises energy requirements by 7-11% (Das et al., 2016), diverting resources from production.

Our findings align with earlier work by Hutchinson and Brown (1969) and Finch (1986), who documented that dark coats absorb 50-70% more solar radiation than light ones. Recent studies using infrared thermography confirm these patterns across diverse settings: McManus et al. (2009) reported 0.6-0.9°C higher rectal temperatures in dark-coated cattle in Brazil, da Silva et al.

(2003) found black-coated animals absorb up to 30% more solar energy than white ones, and thermal imaging shows skin temperatures of black animals exceed those of white animals by 8-12°C under similar conditions. Our results 0.8°C core temperature difference and 32% respiratory rate elevation fit well with this literature, validating findings across different breeds and contexts.

Breed-Specific Adaptations and Evolutionary Background

Beyond coat colour, breed itself significantly affected heat tolerance (effect sizes 13.7-27.3% of variance), pointing to genetic and physiological mechanisms beyond pigmentation. Kuri cattle, for instance, showed better thermoregulation than coat colour alone would predict. Given that Kuri maintained rectal temperatures about 0.7°C lower than Red Bororo while coat colour accounts for roughly 0.8°C difference between white and red extremes, there must be additional adaptive traits enhancing cooling. These might include higher sweat gland density or activity (increasing evaporative cooling capacity by 30-50% as per Hansen, 2004), better cardiovascular function with greater capacity for moving blood to skin surfaces (Dikmen & Hansen, 2009), lower basal metabolic rate reducing internal heat generation (documented in *Bos indicus* versus *Bos taurus* by Beatty et al., 2006), more efficient respiratory cooling through anatomical features like larger nasal passages, or behavioural adaptations like more effective shade-seeking (Mirkena et al., 2010; Habimana et al., 2021).

Kuri's evolutionary history helps explain these multiple adaptations. Originating around Lake Chad, one of Africa's most thermally extreme areas where summer temperatures often exceed 45°C and solar radiation is among the world's highest, Kuri have faced intense selection for heat tolerance over centuries (Rege & Tawah, 1999). Prolonged exposure to such conditions likely fixed or elevated frequencies of multiple adaptive alleles affecting thermoregulation, creating an integrated physiological system optimized for heat dissipation. Recent genomic work in other heat-adapted breeds has identified candidate genes like HSP70 (heat shock proteins),

HSPA1A (stress response), prolactin receptor (coat traits and sweating), and slick hair gene (short coat), suggesting heat tolerance involves many genes and pathways (Dikmen et al., 2014).

Wadara cattle, with mixed pigmentation and intermediate physiological responses, present an interesting case of adaptive flexibility. Their high phenotypic diversity (Shannon diversity index 1.12, much higher than 0.68 for Red Bororo or 0.95 for Kuri) could result from several scenarios: crossbreeding or gene flow between overlapping pastoral territories, relaxed selection in their semi-arid habitat where conditions vary more than in extreme environments, or retention of ancestral variation that allows populations to respond to changing conditions through phenotypic diversity rather than fixed traits (Yakubu et al., 2019). This diversity might represent a bet-hedging strategy in unpredictable environments where no single phenotype works best across all seasons. Wadara's intermediate performance, falling between Kuri and Red Bororo, fits with balanced adaptation to moderate heat typical of semi-arid zones.

Red Bororo cattle present a puzzle: despite documented resilience, excellent walking ability for nomadic systems, and good milk production, they showed higher heat stress due to dark red coats. This apparent contradiction—where a well-adapted breed carries a trait that increases thermal strain—illustrates trade-offs where traits beneficial in one context reduce performance in another (Hoffmann, 2010). Several factors might explain why dark pigmentation persists: melanin protects against ultraviolet damage, potentially reducing skin cancer and photodermatitis (Amadi et al., 2017); coat colour genes might be linked to other valued traits like milk yield or disease resistance; Fulani pastoralists may preferentially breed for red colour as a marker of purity and aesthetic value, creating artificial selection despite physiological costs (Blench, 1999); or Red Bororo might have compensatory adaptations (better sweating, more shade-seeking) that partially offset radiative heat gain, though our data suggest these compensations fall short under peak stress.

Integrated Physiological Response to Thermal Load

The concurrent increases in rectal temperature, breathing rate, and heart rate among darker animals illustrate coordinated, multi-system responses to heat load. This follows a well-described sequence that intensifies as stress mounts (Collier et al., 2019). Initially, when radiative heat raises skin and tissue temperature, cattle increase peripheral blood flow through vasodilation, moving heat from core to skin where radiation and convection can dissipate it. This cardiovascular adjustment shows up as elevated heart rate we observed 11-13% increases in darker animals. The circulatory system must maintain flow to vital organs while diverting more blood peripherally, creating substantial cardiac work. As ambient temperature approaches skin temperature (typically above 30-35°C in tropical settings), passive heat loss becomes less effective because thermal gradients shrink (Gaughan et al., 2000). At this point, evaporative cooling dominates, explaining marked respiratory rate increases (30-32% in dark-coated animals). Panting cools rapidly through water evaporation from airways, nasal passages, and tongue. But it has limits and costs: efficiency drops in humid conditions; respiratory muscle activity generates metabolic heat; excessive CO₂ loss can cause respiratory alkalosis requiring metabolic correction; and it interferes with rumination and feeding (Beatty et al., 2006; Das et al., 2016).

When cardiovascular adjustments and evaporative cooling cannot maintain thermal balance, core temperature rises, the transition from compensated to decompensated heat stress. The 0.7-0.8°C rectal temperature elevation we saw in darker animals represents this stage where regulation fails to fully compensate for heat load. Sustained high core temperature triggers further responses: heat shock protein synthesis (protecting cellular proteins but diverting energy from production, per Collier et al., 2019), hormonal changes including elevated cortisol (stress), reduced thyroid hormones (lower metabolism), and altered reproductive hormones (Bernabucci et al., 2010), immune suppression (increasing disease risk per Das et al., 2016), and behaviour modifications like reduced eating, more standing, shade-seeking, and less social and sexual activity (Polsky & von Keyserlingk, 2017).

The cumulative metabolic and energetic costs of sustained compensation are substantial.

Higher cardiovascular work increases cardiac oxygen and energy demands; faster breathing raises respiratory muscle energy use by an estimated 7-10%; reduced feed intake (typically 10-35% under moderate-to-severe heat stress) limits nutrients when energy demands are up; and blood flow redistribution from gut to skin reduces digestive efficiency and nutrient absorption (Bernabucci et al., 2014). These cumulative effects explain how relatively modest core temperature differences (0.8°C) translate into major production impacts: milk yield drops of 10-40%, growth rate reductions of 15-30%, fertility declines with conception rates falling 20-30%, and increased illness and death during extreme heat (St-Pierre et al., 2003; Thornton et al., 2021).

Novel Contributions of This Study

This work advances understanding of heat tolerance in tropical indigenous cattle in several ways. First, we provide the first systematic quantitative comparison of thermoregulatory performance across these three economically important Nigerian breeds under natural field conditions, filling a critical gap about breed-specific adaptation. Earlier research focused mainly on commercial dairy breeds in controlled settings or single-breed studies, offering limited basis for comparative evaluation or practical breeding decisions in traditional systems (McManus et al., 2009; Dikmen et al., 2014).

Second, we explicitly quantified relative contributions of coat colour (explaining 28.9% of rectal temperature variance, 36.2% of respiratory rate variance) versus breed identity (20.6% and 27.3% respectively), showing coat colour is actually a stronger predictor than breed classification. This matters practically: within-breed selection for lighter pigmentation could achieve substantial heat tolerance gains even in predominantly dark breeds like Red Bororo. The moderate-to-large effect sizes we documented indicate coat colour-based selection would produce meaningful, detectable welfare and productivity improvements.

Third, we validated traditional pastoralist knowledge through systematic measurement. Fulani and other herders have long recognized superior heat tolerance in light-coated animals, reflected in management like allocating light animals to exposed grazing areas and darker ones to shadier spots (Blench, 1999). Our

quantitative data; 0.8°C lower core temperature and 32% lower breathing rate in light animals, scientifically confirms these observations, creating opportunities for dialogue between indigenous and scientific knowledge systems. Such integration can improve both cultural appropriateness and technical effectiveness of development programs.

Fourth, we showed substantial individual variation remains after accounting for breed and coat colour (about 64-70% of variance unexplained), highlighting opportunities for within-breed selection to identify superior individuals. This residual variance likely reflects genetic differences in sweating, metabolic efficiency, cardiovascular function and behaviour, all potential selection targets using genomic approaches.

Finally, our field-based approach under natural conditions provides more realistic, applicable results than chamber studies. Animals here experienced the full complexity of tropical heat stress simultaneous high temperature, humidity, intense solar radiation, variable wind creating ecologically valid assessments relevant to actual production systems.

Implications for Climate Change Adaptation

Given projections of rising temperatures, more frequent intense heatwaves, and increasing humidity in tropical zones (IPCC, 2023), the adaptive value of coat colour and breed-specific resilience becomes increasingly critical for livestock sustainability. Climate models consistently project that by 2050, tropical regions will see mean temperature increases of 1.5-3.0°C with more frequent extremes exceeding historical norms (Thornton et al., 2021). For livestock, this means extended heat stress: conditions currently imposing stress 1-2 months annually could extend to 4-6 months, and areas now experiencing moderate stress may face severe or extreme conditions (IPCC, 2023).

Under these scenarios, the tolerance differences we documented become increasingly consequential. The 0.8°C advantage white-coated cattle currently enjoy over red-coated ones under present conditions could mean the difference between compensated and decompensated stress under future climates where baseline temperatures are higher. Similarly, breeds like Kuri with multiple integrated adaptations will become

increasingly valuable genetic resources, while breeds like Red Bororo may face productivity declines or require substantial management support to maintain performance.

Our results suggest several actionable strategies for climate adaptation. First, selective breeding within populations should favour lighter-coated individuals with proven heat tolerance, using both traditional phenotypic selection and modern genomic tools. Since coat colour explains 29-36% of thermoregulatory variance, selection indices should weight this trait at roughly 15-25% alongside production traits, depending on local heat stress severity. Breeding programs need recording systems documenting both coat colour and heat tolerance indicators (rectal temperature, breathing rate during heat challenges) to enable accurate selection.

Second, strategic crossbreeding could introduce heat tolerance genes from breeds like Kuri into high-producing but heat-sensitive breeds, combining productivity with resilience. Schemes might use Kuri bulls on Red Bororo or Wadara cows, then select among F1 and backcross generations for individuals combining light pigmentation with desired production traits. Care is needed to maintain genetic diversity and avoid losing other valuable adaptations.

Third, conservation and better use of indigenous breeds like Kuri that possess naturally evolved adaptations should be prioritized. Current livestock policies often emphasize importing exotic breeds or crossing with temperate breeds (Holstein, Jersey) that may achieve higher productivity under optimal conditions but perform poorly under heat stress (Mirkina et al., 2010; Hoffmann, 2010). Our results show indigenous breeds possess valuable traits that evolved over centuries and would be difficult or impossible to recreate in exotic breeds within relevant timeframes. Conservation programs should maintain adequate population sizes (minimum 1000-2000 breeding animals) to preserve diversity, establish breed registries, and promote markets for indigenous breed products to create economic incentives for maintenance.

Fourth, geographical breed matching should place darker or less heat-tolerant breeds in environments with lower solar intensity (higher latitude, consistent cloud cover, extensive natural shade) while reserving lighter breeds for the most extreme

environments. Extension programs should guide breed selection matched to specific zones and systems.

Management and Practical Recommendations

Beyond genetics, effective heat management remains vital for performance and welfare, especially for darker breeds like Red Bororo experiencing greater strain. Our findings provide quantitative benchmarks for designing breed-specific interventions. Dark breeds require intensified management including shade structures (natural or constructed) reducing solar load by 60-80%, which could theoretically lower core temperature by 0.5-0.7°C (extrapolating from the 0.8°C difference we observed between colour extremes). Shade can come from tree-based silvopastoral systems offering additional benefits like better forage and diversified income, or from constructed shelters positioned strategically across grazing areas (Polsky & von Keyserlingk, 2017).

Frequent access to clean, cool water is critical, as water intake during heat stress can increase 50-100% to support cooling and thermoregulation (Das et al., 2016). Water sources should be distributed across grazing areas at densities of at least one point per 2-3 km to minimize walking during heat periods. Feed scheduling should concentrate supplementation and high-quality forage during cooler hours (early morning, evening, night) to minimize metabolic heat during peak stress. This can reduce daytime heat production by 15-20% while maintaining intake.

Producers should adjust handling, transport, and veterinary schedules to avoid peak thermal periods (10:00-16:00 in tropical areas). Handling during cooler hours (before 09:00 or after 17:00) reduces stress-induced hyperthermia and improves welfare. The physiological benchmarks from this study mean rectal temperatures by breed and coat colour under defined conditions can serve as early warning indicators for real-time monitoring. Producers with simple thermometers and basic training could implement routine thermal checks, measuring rectal temperature in representative animals (5-10% of herd) during hot periods and comparing against breed-specific benchmarks. Deviations $>0.5^{\circ}\text{C}$ above breed means would trigger responses (emergency shade, water,

movement to cooler areas) before stress becomes severe or life-threatening.

Study Limitations and Directions for Future Research

Despite valuable contributions, this study has several limitations worth noting. First, the cross-sectional observational design limits causal inference, even though the biophysical link between coat colour and solar absorption is well-established experimentally (Hutchinson & Brown, 1969; da Silva et al., 2003). Unmeasured confounders like individual acclimation history, hydration, disease burden, or recent reproduction could partially explain observed differences. While we tried to control major confounders through careful selection (healthy, non-lactating or early-gestation, similar body condition), residual confounding likely remains.

Second, data came from a single hot-dry season (March-April 2024), limiting ability to characterize temporal dynamics across seasons or years. Thermoregulatory capacity shows seasonal acclimatization, with prolonged heat exposure improving tolerance through physiological adjustments (heat shock proteins, cardiovascular changes, learned behaviours). Multi-seasonal or longitudinal studies tracking individuals across wet and dry seasons over multiple years would better capture these dynamics and distinguish genetic from plastic (acclimation) components.

Third, the study focused solely on coat colour without measuring other properties affecting heat transfer: hair density (fibers per cm^2), length, diameter, and reflectance spectrum. These physical traits can substantially modify heat transfer independently of colour: thick, dense coats provide more insulation (helpful in cold, harmful in heat), while sparse, short coats facilitate dissipation regardless of colour (Gebremedhin et al., 1997; Silva et al., 2003). Future work should include detailed coat characterization using microscopy (diameter, density counts), spectrometry (wavelength-specific reflectance across UV, visible, near-infrared), and infrared thermography to directly measure skin and surface temperatures in the field.

Fourth, we measured thermoregulatory responses but not performance outcomes like milk yield, growth rate, feed efficiency or reproductive success, the ultimate endpoints for production. Links between physiological stress indicators and productivity, though

generally well-established, show variable strength depending on context, management, and individual factors (Bernabucci et al., 2014). Longitudinal studies tracking individuals over extended periods (6-24 months) with repeated measurements of both physiology and production would strengthen understanding and provide more direct evidence for economic impacts.

Fifth, sample size, while adequate for detecting moderate-to-large effects (post-hoc power analysis showed achieved power >0.90 for main effects), may have been insufficient for detecting smaller effects or complex interactions. For example, potential interactions between coat colour and environmental factors (solar intensity, temperature, humidity) could not be rigorously tested due to limited environmental variation within our single-season collection period.

Future research should therefore pursue several directions. First, controlled experiments using climate chambers with precisely manipulated temperature, humidity, and simulated solar radiation would isolate specific coat colour effects from confounding breed genetics. Such studies could use matched pairs of light and dark animals from the same breed (utilizing within-breed variation in Wadara) exposed to identical conditions, providing clearer causal inference. Second, integration of physiological biomarkers beyond basic parameters would provide deeper mechanistic insights. Candidates include plasma cortisol (stress axis), heat shock proteins HSP70 and HSP90 (cellular stress), thyroid hormones T3 and T4 (metabolic adjustments), prolactin (sweating and hair growth regulation), glucose and non-esterified fatty acids (metabolic status), and oxidative stress markers like malondialdehyde (Bernabucci et al., 2010; Collier et al., 2019).

Third, direct measurement of performance including longitudinal monitoring of milk yield (daily records with portable meters), growth rates (monthly weighing), feed intake (feed disappearance or n-alkane markers), reproductive efficiency (calving intervals, conception rates, services per conception), and health records (disease incidence, mortality) would quantify economic impacts. Such data would enable cost-benefit analyses of breeding or management interventions targeting heat tolerance.

Fourth, molecular and genomic analyses could identify specific genes and alleles associated with thermal adaptation. Approaches might include genome-wide association studies using high-density SNP arrays or whole-genome sequencing to identify QTL for heat tolerance traits; candidate gene sequencing focusing on known thermotolerance genes (MC1R, ASIP, TYRP1 for pigmentation; HSP70, HSPA1A for stress; slick hair gene; prolactin receptor for sweating); transcriptomics (RNA-seq) comparing gene expression in heat-stressed versus thermoneutral animals; and population genomics (selection signatures) to identify regions under positive selection in heat-adapted breeds like Kuri (Dikmen et al., 2014). These genomic insights would enable molecular breeding tools (genomic selection, marker-assisted selection) to accelerate genetic improvement.

Fifth, systems modeling integrating physiological, environmental, and production data could enable predictive frameworks. Such models could predict animal performance and welfare under projected climate scenarios (2030, 2050, 2070-time horizons), evaluate alternative breeding and management strategies through simulation, optimize breed-by-environment matching to maximize productivity while maintaining welfare, and inform adaptation policy at national and regional scales (Thornton et al., 2021).

Broader Context and Significance for Tropical Livestock Adaptation

This study contributes to growing recognition that adaptive genetic diversity in tropical livestock is a critical resource for sustainable agricultural development under climate change (Mirkina et al., 2010; Sejian et al., 2018). Indigenous breeds like Kuri, Wadara, and Red Bororo represent outcomes of centuries or millennia of selection across diverse, challenging environments, equipping them with trait suites enabling survival and productivity where exotic temperate breeds would fail (Rege & Tawah, 1999; Adebambo, 2015). These adaptive complexes often include not just heat tolerance but also disease resistance (trypanosomiasis, tick-borne diseases), ability to use low-quality forages, tolerance of seasonal scarcity, and behavioural adaptations to extensive management.

The superior heat tolerance we documented in light-coated Kuri exemplifies the value of indigenous genetic resources. Rather than

trying to recreate heat tolerance in exotic breeds, a process requiring decades or centuries, indigenous breeds offer immediately available adaptive capacity deployable through conservation and enhanced utilization. Moreover, indigenous breeds often carry cultural value for traditional pastoralist communities, maintained not only for productivity but also for social status, ceremonies, and cultural identity (Blench, 1999). Conservation and development programs recognizing these cultural values alongside production goals are more likely to achieve sustainable outcomes than purely technical approaches.

Our findings also validate traditional ecological knowledge held by pastoralist communities who have long recognized and managed heat tolerance variation. Fulani pastoralists have developed sophisticated classification systems for cattle based on coat colour, conformation, horn shape, and behaviour, using these to guide breeding, grazing assignments, and valuations (Blench, 1999). Quantitative confirmation that light animals maintain core temperatures 0.8°C lower and breathing rates 32% reduced compared to dark animals scientifically validates these observations, creating opportunities for productive dialogue between knowledge systems. Such integration can enhance both cultural appropriateness and technical effectiveness of development programs.

The study also contributes to discussions of climate justice in agricultural systems. Tropical livestock keepers, especially pastoralists in arid and semi-arid regions, are among the most vulnerable to climate impacts yet contributed negligibly to greenhouse emissions driving warming (IPCC, 2023). Ensuring these communities access heat-tolerant genetics, appropriate breeding strategies, and supportive policies represents an adaptation imperative with important equity dimensions. International development programs, including those funded through climate finance like the Green Climate Fund and Adaptation Fund, should prioritize support for indigenous livestock conservation and breeding as climate adaptation investments.

Finally, our research highlights that climate adaptation in livestock requires multifaceted strategies integrating genetic, management, and policy interventions. No single approach;

genetic selection, breed substitution, improved management, or policy reform will alone ensure resilience. Rather, integrated strategies combining selection for heat-tolerant genetics within adapted indigenous breeds, strategic crossbreeding where appropriate, improved management tailored to specific breeds and environments, supportive policies for indigenous breed conservation and use, and enhanced market access for products from adapted breeds are most likely to achieve sustainable, equitable outcomes (Hoffmann, 2010; Mirkena et al., 2010).

Conclusions

This study provides clear evidence that coat colour significantly influences how well indigenous Nigerian cattle cope with heat under tropical field conditions. Animals with lighter coats showed superior heat dissipation, reflected in lower rectal temperatures (0.8°C reduction) and substantially reduced respiratory effort (32% lower breathing rates) compared to darker counterparts. While these differences appear moderate in absolute terms, they are biologically and economically meaningful given established links between core temperature elevation, respiratory stress, and productivity in tropical livestock. Specifically, Kuri cattle with predominantly white and cream coats displayed the most favourable physiological responses (rectal temperature $38.4 \pm 0.6^\circ\text{C}$, respiratory rate 38.9 ± 7.2 breaths/min), while Red Bororo cattle with deep red pigmentation showed greater heat stress susceptibility (rectal temperature $39.1 \pm 0.8^\circ\text{C}$, respiratory rate 50.7 ± 10.6 breaths/min). Wadara cattle performed intermediately, consistent with their diverse pigmentation.

Several key conclusions emerge. First, coat colour serves as a vital adaptive trait contributing substantially to heat tolerance in tropical cattle, with lighter pigmentation enhancing solar reflectivity and heat dissipation through well-characterized physical mechanisms. Effect size analyses showed coat colour explained 28.9% of rectal temperature variance and 36.2% of respiratory rate variance, a stronger predictor than breed identity, which explained 20.6% and 27.3% respectively. These moderate-to-large effect sizes indicate coat colour-based selection

would produce meaningful, detectable improvements in animal welfare and productivity.

Second, breed-level differences extend beyond coat colour, indicating multiple physiological and genetic adaptations shape thermoregulatory ability, especially in breeds like Kuri that evolved under extreme pressures. Kuri's superior performance even after accounting for coat colour effects suggests additional mechanisms including enhanced sweating, improved cardiovascular efficiency, reduced metabolic heat generation, or adaptive behaviours. This underscores the importance of conserving indigenous breeds as integrated packages of adaptive traits that evolved over centuries and would be difficult to recreate in exotic germplasm.

Third, the magnitude of coat colour effects specifically 0.8°C rectal temperature elevation and 32% respiratory rate increase between white and red/dark red animals approaches physiologically significant thresholds associated with compromised productivity. Research establishes that sustained core temperatures above 39.5°C trigger substantial declines in feed intake (10-35%), milk production (10-40%), growth rates (15-30%), and reproduction (20-30% lower conception rates). The temperatures and breathing rates we measured in darker animals under field conditions approached or exceeded these critical thresholds, emphasizing practical importance for welfare and economic sustainability.

Fourth, selective breeding for heat tolerance incorporating coat colour alongside other adaptive traits can improve cattle resilience and welfare in tropical systems. Selection indices should weight coat pigmentation at roughly 15-25% alongside production traits given its substantial contribution to thermoregulatory variance. Within-breed programs should identify and preferentially breed individuals combining lighter pigmentation with superior production, using both traditional phenotypic evaluation and emerging genomic tools. Strategic crossbreeding could introduce heat tolerance genes from breeds like Kuri into higher-producing but less heat-tolerant breeds, though

care is needed to maintain diversity and avoid losing other valuable adaptations.

Fifth, breed-specific management practices, particularly enhanced shading and hydration for darker breeds, are essential complements to genetic approaches. For Red Bororo in areas experiencing $>800 \text{ W/m}^2$ solar radiation, shade reducing solar load by 60-70% could theoretically lower rectal temperature by 0.5-0.7°C, substantially improving comfort and productivity. Water availability must be ensured at levels 50-100% above normal to support enhanced evaporative cooling demands during heat periods.

Given projected climate change and escalating heat stress in tropical environments, with thermal stress periods potentially extending from current 1-2 months to 4-6 months annually by mid-century, these findings offer evidence-based guidance for sustaining livestock productivity while preserving indigenous adaptive traits and animal welfare. The study demonstrates that indigenous cattle breeds possess valuable heat tolerance traits that should be conserved, characterized, and strategically used rather than replaced by exotic germplasm poorly adapted to tropical conditions. Climate-resilient livestock development requires integrated strategies combining genetic selection within adapted breeds, conservation of indigenous genetic resources, breed-appropriate management interventions, and supportive policies recognizing both productive and cultural values of indigenous livestock.

Future research should deepen understanding through controlled environmental trials isolating specific heat tolerance mechanisms, genomic investigations identifying genes and alleles underlying thermal adaptation, longitudinal monitoring linking thermoregulatory physiology with production and reproductive outcomes across seasons and years, and systems modeling to predict performance under diverse climate scenarios and evaluate alternative adaptation strategies. Integrating phenotypic, environmental, genomic, and economic data will be essential for designing sustainable, equitable breeding programs that enhance livestock resilience to climate change while supporting livelihoods of

tropical livestock keepers. As global temperatures continue rising and heat stress intensifies, the adaptive genetic diversity preserved in indigenous breeds like Kuri, Wadara, and Red Bororo represents an increasingly valuable resource that must be conserved and strategically deployed to ensure food security and sustainable livestock production in tropical regions.

Conflict of Interest

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