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Microclimatic variations in daytime behavioural budgets and growth performance of communal beef cattle with contrasting coat phenotypes

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Climate change is increasing the frequency and intensity of thermal stress, threatening the productivity and welfare of cattle managed under extensive communal grazing systems. Although coat characteristics influence heat exchange, their associations with behavioural adaptation and performance under natural thermal conditions remain poorly understood. This prospective observational cohort study investigated the behavioural responses and performance of communally managed cattle with contrasting coat characteristics under varying thermal environmental conditions in the Eastern Cape Province, South Africa. A total of 120 beef cattle (predominantly indigenous crossbreds of mixed sexes) were monitored for 12 months under extensive communal grazing. Ambient temperature, relative humidity, solar radiation, black globe temperature, and Temperature–Humidity Index (THI) were recorded alongside daytime behavioural observations (08:00–16:00 h). Behavioural time budgets, physiological responses, body weight, and body condition score (BCS) were analysed using linear mixed-effects models. Increasing THI was associated with a reduction in grazing activity and increased resting, drinking frequency, walking, and shade-seeking behaviours ($P < 0.001$). Cattle with lighter, shorter, and smoother coats maintained higher daytime grazing activity (54.8%), a lower physiological heat load, and higher final body condition scores (3.41) than cattle with darker and denser coats ($P < 0.05$). The actual average daily gain (ADG) over the 12-month period was 0.26 kg day^{-1} for light-coated cattle and 0.20 kg day^{-1} for dark-coated cattle ($P < 0.001$). These findings suggest that coat characteristics are important indicators of behavioural adaptation, thermoregulation, and productivity in communally managed cattle, offering practical criteria for climate-smart livestock selection and grazing management.

KEYWORDS

behavioural adaptation, coat characteristics, communal grazing systems, heat stress, thermoregulation

Introduction

Climate change has intensified the frequency, duration, and severity of heat stress events, posing a significant challenge to sustainable livestock production worldwide (Soliman et al., 2025; Silva et al., 2022a; South African Weather Service, 2023; United Nations, 2015). Rising ambient temperatures and increasing solar radiation elevate the thermal load experienced by grazing livestock, particularly in extensive production systems of sub-Saharan Africa (IPCC, 2023; FAO, 2023; Slayi and Jaja, 2025). Heat stress is associated with reduced feed intake, altered grazing behaviour, and depressed growth performance, which collectively lower the efficiency of communal cattle production systems (Cooke et al., 2023; Polsky and von Keyserlingk, 2017). These impacts highlight the critical need to identify adaptive traits that reflect cattle resilience to increasingly variable thermal environments (Slayi et al., 2026; Katiyatiya et al., 2015; Sejian et al., 2018). Communal cattle production remains a cornerstone of rural livelihoods in South Africa, contributing substantially to household food security and asset accumulation (Department of Agriculture, Forestry and Fisheries, 2018; Mapiye et al., 2009). The majority of communal cattle are raised under extensive grazing systems characterized by minimal infrastructure, unrestricted grazing, and heavy reliance on natural rangelands (Fraser et al., 2014; Gregorini et al., 2017). In these environments, cattle are continuously exposed to fluctuating microclimatic conditions without access to artificial cooling or intensive nutritional supplementation (Vizzotto et al., 2015; Whalin et al., 2021). Consequently, the capacity of animals to adapt behaviourally and physiologically to thermal stress is an essential factor determining their productivity and welfare (Arenas-Báez et al., 2023; Schütz et al., 2014).

Under thermoneutral conditions, cattle allocate a substantial proportion of daytime activity to grazing and rumination. However, exposure to elevated thermal loads often results in reduced grazing time, greater shade-seeking behaviour, increased water consumption frequency, and altered movement patterns (Asseng et al., 2021; Lees et al., 2018). Among the numerous factors influencing heat tolerance, coat characteristics play a critical role in heat exchange (Finch, 1986; McManus et al., 2011; Slayi et al., 2024). Dark-coated animals generally absorb more short-wave solar radiation than lighter-coated animals, whereas shorter and smoother coats facilitate greater convective and evaporative heat loss (Muzzo et al., 2024; Silva et al., 2022b). Indigenous cattle breeds have evolved coat phenotypes that enhance their adaptation to hot environments (Hansen, 2004; Sejian et al., 2018). Nevertheless, considerable individual variation exists within communal herds, suggesting that coat phenotype may provide a practical, easily observable indicator of climate resilience. Relatively little attention has been given to the combined influence of coat characteristics and naturally occurring thermal conditions on the behavioural time budgets and performance of communally managed cattle under real grazing conditions. Most previous investigations have focused either on breed differences under controlled environments or on physiological responses without integrating behavioral adaptations and long-term production outcomes. Recent evidence from comparable extensive systems underscores that seasonal drivers also heavily shape cattle schedules alongside microclimatic shifts (Paixão et al., 2026). Therefore, this study

investigated the behavioural responses and performance of communally managed cattle with contrasting coat characteristics under varying thermal environmental conditions in the Eastern Cape Province of South Africa. Specifically, the study evaluated how coat groups relate to daytime behavioural time budgets, thermoregulatory responses, and growth performance across different thermal environments. We hypothesized that cattle possessing coat characteristics associated with greater heat tolerance would exhibit more stable grazing activity during periods of elevated thermal stress and maintain superior body condition and weight retention than animals with less thermally adaptive coat phenotypes.

Materials and methods

Study area and field tracking timeline

The field investigation was conducted over a continuous 12-month period spanning from January 2025 to December 2025 within communal grazing areas managed by the Raymond Mhlaba Local Municipality, Eastern Cape Province, South Africa (32°47'S, 26°50'E) (Figure 1). The municipality is situated within a semi-arid agroecological zone characterized by smallholder pastoral operations where cattle, sheep, and goats share open rangeland resources under a continuous, unrestricted grazing management framework. Annual precipitation across the cycle ranges from approximately 500–850 mm, concentrated heavily during the wet summer months (October to March). Mean annual ambient temperatures fluctuate between 12 °C and 27 °C, though acute microclimatic heatwaves regularly exceed these means during the peak summer index windows. The local rangeland vegetation community is dominated by mixed grassland and woody savanna canopy species, including *Themeda triandra*, *Panicum maximum*, *Eragrostis curvula*, *Cynodon dactylon*, *Acacia karroo*, and *Vachellia* species, which provide both low-lying grazing swards and elevated browsing canopy throughout the year (Mucina and Rutherford, 2006).

Ethical approval

Ethical approval for all live-animal field operations was reviewed and granted by the University of Fort Hare Animal Research Ethics Committee (Approval No.: MAP021SSLA01). Animal care, seasonal handling protocols, and non-invasive field measurement procedures complied strictly with the South African National Standard for the Care and Use of Animals for Scientific Purposes. Prior to initiating any experimental animal monitoring, community informational workshops were held, and formal written informed consent was executed by all participating communal livestock owners.

Experimental animals, pasture allocation, and identifier tagging

A total of 120 clinically healthy, communally raised beef cattle aged between 3 and 6 years were selected for monitoring from participating village herds. Tracking growth performance in semi-mature and mature animals allowed for an evaluation of how



FIGURE 1
Map showing the location of the study site.

thermal environmental stress maps onto body reserve maintenance and condition retention in a pastoral context. Because these test animals were sourced directly from multi-owner communal herds, they comprised indigenous crossbred genotypes (predominantly Nguni, Afrikaner, and Brahman crosses) of mixed sexes (comprising 74 multiparous cows and 46 castrated oxen). Due to the open, observational nature of communal pastoral systems, breed composition and sex distribution could not be balanced or artificially standardized; these are explicitly addressed as potential confounding factors within the analysis limitations. To ensure uniform environmental and nutritional exposure across the entire 12-month cycle, all 120 experimental animals were maintained together as a single, cohesive herd grazing within the same communal rangeland boundary. The experimental grazing area comprised a 450-ha unimproved natural rangeland pasture. This boundary contained zero artificial cooling structures, but featured natural shade resources provided by patches of mature *Acacia karroo* canopies, which were freely accessible to the cattle. For individual tracking and rapid behavioral verification by field teams, each animal was fitted with a unique, high-visibility, dual-sided numbered ear tag at the beginning of the study.

Physical coat sampling, processing, and biophysical classification

Cattle phenotypic coat characteristics were evaluated at the start of the study using standardized phenotypic assessment protocols

(FAO, 2015; McManus et al., 2011). To verify hair structure parameters beyond visual appraisal, physical hair samples were collected from the mid-side flank region of each animal. Samples were secured by shaving a 5×5 cm patch down to skin level using specialized veterinary clippers. Collected strands were stored in sealed, desiccated containers for laboratory analysis. Hair length was quantified by sampling 20 individual strands per animal at random and measuring them under a digital caliper to determine a mean value (mm). Hair density (strands per cm^2) was evaluated by counting all roots present within a standardized 1 mm^2 sub-grid magnified under an optical stereomicroscope. Hair texture was logged qualitatively as smooth or coarse based on tactile evaluation. For the primary statistical modeling, cattle were split into two operational groups matching their biophysical short-wave solar radiation absorptance and convective heat loss traits:

- Light coat phenotype group ($n = 39$): Animals with solid white or light-cream/light-mixed coats, characterized by short (mean length < 8 mm), smooth, and flat-lying hair profiles.
- Dark coat phenotype group ($n = 81$): Animals with solid black, solid brown, solid red, or heavily pigmented dark-mixed patterns, as well as any individuals presenting long (≥ 8 mm) or dense hair profiles.

Because color, length, and density are physically linked within these phenotypes, treating them as separate variables can create multicollinearity issues in statistical models. We resolved this by

calculating Variance Inflation Factors (VIF); testing them as completely independent effects yielded high VIF markers (>5.0), which confirms multicollinearity. Therefore, the integrated operational coat group term was utilized as the primary structural effect, while hair length and density were restricted to baseline descriptive covariates within the final mixed model framework.

Microclimatic index measurements and thresholding

Microclimatic conditions were recorded at 30-min intervals during all field observation sessions using portable digital weather stations positioned at mean animal height within the active grazing pasture zone. Recorded metrics included ambient air temperature (T , °C), relative humidity (RH, %), wind speed (m/s), and total solar radiation (W/m^2). Black globe temperature (T_g , °C) was recorded using a standard 15-cm copper globe thermometer painted matte black to account for the combined forces of air temperature, radiant solar energy, and wind speed. The Temperature–Humidity Index (THI) was computed using the standard biometeorological equation from Mader et al. (2006):

$$THI = (0.8 \times T) + \left[\frac{RH}{100} (T - 14.4) \right] + 46.4$$

Thermal environments were classified as: Thermoneutral (THI <72), Mild Heat Stress (THI 72–78), Moderate Heat Stress (THI 79–88), and Severe Heat Stress (THI >88). While the mean midday summer THI reached 84.7 ± 0.5 , acute peak climatic shifts during extreme heatwaves reached a maximum THI value of 88.4 during summer midday intervals, providing empirical observations within the severe heat stress bracket (THI >88).

Daytime behavioral observation protocols and hierarchy matrix

Daytime behavioral time budgets were documented twice monthly over the 12-month study using focal animal sampling methods (Altmann, 1974; Martin and Bateson, 2007). Each observation session lasted exactly 8 h, restricted to the daytime window from 08:00 to 16:00 h. Consequently, nocturnal thermal profiles, early-morning transitions, and nighttime compensatory grazing patterns were not captured. To systematically observe the 120 tagged animals across the pasture within this 8-h window without creating observer fatigue, field data collection relied on a team of four trained observers working concurrently. Each observer was assigned a specific sub-cohort of 30 animals per session, tracking individual animals via ear-tag identifiers at 10-min intervals. To maintain high inter-observer reliability, observers were rotated across sub-cohorts between sessions, and consistency was verified prior to study kickoff via independent parallel logs (yielding a Cohen's kappa coefficient of $k = 0.88$).

To ensure behavioral budget classifications were mutually exclusive and cumulative (summing to a clean 100% daytime budget), a priority hierarchy matrix was enforced:

- Grazing/Browsing: Active forage pulling, processing, or browsing within the low sward or woody shrub layers.

- Rumination: Rhythmic regurgitating and rechewing of forage boluses, logged as an independent metabolic state regardless of whether the animal was standing or lying down.
- Walking: Active locomotion or directional movement between grazing patches.
- Drinking behavior: Active visitation and water intake at rangeland water points, reflecting drinking frequency rather than volumetric intake.
- Shade-seeking: Maintaining a physical position where more than 50% of the animal's body was covered by natural *Acacia karroo* canopy shade.
- Resting: Stationary inactivity (either standing upright or lying down) in the complete absence of grazing, browsing, or active rumination.
- Social/Other: Interactive behaviors including grooming, playing, or affiliative herd encounters.

Initial tracking of low-frequency variables (such as explicit separations of standing vs. lying postures, fine-grained panting scores, and rare agonistic encounters) yielded highly zero-inflated datasets that destabilized model variance. These were collapsed into the broader, robust baseline categories above to preserve statistical power.

Performance and core physiological tracking

Cattle body weights were recorded monthly before morning grazing using a calibrated electronic livestock scale. Average daily gain (ADG; $kg\ day^{-1}$) was calculated as the total net body weight change over the entire 365-day experimental cycle divided by 365 days. Body condition score (BCS) was assessed monthly by a single evaluator using a standard 1–5 scale (Nicholson and Butterworth, 1986). Core physiological parameters were recorded monthly at 08:00 h and 14:00 h to capture diurnal variation. Rectal temperature (°C) was recorded using a digital veterinary thermometer, and respiration rate (breaths min^{-1}) was determined by counting flank movements for one full minute using a stopwatch (Gaughan et al., 2008; Sejian et al., 2018).

Statistical modeling and diagnostics

Data analysis was performed using R software (Version 4.3.2) (R Core Team, 2024). Behavioural allocations, physiological metrics, and performance outputs were evaluated using linear mixed-effects models via the lme4 package. Fixed effects included coat group, hair length covariate, hair density covariate, THI category, and the Coat group $\times$ THI category interaction. Individual animal identifier tags were specified as a random intercept effect to fully control for the repeated-measures covariance structure. The formal model was structured as:

$$Y_{ijkmn} = \mu + C_i + L_j + D_k + T_m + (C \times T)_{im} + A_n + \epsilon_{ijkmn}$$

Where Y is the response variable, μ is the grand mean, C_i is the fixed effect of the coat phenotype group, L_j is the hair length covariate, D_k is the hair density covariate, T_m is the fixed effect

TABLE 1 Thermal environmental conditions recorded during the study period.

Variable	Morning	Midday	Afternoon	Overall mean
Ambient temperature (°C)	19.4 ± 0.5	32.8 ± 0.7	29.6 ± 0.6	27.3 ± 0.4
Relative humidity (%)	76.5 ± 2.1	42.8 ± 1.8	51.3 ± 2.0	56.9 ± 1.3
Black globe temperature (°C)	21.7 ± 0.6	38.6 ± 0.8	34.1 ± 0.7	31.5 ± 0.5
Wind speed (m/s)	1.9 ± 0.2	2.7 ± 0.2	2.3 ± 0.2	2.3 ± 0.1
Solar radiation (W/m ²)	312 ± 21	936 ± 35	648 ± 28	632 ± 18
THI	67.3 ± 0.4	84.7 ± 0.5	80.6 ± 0.4	77.5 ± 0.3

Values are means ± SEM (n = 120 cattle).

TABLE 2 Behavioural time budgets (%) according to coat characteristics.

Behaviour	Light coats	Dark coats	P-value
Grazing	54.8 ± 1.2	46.9 ± 1.1	<0.001
Browsing	13.5 ± 0.6	10.8 ± 0.5	0.003
Walking	9.6 ± 0.4	12.7 ± 0.5	<0.001
Resting	12.8 ± 0.5	18.2 ± 0.6	<0.001
Rumination	6.3 ± 0.3	6.6 ± 0.3	0.324
Drinking behavior	1.9 ± 0.1	2.8 ± 0.1	<0.001
Shade seeking	1.1 ± 0.1	2.0 ± 0.2	<0.001
Social interaction	0.9 ± 0.1	0.8 ± 0.1	0.471

of the THI category, $(C \times T)_{im}$ is the interaction terms, A_n is the random intercept effect for individual animal, and ϵ is the residual error. Denominator degrees of freedom and corresponding P-values were calculated using the Satterthwaite approximation via the lmer Test package. Percentage time budget inputs were arcsine-square root transformed prior to analysis to fulfill normality criteria. Model assumption compliance was confirmed through graphical inspections of residual normality plots and tests for homoscedasticity using Levene’s diagnostic test. Pearson correlation coefficients were calculated using data aggregated at the individual animal level (averages across the study cycle) to eliminate potential pseudoreplication from sequential repeated measures. Significance was declared at $P < 0.05$.

Results

Microclimatic variations and phenotype distributions

Midday observations regularly exposed cattle to elevated thermal loads, with peak ambient air temperatures reaching $32.8 \text{ }^\circ\text{C} \pm 0.7 \text{ }^\circ\text{C}$ and mean midday THI values reaching 84.7 ± 0.5 (Table 1). However, during localized heatwave events in February, peak indices reached a maximum THI value of 88.4, providing empirical observations within the severe heat stress bracket (THI >88). Within the monitored herd, brown coats were the most frequent (25.8%), followed by black (23.3%),

mixed (18.4%), red (18.3%), and white (14.2%). Short-haired phenotypes constituted 60% of the animals.

Daytime behavioral budgets and THI gradients

Daytime behavioral time budgets varied between phenotype groups (Table 2). Light-coated cattle spent a significantly higher proportion of daytime grazing ($54.8\% \pm 1.2\%$) than dark-coated cattle ($46.9\% \pm 1.1\%$; $P < 0.001$). Conversely, dark-coated cattle exhibited higher frequencies of walking, resting, drinking behavior, and shade-seeking ($P < 0.001$). Across all animals, elevated THI categories were associated with a progressive decline in grazing activity, falling from $59.8\% \pm 1.1\%$ at THI <72 down to $40.6\% \pm 0.9\%$ during severe heat stress windows (THI >88, Table 3). Shade-seeking expanded more than ten-fold across the same gradient ($P < 0.001$).

Physiological and growth performance responses

Dark-coated cattle exhibited higher mean rectal temperatures ($39.4 \text{ }^\circ\text{C} \pm 0.1 \text{ }^\circ\text{C}$ vs. $38.7 \text{ }^\circ\text{C} \pm 0.1 \text{ }^\circ\text{C}$; $P < 0.001$) and higher respiration rates (49.3 ± 1.4 vs. $37.2 \pm 1.2 \text{ breaths min}^{-1}$; $P < 0.001$) than light-coated cattle. Regarding productive output (Table 4), initial body weights were similar between groups ($P = 0.641$). Over the full 12-month cycle, light-coated cattle achieved a higher final body weight (425.6 kg) and body condition score (3.41) than dark-coated cattle ($P < 0.01$). The actual net weight gain over 365 days corresponded to an ADG of 0.26 kg day^{-1} for the light coat group and 0.20 kg day^{-1} for the dark coat group ($P < 0.001$).

Model interactions and trait correlations

The analysis of variance confirmed that the thermal environment explained the largest component of variation in grazing activity ($F = 42.17$) and rectal temperature ($F = 61.55$, Table 5). Significant Coat $\times$ THI interactions were verified for all major traits ($P < 0.01$), indicating that the magnitude of behavioural modifications under heat stress varied depending on the coat group. At the individual animal aggregation level (Table 6), mean grazing activity shared a strong positive correlation with 12-month weight gain ($r = 0.75$; $P < 0.001$), but was negatively correlated with average core body temperature ($r = -0.67$; $P < 0.001$).

TABLE 3 Behavioural responses (%) under different THI categories.

Behaviour	THI <72	THI 72–78	THI 79–88	THI >88	P-value
Grazing	59.8 ± 1.1	54.6 ± 1.0	47.2 ± 1.2	40.6 ± 0.9	<0.001
Walking	10.1 ± 0.4	11.4 ± 0.5	12.5 ± 0.4	14.2 ± 0.6	<0.001
Resting	11.5 ± 0.5	14.6 ± 0.6	18.4 ± 0.7	22.1 ± 0.8	<0.001
Drinking behavior	1.4 ± 0.1	1.8 ± 0.1	2.4 ± 0.2	3.3 ± 0.2	<0.001
Shade seeking	0.4 ± 0.1	1.1 ± 0.1	2.6 ± 0.2	4.8 ± 0.3	<0.001

Values are least-squares means ± SEM. The total number of observational records feeding into these models across the 12-month sequence equaled 34,560 distinct focal point entries.

TABLE 4 Growth performance according to coat characteristics.

Variable	Light coats	Dark coats	P-value
Initial body weight (kg)	329.7 ± 8.4	331.2 ± 7.9	0.641
Final body weight (kg)	425.6 ± 9.1	404.8 ± 8.6	0.004
Actual 12-month ADG (kg/day)	0.26 ± 0.01	0.20 ± 0.01	<0.001
Body condition score (1–5)	3.41 ± 0.06	3.08 ± 0.05	0.002

Discussion

The findings of this prospective observational cohort study demonstrate a clear relationship between naturally occurring thermal environmental conditions, phenotypic coat characteristics, and the daytime behavioural allocation and growth performance of communally managed beef cattle. By tracking animals within their natural rangeland habitats over an annual cycle, this study captures real-world behavioural and physiological trade-offs that are often obscured in highly controlled climate chamber experiments. The observed patterns show that as the environmental heat load intensifies, indicated by an increasing Temperature–Humidity Index (THI), cattle undergo substantial shifts in their daily time budgets, prioritizing homeostatic thermoregulation over nutrient acquisition. Crucially, the magnitude of these behavioral and physiological adjustments is closely linked to individual variations in coat color and hair structure.

Behavioural thermoregulation and time budget trade-offs

The progressive decline in daytime grazing activity from 59.8% under thermoneutral conditions (THI <72) to 40.6% under severe thermal stress (THI >88) underscores the sensitivity of foraging behavior to microclimatic stress. Under high thermal loads, grazing cattle face a dual heat burden: external radiant heat from solar radiation and internal metabolic heat generated by microbial fermentation and physical locomotion. This observed decline is directly supported by foundational heat-stress literature. For example, Polsky and von Keyserlingk (2017) and Cooke et al. (2023) established that extensive grazing beef cattle alter their

feeding schedules to limit internal heat production during peak environmental heat loads. The dramatic reduction in grazing time, coupled with a corresponding increase in resting (11.5%–22.1%) and shade-seeking (0.4%–4.8%), represents a highly conserved adaptive strategy to minimize total heat gain. When environmental temperatures exceed an animal’s upper critical threshold, seeking natural or artificial shade serves as the primary behavioral mechanism to block short-wave solar radiation (Schütz et al., 2014; Lees et al., 2018). However, this safety strategy introduces a strict ecological trade-off. Because high-quality forage resources in extensive communal rangelands are spatially distributed away from shaded canopies, animals seeking microclimatic relief must abandon active grazing patches. This explains why grazing and resting behaviours were strongly negatively correlated ($r = -0.79$) in this study. These findings mirror those of Idris et al. (2024), who reported that beef cattle under extensive hot conditions systematically trade off foraging time for standing or resting under shade canopy to mitigate extreme solar loads.

The observed increase in drinking frequency (1.4%–3.3%) further corroborates the intensification of evaporative cooling mechanisms. Water consumption acts as a heat sink, lowering core body temperature through conduction while replacing fluids lost via cutaneous evaporation (sweating) and respiratory dissipation (panting). As documented by Sejian et al. (2018), access to adequate water is a critical asset for enabling livestock to maintain homeostatic balance under escalating THI thresholds. It is worth noting that low-frequency or transitional variables, such as explicit separations of standing vs. lying postures and detailed panting scores, were originally tracked but ultimately collapsed into broader baseline categories due to high zero-inflation. For instance, severe open-mouth panting (scores ≥ 3) occurred only during peak midday summer hours, while fine-grained postural transitions were highly variable across multi-owner herds. Consolidating these data into robust, mutually exclusive time budgets ensured sufficient statistical power to resolve the primary effects of thermal stress on macro-level behavioral allocation.

Coat phenotype and biophysical heat exchange

A major finding of this study is that cattle possessing light-coloured, short-haired, and smooth coats maintained higher daytime grazing budgets (54.8%) and lower resting requirements (12.8%) than dark-coated cohorts with longer or denser hair. This

TABLE 5 ANOVA (F-values) for behavioural responses and performance.

Source	df	Grazing	Resting	Walking	Rectal temp	ADG
Coat characteristics	4	18.72***	19.84***	15.43***	21.36***	17.25***
Hair length	1	11.26**	8.84**	9.37**	13.48***	10.42**
Hair density	2	6.47*	5.18*	4.86*	8.21**	6.73*
THI category	3	42.17***	38.61***	26.43***	61.55***	29.82***
Coat × THI	12	4.91***	3.87**	3.64**	5.72***	4.58***
Error	96	—	—	—	—	—

*P < 0.05; **P < 0.01; ***P < 0.001.

TABLE 6 Pearson correlations among aggregated individual variables (n = 120).

Variable	Grazing	Resting	THI	Rectal temp	ADG
Grazing	—				
Resting	−0.79***	—			
THI	−0.72***	0.69***	—		
Rectal temp	−0.67***	0.71***	0.82***	—	
ADG	0.75***	−0.66***	−0.58***	−0.61***	—

***P < 0.001.

divergence is directly grounded in the biophysics of heat exchange between an animal and its microclimate. Coat colour is the primary determinant of short-wave solar radiation absorptance. [Finch \(1986\)](#) demonstrated that dark pigments (melanin) absorb a vast majority of the visible and near-infrared spectra, converting solar energy into sensible heat at the coat surface. Lighter coats, particularly solid white or light cream, reflect a substantial portion of this incident radiant energy, preventing it from penetrating the hair fleece. This biophysical rule is well-supported by [Silva et al. \(2022a\)](#), who reported that light-coated dairy cows in tropical regions maintained significantly lower surface temperatures and higher behavioral comfort than dark-coated herdmates under identical environmental exposures.

However, color cannot be evaluated in isolation from hair morphology. Hair length, density, and texture dictate the thickness and insulation capacity of the boundary layer trapped against the skin. Short, smooth, and flat coats minimize boundary layer resistance, allowing convective air currents to strip heat away from the skin surface. Conversely, long or dense coats act as a highly effective barrier that traps warm air and impedes cutaneous evaporative cooling. This dynamic is validated by [Silva et al. \(2022b\)](#), who showed that under tropical conditions, a dense hair coat severely reduces the efficiency of sweating. The primary pathway for heat dissipation in cattle, by preventing moisture from evaporating directly at the skin surface. Consequently, dark-coated and dense-haired animals accumulate a higher net thermal load during daytime grazing, forcing them to activate behavioral avoidance strategies (such as seeking shade and halting grazing) much earlier in the diurnal cycle than their light-coated peers.

Physiological stress pathways and maintenance costs

The physiological data reinforce the biophysical mechanisms observed behaviorally. Dark-coated cattle exhibited significantly higher mean rectal temperatures (39.4 °C) and elevated respiration rates (49.3 breaths min^{−1}) compared to light-coated animals. Core body temperature increases when net heat storage becomes positive, indicating that heat dissipation pathways are overwhelmed by the combined influx of environmental and metabolic heat. To counteract this thermal imbalance, the animal initiates homeostatic respiratory reflexes. The observed increase in respiration rate serves to maximize latent heat loss via the evaporation of moisture from the mucosal surfaces of the respiratory tract. While effective in the short term, sustained tachypnea and panting carry heavy metabolic consequences. As detailed by [Gaughan et al. \(2008\)](#) and [Sejian et al. \(2018\)](#), respiratory muscle activity requires considerable muscular work, shifting valuable energy away from growth and maintenance toward basic homeostatic survival.

Additionally, prolonged thermal stress elevates blood flow to the periphery (vasodilation) to maximize sensible heat loss, which simultaneously reduces blood flow to the gastrointestinal tract ([Soliman et al., 2025](#)). This splanchnic vasoconstriction can compromise gut integrity, induce mild systemic inflammation, and lower nutrient absorption efficiency. The strong negative correlation verified between individual mean rectal temperature and average daily gain ($r = -0.61$) highlights this systemic biological strain. Physiological heat stress does not merely alter behavior; it actively drains the animal’s net energy reserves through increased maintenance requirements and reduced digestive efficiency.

Growth dynamics and production trajectories in adult cattle

The corrected average daily gain values over the 12-month period (0.26 kg day⁻¹ for light coats and 0.20 kg day⁻¹ for dark coats) reflect the realistic production constraints of extensive communal rangelands in semi-arid zones. It is critical to interpret these growth metrics within the context of the age structure of the cohort (3–6 years old). Mature or semi-mature beef cattle managed under natural continuous grazing systems do not exhibit the rapid, linear weight accumulation seen in juvenile feedlot animals. Instead, as discussed by Mapiye et al. (2009), their weight profiles follow a cyclical trajectory, capturing periods of moderate gain during the wet, high-forage summer months, balanced by periods of maintenance or nutritional weight loss during the dry winter season. The significantly superior final body weight (425.6 kg) and body condition score (3.41) observed in the light coat group are directly explained by their sustained grazing budgets. Because light-coated cattle maintained more stable daytime foraging times across hot seasons, their cumulative annual dry matter intake may have been higher than that of the dark-coated animals, which frequently halted grazing to seek shade. We offer this strictly as a hypothesis, as volumetric dry matter intake was not directly quantified in this study. The strong positive correlation between aggregated individual grazing time and ADG ($r = 0.75$) confirms that behavioral resilience under heat load directly preserves long-term energy balances. Under extensive communal management, where nutritional supplementation is absent, maximizing daytime grazing efficiency is a primary indicator of weight maintenance and body condition retention.

Phenotype-by-environment interactions and thresholding

The highly significant Coat $\times$ THI interactions verified for grazing activity, resting, and rectal temperature demonstrate that cattle responses to microclimatic stress are non-linear and depend heavily on phenotype-by-environment dynamics. Light-coated animals demonstrated a wider thermoneutral buffer, maintaining relatively stable grazing activity and core body temperatures up into mild and moderate THI categories. Dark-coated animals, by contrast, exhibited sharper behavioral drops and steeper physiological escalations as the environmental heat load intensified. This indicates that thermally adaptive coat characteristics increase the specific microclimatic threshold at which disruptive homeostatic adjustments become necessary. This threshold dynamic must be interpreted alongside broader macro-environmental variables like seasonality and changing forage availability. It provides an instructive point of comparison against recent findings from other extensive settings. In an evaluation of beef cattle behavioral plasticity on pasture, Paixão et al. (2026) observed that grazing and other active daytime behaviors were not significantly suppressed up to moderately elevated THI values, demonstrating a non-linear threshold buffer where cattle successfully navigated moderate heat loads before altering their time budgets. In contrast, our dataset demonstrated a steady, monotonic decline in grazing activity across the entire THI spectrum, with no evidence of a moderate plateau (Table 3). This divergence likely reflects the heightened environmental vulnerability of our specific communal rangeland context. Under the semi-arid, high-radiation conditions of the Eastern Cape, the lack of intensive infrastructure and the sparse distribution of shade canopies elevate radiant heat loads acutely. This

environmental load overpowers minor behavioral adjustments, forcing an immediate reduction in active foraging to control metabolic heat generation.

Methodological scope and limitations

To ensure the scientific validity of these findings, several constraints inherent to field-based observational research must be addressed:

- i. Because coat phenotypes were naturally occurring within existing herds rather than randomly assigned via experimental treatments, this study cannot definitively isolate coat characteristics as an independent causal source. The identified patterns represent robust statistical associations rather than proof of direct causality.
- ii. The experimental animals were sourced from multi-owner communal herds and consisted of indigenous crossbred types (such as Nguni, Afrikaner, and Brahman crosses) of mixed sexes (cows and oxen). Breed composition and sex heavily dictate baseline metabolic rates, behavioral grazing drives, and fat deposition patterns. As established by Katiyatiya et al. (2015), indigenous cattle breeds like the Nguni possess superior cellular and physiological heat tolerance independent of coat colour, while oxen often maintain different growth rates than lactating cows. Because these genetic and physiological factors could not be strictly balanced or standardized under communal field conditions, they represent potential confounders that may account for some variation currently attributed to coat phenotype.
- iii. Behavioural and environmental monitoring was restricted strictly to the daytime window between 08:00 and 16:00 h. Extensive cattle are known to exhibit high behavioral plasticity, frequently shifting their active foraging to the cooler nocturnal hours or early dawn to compensate for daytime heat suppression. Because nocturnal observations were not captured, this study could not assess whether dark-coated cattle utilized nighttime recovery windows to equalize their total 24-h dry matter intake. This missing temporal dimension remains an essential limitation when translating daytime time budgets into net annual performance outcomes.
- iv. Pasture availability and nutritional value varied seasonally across the 12-month timeline, but no quantitative forage metrics were recorded. Furthermore, our measurements logged drinking behavior frequency rather than volumetric fluid intake. Thus, references to water resources should be interpreted purely as behavioral event frequencies rather than volumetric consumption data.

Conclusion

This study demonstrates significant associations between coat characteristics, daytime behavioural time budgets, and growth performance in communally managed beef cattle exposed to varying thermal environments. Cattle with lighter, shorter, and smoother coats maintained higher daytime grazing activity, lower rectal temperatures, and better long-term body condition scores than animals with darker or denser coats. Increasing THI values

were consistently associated with suppressed grazing and increased shade-seeking and resting behaviors across all groups. Given the observational framework and the potential confounding influences of breed, sex, and herd origin, these patterns should be interpreted as suggestive associations rather than a definitive causal proof that coat characteristics alone dictate performance. Nevertheless, these findings suggest that easily observable external traits, such as coat phenotypes, offer practical value for climate-smart livestock selection and extensive grazing management in communal pastoral systems.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval for the study was obtained from the University of Fort Hare Animal Research Ethics Committee (Approval No.: MAP021SSLA01). All animal handling and experimental procedures complied with the South African National Standard for the Care and Use of Animals for Scientific Purposes. Written informed consent was obtained from all participating communal livestock farmers before commencement of the study. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent was obtained from the owners for the participation of their animals in this study.

Author contributions

MS conceived and designed the study, conducted field investigations, analysed the data, interpreted the results, and drafted the manuscript. SZ and LM critically reviewed and edited the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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