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Climate Variability and Dairy Cattle Welfare in Rwanda: A Regional Comparison of Physiological and Behavioral Indicators in Eastern and Southern Agro-Ecological Zones

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Abstract : *Climate variability increasingly threatens sustainable dairy production by compromising animal welfare, productivity, and resilience, particularly in tropical smallholder farming systems. This study evaluated the effects of climate variability on the physiological and behavioural welfare of dairy cattle across contrasting agro-ecological zones in Rwanda. A cross-sectional survey was conducted on 167 smallholder dairy farms in six districts representing the Central Plateau (Huye, Kamonyi, Nyanza, and Ruhango) and the Eastern Dry Zone (Nyagatare and Rwamagana). Ambient temperature and relative humidity were recorded during farm visits, while standardised animal-based measures assessed physiological indicators (body condition score, respiration rate, rectal temperature, lameness, and injuries) and behavioural responses (panting, shade seeking, prolonged standing, and reduced feed intake). Non-parametric statistical tests compared climatic variables and welfare indicators between agro-ecological zones. The Eastern Dry Zone recorded significantly higher ambient temperatures than the Central Plateau (26.56 ± 1.52°C vs. 21.82 ± 2.22°C; $p < 0.001$), whereas relative humidity was significantly higher in the Central Plateau (73.40 ± 18.30% vs. 66.16 ± 12.80%; $p = 0.005$). Cattle in the Eastern Dry Zone exhibited significantly higher respiration rates, rectal temperatures, panting scores, prolonged standing, reduced feed intake, heat stress scores, lameness, and injury prevalence ($p < 0.05$). Body condition score and shade-seeking behaviour did not differ significantly between zones. Ambient temperature correlated positively with respiration rate and rectal temperature, whereas relative humidity showed negative associations. These findings highlight the need for climate-smart housing, shade, water, nutrition, and routine welfare monitoring to strengthen resilience in Rwanda's smallholder dairy systems.*

Keywords: Agro-ecological zones, animal-based welfare indicators, climate variability, dairy cattle welfare, heat stress, smallholder dairy system

INTRODUCTION

Higher levels of global warming are projected to intensify food insecurity, malnutrition, and livelihood losses, particularly in Sub-Saharan Africa, through reduced agriculture productivity, as well as increased risks to water and energy security. Rwanda is among the vulnerable developing countries due to its strong dependence on climate-sensitive agricultural systems and natural resources increase (IPCC, 2023). Related studies conducted in Rwanda have shown significant spatial and temporal variability in rainfall patterns, with decreasing rainfall trends particularly observed in the Southern and Eastern regions of the country (Ndakize et al., 2022; Rwema, 2024). The meta-analysis demonstrated that heat stress has significant negative effects on dry matter intake (DMI) and energy-corrected milk (ECM), highlighting the severe impact of thermal stress on dairy production (Cartwright et al., 2023). In dairy production systems, climate variability contributes to heat stress, feed scarcity, water shortages, increased disease occurrence, and reduced adaptive capacity among smallholder farmers (Chen et al., 2024). Rising temperatures and rainfall variability have significant negative effects on livestock production in sub-Saharan Africa, particularly under drought conditions where reduced water availability constrains animal productivity (Ateba Boyomo, Ongo Nkoa, and Awah Manga, 2024). Recent studies have demonstrated that elevated Temperature Humidity Index (THI) levels significantly affect dairy cattle welfare by increasing respiration rate, rectal temperature, heart rate, and cortisol concentration while simultaneously reducing feed intake, milk production, rumination, and reproductive performance (Cartwright et al., 2023; Ferag, et al., 2024). In tropical livestock systems, prolonged exposure to thermal stress has been associated with metabolic disturbances, oxidative stress, and immune suppression among dairy cattle (Alberghina et al., 2024). Heat stress resulting from climate variability substantially modifies cattle behavior as animals attempt to regulate body temperature and maintain physiological balance. Under high environmental temperatures, dairy cattle commonly exhibit increased standing time, reduced lying behavior, excessive panting, shade-seeking behavior, reduced feed intake, increased water consumption, and decreased rumination activity (Habeeb et al., 2023; Tu, et al., 2025). These behavioral adaptations are aimed at enhancing heat dissipation; however, prolonged exposure to thermal stress compromises animal welfare and productivity.

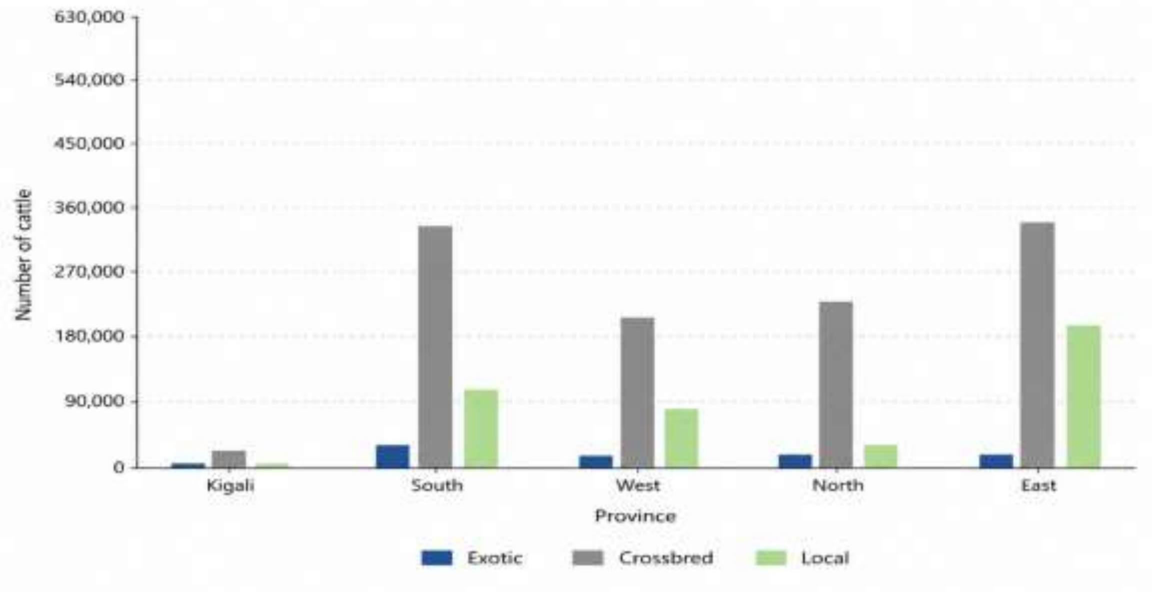
Among behavioral indicators, lying behavior is widely used in dairy welfare assessment because it reflects animal comfort, rest, and health status. Studies have shown that heat-stressed cattle reduce lying duration and spend more time standing to increase body surface exposure for heat loss (Tucker et al., 2021). Reduced lying time has been associated with increased lameness risk, fatigue, stress, and reduced milk production among dairy cattle. Similarly, excessive standing behavior under hot conditions may increase hoof disorders and negatively affect animal comfort.

In Rwanda, empirical evidence regarding behavioral welfare indicators among dairy cattle under climate variability remains scarce. Existing livestock studies have primarily focused on milk production, breed improvement, and climate-smart agriculture with limited attention given to behavioral welfare assessment. Moreover, little is known about how climatic conditions influence behaviors such as lying time, standing behavior, feeding patterns, and shade-seeking behavior across Rwanda's different agro-ecological zones.

Previous studies investigating climate variability and dairy cattle welfare have employed diverse methodological approaches depending on the study objectives, environmental conditions, and welfare indicators under investigation. These methodologies generally combine climatic data analysis, physiological measurements, behavioral observations, nutritional assessments, and farmer-based surveys to evaluate the effects of climate-related stressors on livestock systems (Haider, Li and Viet Ha, 2025).) Understanding methodologies used in previous studies is important for identifying appropriate techniques and analytical approaches relevant to the present study.

Nutritional welfare studies commonly employ body condition scoring, feed intake measurement, milk yield analysis, forage quality assessment, and water access evaluation to assess the effects of climate variability on dairy cattle nutrition (Roche et al., 2026). Body condition scoring systems are particularly useful because they provide simple and cost-effective indicators of long-term nutritional status and animal welfare. Several studies have also combined household surveys with farm-level welfare scoring systems to evaluate the effectiveness of adaptation strategies in improving dairy cattle welfare. Welfare assessment protocols often integrate physiological, behavioral, nutritional, and environmental indicators into composite welfare indices. Such multidimensional approaches enable comprehensive evaluation of animal welfare under diverse production and climatic conditions. Despite the availability of diverse methodological approaches globally, limited integrated methodologies have been applied in Rwanda to simultaneously assess climate variability, physiological welfare indicators, behavioral responses, nutritional welfare, and adaptation strategies among dairy cattle systems. Most existing studies in Rwanda focus on climate trends, productivity, or agricultural adaptation separately without combining animal welfare assessment with climatic and management variables.

Therefore, the present study adopts a multidisciplinary methodological approach integrating climate analysis, physiological measurements, behavioral observations, nutritional assessments, and farmer surveys to comprehensively evaluate the effects of climate variability on dairy cattle welfare in Rwanda.



Source: NISR, AHS, 2024.
Figure 1: Cattle population by breed type across provinces of Rwanda

Crossbred cattle constituted the largest proportion of the cattle population in all provinces, which indicates their dominant role in Rwanda's dairy production systems. The highest cattle populations were recorded in the Eastern and Southern provinces, which together accounted for a substantial share of the national herd. Local cattle were also present in considerable numbers, particularly in the Eastern and Southern provinces, whereas exotic cattle represented the smallest proportion across all provinces. These patterns highlight the importance of the Eastern and Southern regions for dairy cattle production and justify their selection as study areas for assessing the effects of climate variability on dairy cattle welfare and adaptation strategies.

METHODOLOGY

Study area

This study was conducted in Rwanda, a landlocked country in East-Central Africa where livestock production constitutes an important component of rural livelihoods, food security, and agricultural development. The dairy sector has expanded considerably over the past two decades following the introduction of improved dairy breeds and government initiatives aimed at increasing milk production and household income. Crossbred cattle constitute the predominant dairy population across the country because of their superior milk yield and adaptability to local production systems. The Eastern and Southern provinces account for the largest proportion of Rwanda's dairy herd, and makes these regions particularly important for evaluating the impacts of climate variability on dairy cattle welfare.

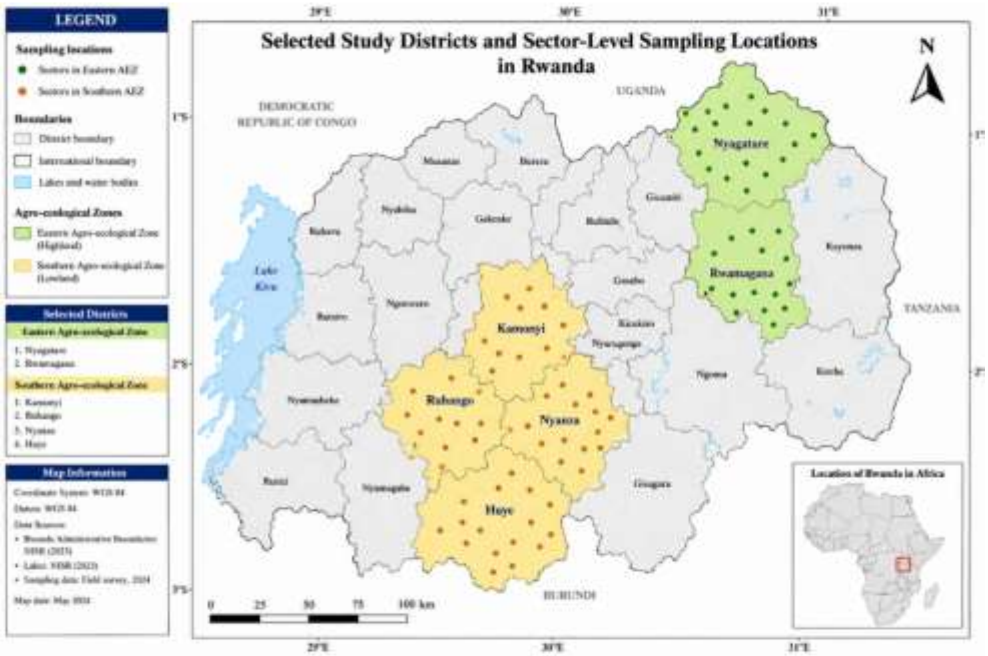


Figure 1: Selected district and sampling locations

The study was undertaken in six major dairy-producing districts representing two contrasting agro-ecological zones: the Eastern Dry Zone and the Central Plateau (Figure 1). The Eastern Dry Zone comprised Nyagatare and Rwamagana districts, characterised by relatively high ambient temperatures, prolonged dry seasons, lower annual rainfall, and recurrent drought conditions. In contrast, the Central Plateau included Huye, Nyanza, Ruhango, and Kamonyi districts, which experience comparatively cooler temperatures, higher rainfall, and greater relative humidity. These contrasting climatic conditions provide a suitable natural setting for examining the influence of environmental variability on dairy cattle welfare.

The selected districts are dominated by smallholder dairy farming, with zero-grazing and semi-zero-grazing systems constituting the principal production systems. Farmers primarily rear crossbred dairy cattle under varying levels of housing, feeding, and management practices, making the study areas representative of Rwanda's dairy production systems. The marked climatic differences between the two agro-ecological zones provided an appropriate framework for comparing physiological and behavioural responses of dairy cattle to environmental stress while generating evidence to support climate-smart livestock management strategies under changing climatic conditions.

Study design

A cross-sectional study was conducted between May and June 2026 to investigate the effects of climate variability on the physiological and behavioural welfare of dairy cattle in Rwanda. The cross-sectional design was considered appropriate because it enabled the simultaneous assessment of environmental conditions and animal welfare outcomes across different agro-ecological settings during the study period. By comparing farms exposed to contrasting climatic conditions, the study generated empirical evidence on the relationship between climatic variability and indicators of dairy cattle welfare under typical smallholder production systems.

The study adopted a multidisciplinary approach by integrating environmental measurements, physiological assessments, behavioural observations, and farmer interviews. This combination of data sources provided a comprehensive understanding of how climatic conditions influence cattle welfare while allowing measured environmental variables to be interpreted alongside farmers' experiences of changing climatic patterns. Such an integrated framework is increasingly recommended for livestock welfare research because welfare outcomes are influenced by interactions between environmental, biological, and management factors rather than by individual variables in isolation.

The target population consisted of smallholder dairy farmers managing lactating crossbred dairy cattle under zero-grazing and semi-zero-grazing production systems. These systems dominate dairy production in the selected districts and therefore provide a representative context for evaluating climate-related welfare challenges facing Rwanda's dairy sector. One apparently healthy lactating cow was selected from each participating farm to ensure independence of observations and to minimise potential bias associated with repeated measurements within herds. Restricting the study to lactating cows was justified because these animals experience greater metabolic demands and are generally more susceptible to heat stress than non-lactating cattle. Consequently, they provide sensitive indicators of the effects of climatic variability on dairy cattle welfare under smallholder management conditions.

Sampling procedure

A multistage sampling strategy was employed to obtain a representative sample of smallholder dairy farms across the selected agro-ecological zones. In the first stage, six districts were purposively selected based on their contrasting climatic characteristics, dairy cattle population density, and strategic importance within Rwanda's dairy industry. The Eastern Dry Zone was represented by Nyagatare and Rwamagana districts, whereas the Central Plateau comprised Huye, Nyanza, Ruhango, and Kamonyi districts. Selection of these districts enabled comparison of dairy cattle welfare under markedly different environmental conditions.

During the second stage, sectors and villages with active dairy production were identified in collaboration with district veterinary officers and local livestock extension personnel. Lists of registered dairy farmers were obtained from local administrative records to establish an appropriate sampling frame. Farms were subsequently selected through simple random sampling to reduce selection bias and improve the representativeness of the study population.

A total of 167 smallholder dairy farms participated in the study, including 122 farms from the Central Plateau and 45 farms from the Eastern Dry Zone. Each participating farm contributed one apparently healthy lactating dairy cow for welfare assessment. Selecting a single animal per farm ensured statistical independence of observations and reduced clustering effects associated with herd-level management practices. Farmers were eligible to participate if they owned lactating dairy cattle and consented voluntarily to the study. Farms without lactating cows or whose owners declined participation were excluded. The sampling approach provided broad geographical coverage while capturing variability in housing systems, feeding practices, and environmental conditions characteristic of Rwanda's smallholder dairy production systems, thereby enhancing the external validity of the findings.

Measurement of climatic variables

Environmental conditions were characterised using both objective climatic measurements and farmers' perceptions of climate variability. Ambient temperature (°C) and relative humidity (%) were obtained from the nearest Rwanda Meteorology Agency stations serving each study district during the survey period. These variables were selected because they are widely recognised as primary environmental determinants of heat stress and have direct implications for dairy cattle physiology, behaviour, productivity, and welfare.

Meteorological data were matched with the corresponding farm locations to characterise the climatic conditions prevailing during field assessments. Mean ambient temperature and relative humidity were subsequently compared between districts and agro-ecological zones to quantify spatial differences in environmental exposure. These climatic variables also served as explanatory variables in subsequent analyses examining their associations with physiological and behavioural welfare indicators.

To complement measured environmental data, participating farmers were interviewed using a structured questionnaire to document their perceptions of long-term changes in rainfall amount, rainfall distribution, seasonal variability, and the frequency of drought events. Incorporating farmers' perceptions provided valuable contextual information because livestock producers directly experience climatic changes that may not be fully captured by short-term meteorological observations. The integration of instrumental climatic records with local knowledge therefore strengthened interpretation of the study findings and provided a broader understanding of climate variability within the study areas.

Quality assurance procedures included verification of meteorological records before analysis and the use of standardised questionnaires administered by trained enumerators to ensure consistency in data collection. Combining objective environmental measurements with farmers' experiential knowledge provided a robust framework for evaluating the influence of climate variability on dairy cattle welfare under smallholder farming conditions.

Assessment of physiological welfare indicators

Physiological welfare indicators were assessed using established animal-based measures recommended for evaluating the welfare status of production animals under variable environmental conditions. These indicators were selected because they provide direct information on the biological responses of dairy cattle to climatic stress, nutritional challenges, and management conditions. Particular emphasis was placed on parameters associated with thermal regulation and general health status, as climate variability can alter physiological functioning, reduce productive performance, and compromise animal resilience.

Body condition score (BCS) was evaluated using a standardised five-point scoring system, where a score of 1 represented an extremely thin animal and a score of 5 represented excessive fat deposition. Assessment was performed through visual observation and palpation of key anatomical regions, including the lumbar vertebrae, ribs, hooks, pins, and tail head. Body condition was included as an indicator of welfare because it reflects the long-term interaction between nutritional adequacy, health status, metabolic demands, and environmental stress. Animals experiencing prolonged heat stress may reduce feed intake, resulting in negative energy balance and subsequent deterioration in body condition.

Rectal temperature was measured as a direct indicator of core body temperature and physiological response to heat load. Measurements were obtained using a calibrated digital veterinary thermometer inserted rectally until a stable reading was achieved and were recorded in degrees Celsius (°C). Elevated rectal temperature was interpreted as evidence of impaired thermoregulation and increased susceptibility to heat stress.

Respiration rate was determined by counting flank movements for 60 seconds while animals remained undisturbed in their normal farm environment. Values were expressed as breaths per minute. Increased respiration rate represents an important adaptive mechanism through which cattle dissipate excess body heat; however, prolonged elevation may indicate physiological strain and reduced welfare.

Additional physical welfare assessments included evaluation of lameness, injuries, wounds, and general body condition abnormalities. Animals were observed while standing and walking, and the presence or absence of visible lesions, locomotion difficulties, and physical abnormalities was recorded using standardized criteria. Lameness and injuries were included because environmental stress, inadequate housing conditions, and poor management can interact with climate-related challenges to negatively affect overall welfare.

All physiological assessments were conducted by trained personnel following standardised procedures to minimise observer variation and animal disturbance. The combination of physiological and physical health indicators provided a comprehensive assessment of the consequences of climate variability on dairy cattle welfare under smallholder production conditions.

Assessment of behavioural welfare indicators

Behavioural indicators were assessed through direct observation of individual animals during routine farm visits to identify behavioural responses associated with thermal discomfort and environmental stress. Behavioural assessment was incorporated because animal behaviour represents an immediate and sensitive response to environmental challenges and provides complementary information to physiological measurements. Unlike physiological indicators, behavioural responses allow animals to express their attempts to cope with adverse conditions, making them valuable components of comprehensive welfare evaluation.

The behavioural indicators assessed included panting, shade-seeking behaviour, prolonged standing, reduced feed intake, and an overall heat stress score derived from observed responses. Panting was evaluated based on visible respiratory effort and behavioural signs associated with increased heat dissipation demands. Because cattle increase respiratory activity when exposed to high temperatures, panting was considered an important behavioural manifestation of thermal stress.

Shade-seeking behaviour was recorded based on whether animals actively positioned themselves under available shaded areas or protective structures during farm observations. This behaviour reflects an animal's motivation to reduce exposure to solar radiation and represents an adaptive strategy for maintaining thermal balance. Prolonged standing was also assessed because heat-stressed cattle may alter resting behaviour to increase body surface exposure and facilitate heat loss, although excessive standing may also indicate discomfort associated with inadequate housing or flooring conditions.

Reduced feed intake was recorded based on farmer observations and direct assessment during farm visits. Declines in feed consumption are a recognised behavioural response to heat stress, as cattle reduce metabolic heat production by decreasing voluntary feed intake. An overall heat stress score was calculated by integrating observed behavioural responses to provide a broader assessment of thermal discomfort.

Observations were conducted under normal farm management conditions without experimentally manipulating the animals' environment. This approach allowed behavioural responses to be assessed under real-world smallholder farming conditions. Predefined scoring criteria adapted from internationally recognised animal welfare assessment guidelines were used to improve consistency and reliability among observations.

The integration of behavioural indicators with physiological measurements enabled a multidimensional evaluation of dairy cattle welfare. This approach recognises that climate-related stress affects animals through interconnected physiological and behavioural pathways and provides a more comprehensive assessment of welfare challenges associated with increasing climatic variability.

Statistical analysis

Data collected from farm assessments, animal observations, physiological measurements, and farmer interviews were entered, cleaned, and analysed using R statistical software (R Foundation for Statistical Computing, Vienna, Austria) through RStudio Desktop version 2026.06. Prior to analysis, datasets were screened for completeness, consistency, and potential outliers. Descriptive analyses were performed to summarise the characteristics of study variables. Continuous variables, including ambient temperature, relative humidity, respiration rate, rectal temperature, and body condition score, were presented as means and standard deviations (SD), while categorical variables, including the prevalence of lameness, injuries, wounds, and behavioural responses, were summarised using frequencies and percentages.

The distributional characteristics of continuous variables were assessed using the Shapiro-Wilk normality test. Variables meeting the assumptions of normality were analysed using parametric statistical procedures, whereas non-normally distributed variables were evaluated using appropriate non-parametric methods. Differences in climatic and welfare-related variables among the six study districts were assessed using the Kruskal-Wallis test, followed by appropriate post-hoc comparisons where significant differences were detected. Comparisons between the two agro-ecological zones (Central Plateau and Eastern Dry Zone) were performed using the Wilcoxon rank-sum test for non-normally distributed variables. Independent-samples *t*-tests were additionally applied to compare mean ambient temperature and relative humidity between agro-ecological zones because these environmental variables satisfied the assumptions required for parametric analysis and allowed direct comparison of mean climatic conditions.

Associations between categorical welfare outcomes and agro-ecological zones were evaluated using Pearson's Chi-square test, while Fisher's Exact Test was applied where expected cell frequencies were insufficient. Relationships between climatic variables and physiological welfare indicators were examined using Pearson correlation analysis to quantify the strength and direction of associations between environmental exposure and animal responses. Multiple linear regression models were subsequently developed to evaluate the contribution of climatic variables to variation in selected physiological welfare outcomes while accounting for potential confounding effects.

All statistical analyses were conducted using two-tailed tests, and statistical significance was considered at $p < 0.05$. This analytical framework allowed both comparative and predictive evaluation of the relationship between climate variability and dairy cattle welfare indicators across contrasting agro-ecological environments.

Ethical considerations

Ethical approval for this study was obtained from the relevant Ethics Review Committee of the University of Rwanda before commencing field activities. Permission to conduct data collection was also secured from the appropriate district authorities and local administrative structures within the study areas. All procedures involving farmers and animals were conducted in accordance with institutional ethical requirements and internationally accepted principles governing research involving human participants and animals.

Before participation, each farmer was informed about the objectives, procedures, and expected outcomes of the study. Written informed consent was obtained from all participating farmers, and participation was entirely voluntary. Farmers were informed that they could withdraw from the study at any stage without consequences. Confidentiality and anonymity were maintained throughout the research process, and personal identifiers were removed from the analytical dataset to protect participants' privacy.

Animal welfare considerations were integrated throughout the study design and implementation. Only apparently healthy lactating dairy cattle were selected for assessment, and all physiological measurements and behavioural observations were conducted by trained personnel using standard veterinary procedures. Handling practices were designed to minimise animal stress, discomfort, and unnecessary restraint. Rectal temperature measurements and physical examinations were performed carefully to avoid injury or distress.

The assessment procedures followed internationally recognised animal welfare principles, including recommendations provided by the World Organisation for Animal Health (WOAH) for the evaluation and management of welfare in terrestrial production animals. Observations were conducted under normal farm conditions without altering housing, feeding, or management practices, thereby reducing interference with natural animal behaviour.

The study also recognised the importance of responsible engagement with smallholder farming communities. Findings were generated with the aim of supporting evidence-based climate adaptation strategies that improve animal welfare, farmer resilience, and sustainability of dairy production systems. By integrating ethical safeguards for both human participants and animals, the study ensured that scientific objectives were achieved while maintaining respect for welfare, dignity, and responsible research practices.

RESULTS

Climatic characteristics of the study districts and agro-ecological zones

The climatic characteristics of the six study districts are summarised in Table 1 and Figure 1, and highlight substantial variation in environmental conditions across the selected agro-ecological zones. Differences in mean ambient temperature and relative humidity were observed between districts, reflecting the contrasting climatic profiles of the Central Plateau and Eastern Dry Zone. The Eastern Dry Zone exhibited warmer conditions, whereas the Central Plateau was characterized by relatively cooler temperatures and higher humidity levels. These spatial variations provide an important environmental context for evaluating the influence of climate variability on dairy cattle welfare responses. The observed differences in climatic parameters among study locations underline the relevance of agro-ecological classification in assessing thermal stress risks and understanding how local environmental conditions may affect physiological and behavioural adaptation of dairy cattle under smallholder production systems.

Table 1: Climatic characteristics of the six study districts.

District	n	Ambient temperature (°C), Mean ± SD	Mean Relative Humidity (%) ± SD
Huye	34	21.6 ± 1.10	83.5 ± 12.8
Kamonyi	30	22.7 ± 1.66	74.9 ± 10.4
Nyagatare	26	26.8 ± 1.44	65.8 ± 11.3
Nyanza	30	20.3 ± 3.47	61.9 ± 27.9
Ruhango	28	22.7 ± 0.72	71.9 ± 7.63
Rwamagana	19	26.2 ± 1.58	66.6 ± 14.9

Figure 2: spatial variation in climatic conditions across the study districts

Ambient temperature ranged from **20.3 ± 3.47°C** in Nyanza to **26.8 ± 1.44°C** in Nyagatare. Relative humidity ranged from **61.9 ± 27.9%** in Nyanza to **83.5 ± 12.8%** in Huye.

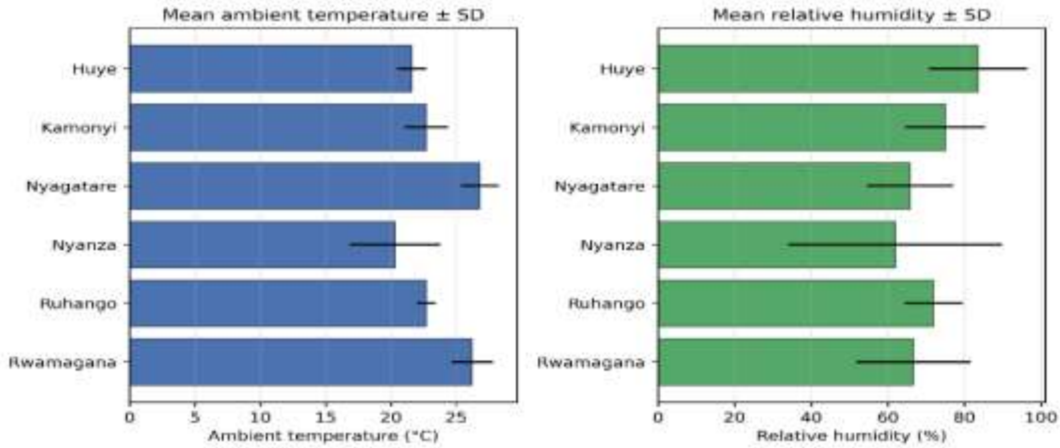


Figure 3 illustrates the spatial distribution of climatic conditions across the six study districts, demonstrating clear variation in temperature and humidity patterns. Nyagatare and

Rwamagana recorded the highest ambient temperatures, reflecting the warmer climatic conditions characteristic of the Eastern Dry Zone, whereas Huye exhibited the highest relative humidity among the surveyed districts. Comparative analysis between agro-ecological zones (Table 2) confirmed significant climatic differences. The Eastern Dry Zone recorded a significantly higher mean ambient temperature (26.56 ± 1.52°C) compared with the Central Plateau (21.82 ± 2.22°C), indicating greater thermal exposure for dairy cattle in this region. Conversely, relative humidity was significantly higher in the Central Plateau (73.40 ± 18.30%) than in the Eastern Dry Zone (66.16 ± 12.80%). These contrasting climatic conditions provide a basis for evaluating differential impacts of environmental stress on dairy cattle welfare.

Table 2: Comparison of climatic conditions between Agro-Ecological Zones

Variable	Central Plateau (n = 122)	Eastern Dry Zone (n = 45)	Test Statistic	p-value
Ambient temperature (°C)	21.82 ± 2.22	26.56 ± 1.52	t = -15.68	<0.001
Relative humidity (%)	73.40 ± 18.30	66.16 ± 12.80	t = 2.87	0.005

Independent samples t-tests demonstrated statistically significant differences in climatic conditions between the two agro-ecological zones. Ambient temperature differed significantly between the Eastern Dry Zone and Central Plateau ($P < 0.001$), confirming greater thermal exposure in the Eastern region. Similarly, relative humidity showed a significant difference between the zones ($P = 0.005$), indicating distinct moisture conditions across the study areas. These findings confirm the presence of contrasting environmental conditions between the two agro-ecological zones, providing an appropriate basis for assessing their potential influence on dairy cattle physiological and behavioural welfare responses.

Table 3: Results of the statistical comparisons of climatic variables

Climate Variable	Statistical Test	Test Statistic	df	p-value
Ambient temperature	Kruskal-Wallis	$\chi^2 = 123.44$	5	<0.001
Relative humidity	Kruskal-Wallis	$\chi^2 = 52.77$	5	<0.001
Rainfall variability	Fisher's Exact Test	—	—	0.325

Significant spatial variation in climatic conditions was observed among the six study districts. Ambient temperature differed significantly across districts (Kruskal–Wallis $\chi^2 = 123.44$, df = 5, $P < 0.001$), which demonstrates substantial differences in thermal environments. Similarly, relative humidity showed significant district-level variation

(Kruskal–Wallis $\chi^2 = 52.77$, df = 5, $P < 0.001$), which indicates contrasting moisture conditions among locations. However, farmers' perceptions of rainfall variability did not differ significantly across districts (Fisher's Exact Test, $P = 0.325$). These findings suggest that while measurable climatic parameters varied geographically, farmers experienced similar perceptions regarding changes in rainfall patterns across the study areas.

Physiological welfare indicators of dairy cattle

The physiological welfare indicators of dairy cattle across the Central Plateau and Eastern Dry Zone are summarized in Table 4. Comparative analyses were conducted to evaluate differences in key physiological responses between the two agro-ecological zones. Body condition score (BCS), respiration rate, and rectal temperature were assessed as indicators of nutritional status, thermal regulation, and physiological stress. Because the distribution of these variables did not meet parametric assumptions, differences between zones were evaluated using the Wilcoxon rank-sum test. This analysis provided insight into how contrasting climatic environments influence physiological welfare responses of dairy cattle under smallholder production conditions.

Table 4: Comparison of physiological welfare indicators between the two Agro-Ecological Zones.

Physiological Welfare indicator	Central Plateau (n = 122)	Eastern Dry Zone (n = 45)	Statistical test	P-value
Body condition score (BCS)	3.09 ± 0.64	3.02 ± 0.40	Wilcoxon rank-sum	0.338
Respiration rate (breaths/min)	30.6 ± 4.97	35.8 ± 6.52	Wilcoxon rank-sum	<0.001
Rectal temperature (°C)	38.3 ± 0.47	39.1 ± 0.48	Wilcoxon rank-sum	<0.001

Body condition score did not differ significantly between dairy cattle reared in the Central Plateau and those in the Eastern Dry Zone (Wilcoxon rank-sum test, $P = 0.338$). In contrast, respiration rate was significantly higher among cattle in the Eastern Dry Zone (35.8 ± 6.52 breaths/min) than in the Central Plateau (30.6 ± 4.97 breaths/min) ($P < 0.001$). Likewise, rectal temperature was significantly higher in cattle from the Eastern Dry Zone than in those from the Central Plateau (Wilcoxon rank-sum test, $P < 0.001$).

Table 5: Selected physiological welfare problems

Indicator	Central Plateau, n (%)	Eastern Dry Zone, n (%)	Statistical test	P-value
Lameness	5 (4.1)	14 (31.1)	Fisher's Exact Test	<0.001
Injuries/wounds	2 (1.6)	12 (26.7)	Fisher's Exact Test	<0.001
Poor body condition	23 (18.9)	9 (20.0)	Fisher's Exact Test	0.829

Significant differences in physical welfare indicators were observed between the two agro-ecological zones (Table 4), demonstrating the influence of contrasting climatic conditions on the health and welfare of dairy cattle. The prevalence of lameness was markedly higher in the Eastern Dry Zone (31.1%) than in the Central Plateau (4.1%), and this difference was highly significant (Fisher's Exact Test, $P < 0.001$).

Similarly, injuries and wounds were significantly more common among cattle in the Eastern Dry Zone (26.7%) compared with those in the Central Plateau (1.6%) ($P < 0.001$). The higher occurrence of these physical welfare problems in the warmer agro-ecological zone may reflect the combined effects of heat stress, prolonged standing, increased locomotion in search of shade or water, and differences in housing and management practices.

In contrast, the prevalence of poor body condition was similar between the Central Plateau (18.9%) and the Eastern Dry Zone (20.0%), with no statistically significant difference detected (Fisher's Exact Test, $P = 0.829$). This finding suggests that body condition may be influenced more by nutritional management, breed adaptability, and long-term husbandry practices than by short-term climatic differences. Overall, these results indicate that climate variability is more strongly associated with physical welfare impairments, particularly lameness and injuries, than with changes in body condition among dairy cattle managed under Rwanda's smallholder production systems.

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Table 6: Mean behavioral welfare scores of dairy cattle by district.

District	Mean panting score	Mean shade-seeking score	Mean prolonged standing score	Mean reduced feed intake score	Mean heat stress score
Huye	0.12	0.18	0.56	0.03	1.12
Kamonyi	1.23	1.53	1.23	1.47	8.13
Nyagatare	1.58	1.42	1.38	1.31	8.92
Nyanza	0	1.43	1.33	0.4	3.53
Ruhango	0.18	0.21	0.21	0	0.82
Rwamagana	1	0.37	1.11	0.84	5.16

Behavioural welfare indicators showed marked variation across the six study districts (Table 5), reflecting differences in climatic conditions and the extent of thermal stress experienced by dairy cattle. Nyagatare recorded the highest mean panting score (1.58), prolonged standing score (1.38), and overall heat stress score (8.92), indicating greater behavioural responses to elevated environmental temperatures. Kamonyi exhibited the highest mean shade-seeking score (1.53) and reduced feed intake score (1.47), together with a relatively high mean heat stress score (8.13), suggesting that cattle adopted multiple behavioural strategies to cope with thermal discomfort. Rwamagana displayed intermediate behavioural responses, with a mean heat stress score of 5.16. In contrast, Huye and Ruhango recorded the lowest behavioural stress indicators, with mean heat stress scores of 1.12 and 0.82, respectively. These findings demonstrate spatial variation in behavioural adaptation to climate conditions across the study districts.

Table 7: Statistical comparison of behavioral welfare indicators among districts

Behavioral indicator	Statistical test	Test statistic	df	P-value
Panting	Kruskal-Walli's test	$\chi^2 = 120.28$	5	<0.001
Heat stress score	Kruskal-Wallis's test	$\chi^2 = 135.64$	5	<0.001

Significant variations in behavioural welfare indicators were identified among the six study districts (Table 6), reflecting differences in environmental exposure and thermal stress conditions across locations. Panting scores, an important behavioural indicator of heat stress and respiratory effort, differed significantly among districts (Kruskal-Wallis $\chi^2 = 120.28$, df = 5, P < 0.001). Similarly, the overall heat stress scores showed significant district-level variation (Kruskal-Wallis $\chi^2 = 135.64$, df = 5, P < 0.001), indicating differential behavioural responses of dairy cattle to climatic conditions. These findings suggest that cattle in warmer districts experienced greater thermal discomfort, resulting in more pronounced behavioural adaptations. The observed spatial differences highlight the importance of agro-ecological conditions in shaping animal welfare outcomes within smallholder dairy production systems.

Table 8: Comparison of behavioral welfare indicators between the Central Plateau and Eastern Dry Zone

Behavioral indicator	Central Plateau (Mean score)	Eastern Dry Zone (Mean score)	Statistical test	P-value
Panting	0.38	1.33	Wilcoxon rank-sum	<0.001
Shade-seeking	0.83	0.98	Wilcoxon rank-sum	0.282
Prolonged standing	0.84	1.27	Wilcoxon rank-sum	<0.001
Reduced feed intake	0.47	1.11	Wilcoxon rank-sum	<0.001
Heat stress score	3.41	7.33	Wilcoxon rank-sum	<0.001

Behavioural welfare indicators differed significantly between the two agro-ecological zones (Table 7), demonstrating the influence of contrasting climatic conditions on the behavioural responses of dairy cattle. Animals reared in the Eastern Dry Zone exhibited significantly higher mean panting scores (1.33 vs. 0.38, $P < 0.001$), and this indicates a greater reliance on respiratory heat dissipation under elevated ambient temperatures. Similarly, prolonged standing scores were significantly higher in the Eastern Dry Zone (1.27 vs. 0.84, $P < 0.001$), which suggests that cattle remained standing for longer periods to facilitate heat loss and reduce contact with warm resting surfaces.

Reduced feed intake scores were also significantly greater among cattle in the Eastern Dry Zone (1.11 vs. 0.47, $P < 0.001$). This reflects a common adaptive response aimed at minimizing metabolic heat production during periods of thermal stress. Consequently, the overall heat stress score was substantially higher in the Eastern Dry Zone than in the Central Plateau (7.33 vs. 3.41, $P < 0.001$), which confirms a greater burden of heat-related behavioural stress in this region.

In contrast, shade-seeking behaviour did not differ significantly between the two agro-ecological zones ($P = 0.282$), which suggests that access to shade or its utilisation may have been influenced more by farm infrastructure and management practices than by climatic differences alone.

Associations between climatic variables and dairy cattle welfare indicators

Understanding the relationships between climatic conditions and animal welfare indicators is essential for identifying the extent to which environmental factors influence the physiological and behavioural responses of dairy cattle. Correlation analysis provides valuable insights into the direction and strength of these associations, which therefore improves the understanding of how climatic variability contributes to heat stress and welfare outcomes under smallholder production systems.

In this study, Spearman's rank correlation coefficient (ρ) was used to examine the relationships between climatic variables and selected dairy cattle welfare indicators because several variables did not satisfy the assumptions of normality. Positive correlation coefficients indicate that welfare indicators increased with increasing climatic variables, whereas negative coefficients indicate inverse relationships. Statistical significance was established at $P < 0.05$.

Table 9: Associations between climatic variables and dairy cattle welfare indicators

Climate variable	Welfare indicator	Spearman's ρ	P-value	Strength of association
Temperature	Respiration rate	0.455	<0.001	Moderate positive
Temperature	Rectal temperature	0.513	<0.001	Moderate positive
Temperature	Heat stress score	0.421	<0.001	Moderate positive
Humidity	Respiration rate	-0.205	0.008	Weak negative
Humidity	Rectal temperature	-0.305	<0.001	Weak to moderate negative
Humidity	Heat stress score	-0.194	0.013	Weak negative

The analysis revealed significant associations between climatic conditions and dairy cattle welfare indicators (Table 9). Ambient temperature was positively correlated with all physiological and behavioural indicators assessed. It demonstrates that increasing temperatures were accompanied by more pronounced signs of thermal stress. Moderate positive correlations were observed between ambient temperature and respiration rate ($\rho = 0.455$, $P < 0.001$), rectal temperature ($\rho = 0.513$, $P < 0.001$), and overall heat stress score ($\rho = 0.421$, $P < 0.001$). These findings indicate that elevated environmental temperatures increase the physiological demands placed on dairy cattle, which results in intensified thermoregulatory responses and behavioural adaptations to maintain thermal balance.

In contrast, relative humidity exhibited significant negative correlations with several welfare indicators, including respiration rate ($\rho = -0.205$, $P = 0.008$), rectal temperature ($\rho = -0.305$, $P < 0.001$), and overall heat stress score ($\rho = -0.194$, $P = 0.013$).

DISCUSSION

Climatic variability across districts and Agro-ecological zones

Climate change has intensified spatial and temporal variability in weather patterns worldwide, exposing livestock production systems to increasingly heterogeneous thermal environments. Rising ambient temperatures, altered humidity patterns, and erratic rainfall have emerged as major constraints to sustainable dairy production, particularly in tropical and subtropical regions where environmental conditions frequently approach or exceed the thermal tolerance limits of dairy cattle (Cartwright et al., 2023; Oliveira et al., 2025).

Consistent with these global trends, the present study revealed marked spatial variation in ambient temperature and relative humidity across the six study districts. The Eastern Dry Zone, represented by Nyagatare and Rwamagana, recorded significantly higher ambient temperatures than the Central Plateau, whereas the Central Plateau exhibited significantly higher relative humidity. These findings reflect Rwanda's diverse Agro-ecological landscape, where differences in altitude, topography, vegetation cover, and atmospheric circulation generate distinct local climatic conditions despite the country's relatively small geographical area. Similar climatic gradients have been documented across Rwanda, with the eastern lowlands consistently characterised by warmer and relatively drier conditions than the central and western highlands. This emphasizes the importance of considering geographical variation when evaluating dairy production environments (Rwema, 2024; Safari and Sebaziga, 2023; Uwizewe et al., 2024).

The mean ambient temperatures recorded in Nyagatare (26.8°C) and Rwamagana (26.2°C) are particularly noteworthy because they approach or exceed the upper limit of the thermoneutral zone commonly reported for high-producing dairy cattle. Under these conditions, the efficiency of sensible heat dissipation through radiation, conduction, and convection declines, forcing animals to rely increasingly on evaporative cooling mechanisms such as panting and sweating to maintain thermal balance (Habimana et al., 2023). Although these responses are essential for maintaining homeostasis, prolonged exposure to elevated temperatures can overwhelm physiological coping mechanisms, leading to heat stress, reduced feed intake, impaired reproductive performance, decreased milk yield, and compromised animal welfare (Cartwright et al., 2023; Souza et al. , 2023). The warmer climatic conditions observed in the Eastern Dry Zone therefore suggest that dairy cattle raised in this region are likely to experience greater thermal stress than those managed in the comparatively cooler Central Plateau.

While the Central Plateau recorded lower ambient temperatures, it exhibited significantly higher relative humidity than the Eastern Dry Zone. Although cooler conditions generally reduce heat stress risk, elevated humidity can also compromise thermal comfort by limiting evaporative heat loss through respiration and sweating. Consequently, cattle may still experience thermal strain when humidity is high, even under moderately warm temperatures.

This finding highlights the importance of evaluating temperature and humidity simultaneously rather than independently, as the combined effects of these variables determine the overall thermal environment experienced by dairy cattle. For this reason, recent studies recommend the use of integrated bioclimatic indices, particularly the Temperature-Humidity Index (THI), to provide a more comprehensive assessment of heat stress risk under field conditions (Oliveira et al., 2025).

Significant differences in ambient temperature and relative humidity among districts further demonstrate that climatic conditions vary considerably within Rwanda's dairy production systems. In contrast, farmers' perceptions of rainfall variability did not differ significantly among districts, which suggests that irregular rainfall has become a widespread climatic phenomenon rather than a localised challenge. This observation is consistent with recent national and regional climate assessments, which report increasing rainfall unpredictability, shifts in seasonal rainfall distribution, and a greater frequency of extreme weather events across Rwanda and other parts of East Africa (Safari and Sebaziga, 2023). Such changes have important implications for dairy production because rainfall variability directly influences forage availability, water resources, pasture quality, and ultimately the capacity of smallholder farmers to sustain livestock productivity under changing climatic conditions. Collectively, these findings demonstrate that Rwanda's contrasting Agro-ecological zones expose dairy cattle to distinctly different climatic environments that are likely to influence their physiological and behavioral responses. To our knowledge, this study is among the first in Rwanda to integrate climatic measurements with comprehensive dairy cattle welfare assessment across contrasting agro-ecological zones, providing important evidence on how local environmental conditions shape animal welfare within smallholder production systems.

These findings highlight the need for location-specific climate adaptation strategies rather than uniform interventions across the country. In the warmer Eastern Dry Zone, priority should be given to heat-abatement measures such as improved housing design, provision of adequate shade, reliable water supply, strategic nutritional management, and the promotion of heat-tolerant dairy genotypes. Meanwhile, dairy systems in the Central Plateau should also consider the potential effects of elevated humidity on animal comfort and heat dissipation.

Body condition score as an indicator of long-term nutritional welfare

This finding suggests that body condition is less responsive to short-term climatic variation than physiological indicators such as respiration rate and rectal temperature. Unlike these immediate thermoregulatory responses, changes in body condition develop gradually because of prolonged imbalances between nutrient intake and energy expenditure. Consequently, heat stress may trigger acute physiological responses before measurable changes in body energy reserves become evident, particularly where adequate nutritional management is maintained (Cartwright et al., 2023; Giannone et al., 2023).

The relatively stable BCS observed in the present study agrees with findings from several tropical dairy systems, where climatic stress did not always translate into reduced body condition when adequate feeding and herd management practices were maintained. Nevertheless, prolonged exposure to recurrent heat stress combined with seasonal feed shortages may eventually reduce body condition by decreasing dry matter intake and increasing maintenance energy requirements, particularly among high-producing dairy cows (Cartwright et al., 2023; Slayi and Jaja, 2025).

Although no statistically significant difference was detected between agro-ecological zones, maintaining an optimal body condition remains essential for dairy cattle welfare because inadequate body reserves increase susceptibility to disease, reduce reproductive efficiency, impair milk production, and compromise resilience to environmental stressors. Consequently, continuous monitoring of body condition should remain an integral component of climate-smart dairy management, particularly as climate change is expected to intensify seasonal feed shortages and increase the frequency of heat stress events across Rwanda. These findings further suggest that physiological indicators reflecting immediate thermal responses may provide earlier evidence of climate-related welfare challenges than body condition score alone.

Elevated respiration rate reflects thermoregulatory adaptation to heat stress

The elevated respiration rates observed in the present study suggest that dairy cattle in the Eastern Dry Zone experienced greater thermal challenges than those in the Central Plateau. As environmental temperatures increase beyond the thermoneutral zone, the efficiency of sensible heat dissipation through radiation, conduction, and convection progressively declines. To compensate, cattle increase respiratory evaporation through accelerated breathing, thereby enhancing heat loss from the respiratory tract. Although this physiological adjustment is essential for maintaining thermal equilibrium, prolonged elevation of respiration rate increases maintenance energy expenditure and may eventually compromise animal welfare if thermal stress persists. Recent studies have consistently identified respiration rate as one of the most practical animal-based indicators for evaluating heat stress under both experimental and field conditions due to its rapid response to changes in ambient temperature and humidity (Zhang et al., 2025; Rakib et al., 2024). Consequently, respiration rate is not only a sensitive indicator of heat stress but also an important measure of physiological resilience and animal welfare. Because it can be assessed rapidly without specialized equipment, routine monitoring of respiration rate, together with behavioral and environmental indicators, offers a practical approach for early detection of heat stress and supports climate-smart dairy management in smallholder production systems (Giannone et al., 2023; Zhang et al., 2025.

The significantly higher rectal temperatures observed in dairy cattle from the Eastern Dry Zone indicate greater thermal strain under warmer climatic conditions. Rectal temperature is a reliable indicator of core body temperature and reflects the animal's capacity to maintain thermal homeostasis. Persistent increases in rectal temperature indicate that environmental heat load exceeds the animal's cooling capacity, with negative consequences for feed intake, milk production, reproductive performance, and overall welfare (Cartwright et al., 2023; Rakib et al., 2024).

Lameness as an indicator of compromised physical welfare under climate variability

The significantly higher prevalence of lameness among dairy cattle in the Eastern Dry Zone suggests poorer locomotor welfare under warmer environmental conditions. Lameness is one of the most important welfare and productivity challenges in dairy cattle because it causes pain, reduces feed intake and milk production, impairs reproduction, and increases the risk of premature culling (Roche et al., 2023).

Although lameness is multifactorial, increasing evidence indicates that heat stress can exacerbate its occurrence through behavioral and physiological pathways. Heat-stressed cattle spend more time standing and less time lying to facilitate heat dissipation, increasing claw loading and the risk of hoof lesions, while reduced feed intake and altered nutrient partitioning may further compromise hoof integrity (Jurkovich, Hejel and Kovács, 2024; Fahim, 2026).

The higher prevalence of lameness observed in the Eastern Dry Zone therefore likely reflects the combined effects of climatic stress and management factors, including housing conditions, flooring, hoof care, and nutrition, rather than elevated temperature alone. Integrating heat-abatement strategies with routine hoof trimming, comfortable resting areas, and regular locomotion scoring could reduce lameness and improve both dairy cattle welfare and productivity under Rwanda's changing climatic conditions.

Injuries and wounds as indicators of compromised physical welfare

The significantly higher prevalence of injuries and wounds among dairy cattle in the Eastern

Dry Zone suggests poorer physical welfare under warmer environmental conditions. Although injuries are primarily associated with housing design, flooring quality, handling practices, and stocking density, heat stress may indirectly increase their occurrence by altering cattle behavior. Heat-stressed cattle often spend more time standing, congregating around shade and water sources, and competing for limited cooling resources, increasing their exposure to traumatic injuries and contact with poorly designed facilities (Cartwright et al., 2023; Jurkovich, Hejel and Kovács, 2024).

The higher prevalence of injuries observed in the Eastern Dry Zone therefore likely reflects the interaction between climatic stress and management factors rather than elevated temperature alone. Similar findings have shown that inadequate housing, poor flooring, insufficient bedding, and ineffective handling practices increase the risk of injuries, particularly when combined with environmental stressors that alter normal behavior (Roche et al., 2023). These findings highlight the need to integrate climate adaptation with improved welfare management in Rwanda's smallholder dairy systems.

From a practical perspective, reducing the prevalence of injuries requires an integrated approach that combines climate adaptation with improved welfare management. Provision of adequate shade, well-designed housing, comfortable resting surfaces, non-slip flooring, appropriate stocking densities, and low-stress animal handling practices should be prioritised alongside routine welfare assessments. Regular inspection of animals for skin lesions and prompt treatment of injuries would further improve animal welfare while reducing the risk of secondary infections and production losses. These measures are particularly important in the Eastern Dry Zone, where higher environmental temperatures may increase behavioral responses that predispose cattle to physical injury.

Behavioral welfare indicators

Panting scores were significantly higher among dairy cattle reared in the Eastern Dry Zone than in the Central Plateau, indicating greater thermal discomfort under warmer environmental conditions. Panting is among the earliest behavioral responses to heat stress because it enhances evaporative heat loss through the respiratory tract before severe hyperthermia develops. The higher panting scores observed in the present study therefore indicate that cattle in the Eastern Dry Zone relied more heavily on behavioral thermoregulation to maintain thermal balance under increasing environmental heat loads. From a practical perspective, panting provides a simple, rapid, and non-invasive animal-based indicator that can be readily incorporated into routine welfare assessments in smallholder dairy systems. Recent find show that observation of panting behavior, combined with environmental monitoring and timely implementation of mitigation measures such as shade provision, improved ventilation, and unrestricted access to drinking water, would facilitate early detection of heat stress and improve dairy cattle welfare under increasingly variable climatic conditions (Habimana, et al., 2023; Slayi and Jaja, 2025; Mylostyvyi and Izhboldina, 2025).

Dairy cattle reared in the Eastern Dry Zone exhibited significantly higher reduced feed intake scores than those in the Central Plateau, indicating that warmer environmental conditions altered feeding behavior. Reduced feed intake is one of the most consistent behavioral responses to heat stress because cattle voluntarily decrease dry matter intake to minimise the metabolic heat generated during ruminal fermentation and nutrient metabolism.

A recent meta-analysis demonstrated that dry matter intake declines significantly as THI increases and that these reductions are closely associated with decreases in energy-corrected milk yield, particularly in mid-lactation cows. Although this adaptation reduces internal heat production, it also limits nutrient availability for milk synthesis, maintenance, immune function, and reproduction, thereby compromising productivity and overall animal welfare (Cartwright et al., 2023; Chen et al., 2024; Nascimento et al., 2025).

The higher frequency of reduced feed intake observed in the Eastern Dry Zone suggests that prolonged exposure to heat stress could eventually deplete body reserves if appropriate nutritional interventions are not implemented. Previous studies have shown that sustained reductions in feed intake reduce nutrient availability, impair feed efficiency, compromise immune and reproductive functions, and decrease resilience to environmental stress, particularly under tropical and subtropical conditions (Cartwright et al., 2023; Zhang et al., 2025; Chen et al., 2024).

However, the absence of significant differences in body condition score between Agro-ecological zones may partly reflect the predominance of locally adapted and crossbred cattle in the Eastern Dry Zone (Figure 1), which are generally more tolerant of heat stress and better able to maintain body condition under challenging environmental conditions.
These findings emphasise the importance of integrating sound nutritional management into climate-smart dairy production systems. Continuous monitoring of feeding behavior, together with physiological and environmental indicators, and the adoption of precision livestock monitoring technologies would facilitate the early detection of heat stress and support timely management interventions to improve dairy cattle welfare, productivity, and resilience in Rwanda's smallholder dairy systems.

CONCLUSION AND RECOMMENDATIONS

This study provides empirical evidence that climate variability significantly influences dairy cattle welfare across contrasting agro-ecological zones in Rwanda. The findings demonstrate that differences in environmental conditions, particularly ambient temperature and relative humidity, are associated with measurable variations in physiological and behavioural responses of dairy cattle.

Animals raised in the Eastern Dry Zone experienced greater climatic stress compared with those in the Central Plateau, as demonstrated by higher thermal exposure and increased indicators of heat stress. Elevated respiration rates, increased rectal temperatures, higher panting scores, prolonged standing behaviour, reduced feed intake, increased heat stress scores, lameness, and injury prevalence indicate that warmer environmental conditions impose substantial challenges to cattle thermoregulation, comfort, and overall welfare.

The observed responses highlight that climate variability affects dairy cattle welfare through multiple interconnected pathways. Physiological responses such as increased respiration rate and rectal temperature reflect the activation of thermoregulatory mechanisms required to maintain homeostasis under heat stress. Similarly, behavioural changes, including panting, altered resting patterns, and reduced feed intake, demonstrate adaptive responses aimed at minimising thermal discomfort.

However, when prolonged, these adaptive mechanisms may negatively influence animal health, productivity, and farm profitability. The higher prevalence of lameness and injuries observed in warmer conditions further suggests that climatic stress may interact with housing conditions, management practices, and environmental constraints to compromise broader aspects of animal welfare.

Although body condition score and shade-seeking behaviour did not differ significantly between agro-ecological zones, these indicators remain valuable components of welfare assessment. The lack of significant differences may indicate that some welfare parameters are influenced by longer-term nutritional management, breed adaptation, farmer practices, or availability of mitigation resources rather than short-term climatic variation alone. This emphasises the importance of using integrated welfare assessment frameworks that combine environmental measurements with physiological, behavioural, and management indicators to obtain a comprehensive understanding of climate-related challenges.

The study demonstrates the importance of combining climatic information with animal-based welfare indicators for evaluating the effects of environmental stress in smallholder dairy systems. Traditional assessments based solely on climatic variables may underestimate the biological consequences of climate variability, whereas animal responses provide direct evidence of how environmental conditions affect welfare. This integrated approach can support early identification of heat stress risks, improve farm-level decision-making, and contribute to the development of targeted climate adaptation strategies.

To enhance the resilience of Rwanda's dairy sector, climate-smart livestock management interventions should be strengthened, particularly in areas exposed to higher thermal stress. Farmers should be encouraged to improve cattle housing structures through better ventilation, appropriate roof designs, and increased access to natural or artificial shade.

Ensuring continuous availability of clean drinking water is essential for supporting thermoregulation, particularly during periods of elevated temperature. Improved nutritional strategies, including adjustment of feeding practices during heat stress periods and ensuring adequate dietary quality, should also be promoted to reduce productivity losses and maintain animal health.

Routine welfare monitoring should become an integral component of dairy management practices. Training farmers and extension personnel to recognise early signs of heat stress, including increased respiration, panting, reduced feed intake, and behavioural changes, would facilitate timely intervention.

Furthermore, the integration of digital livestock monitoring technologies and climate information services could enhance real-time assessment of environmental risks and support evidence-based management decisions. Such innovations have potential to improve early warning systems for heat stress while increasing the efficiency and sustainability of smallholder dairy production.

Policy support and investment are also required to accelerate climate adaptation within Rwanda's dairy sector. Strengthening agricultural extension services, promoting farmer training programmes, and encouraging youth participation in climate-smart livestock enterprises can facilitate the adoption of innovative and sustainable practices. Supporting young farmers and entrepreneurs in developing digital livestock solutions, climate information platforms, and improved dairy management services may contribute to long-term sectoral resilience.

Future research should expand beyond cross-sectional assessments by investigating the long-term effects of climate variability across different seasons, production systems, and genetic backgrounds of dairy cattle. Further studies should also evaluate the economic feasibility and effectiveness of climate-smart interventions, including improved housing, water management, nutritional adaptation, and digital monitoring technologies. Such evidence will be critical for designing locally appropriate strategies that protect animal welfare, enhance farmer livelihoods, and ensure the sustainability of Rwanda's dairy production systems under increasing climatic uncertainty.

REFERENCES

Alberghina, D. et al. (2024). Impact of Heat Stress on the Balance between Oxidative Markers and the Antioxidant Defence System in the Plasma of Mid-Lactating Modicana Dairy Cows. *Animals*, 14 (14). 2034. https://doi.org/10.3390/ani14142034.

Ateba Boyomo, H.A, Ongo Nkoa, B. E, and Awah Manga, L.A. (2024). Climate change and livestock production in Sub-Saharan Africa: Effects and transmission channels. *Food Energy Security*, (13)1. https://doi.org/10.1002/fes3.521.

Cartwright, S.L et al. (2023). Impact of heat stress on dairy cattle and selection strategies for thermotolerance: a review. *Frontiers in Veterinary Science: Animal Behavior Welfare*. Volume 10. https://doi.org/10.3389/fvets.2023.1198697.

Chen, L. et al. (2024). Effects of heat stress on feed intake, milk yield, milk composition, and feed efficiency in dairy cows: A meta-analysis. *Journal of Dairy Science*, 117 (5), 3207-3218. https://doi.org/10.3168/jds.2023-24059.

Fahim, N.H. (2026). Integrated approaches for lameness control in free-stall dairy systems under heat stress and water scarcity. *Tropical Animal Health and Production*, Vol. 58, 184. https://doi.org/10.1007/s11250-026-04948-4.

Ferag, A, et al. (2024). Heat stress effect on fertility of two imported dairy cattle breeds from different Algerian agro-ecological areas. *International Journal of Biometeorology*, 68, 2515-2529. https://doi.org/10.1007/s00484-024-02761-y.

Giannone, C. et al. (2023). Review of the Heat Stress-Induced Responses in Dairy Cattle. *Animals* 13 (22), 3451. https://doi.org/10.3390/ani13223451.

Habeeb, A.A, et al. (2023). The detrimental impact of high environmental temperature on physiological response, growth, milk production, and reproductive efficiency of ruminants. *Tropical Animal Health and Production*, 55, 388. https://doi.org/10.1007/s11250-023-03805-y.

Habimana, V. et al. (2023). Heat stress effects on milk yield traits and metabolites and mitigation strategies for dairy cattle breeds reared in tropical and sub-tropical countries. *Frontiers in Veterinary Science: Animal Behavior Welfare*, Vol.10. https://doi.org/10.3389/fvets.2023.1121499.

Haider, I.; Li, C. and Viet Ha, T.T. (2025). Climate Change's Influence on Dairy Farming in Punjab, Pakistan: Effects on Milk Production, Farmers' Views, and Future Adaptation Strategies. *Agriculture*, 15(11), 1179. https://doi.org/10.3390/agriculture15111179.

Intergovernmental Panel on Climate Change – IPCC. (2023). Climate Change 2021 - The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 1st ed. Cambridge University Press. https://doi.org/10.1017/9781009157896.

Jurkovich, V.; Hejel, P. and Kovács, L. (2024). A Review of the Effects of Stress on Dairy Cattle Behaviour. *Animals*, 14(14). https://doi.org/10.3390/ani14142038.

Mylostyvyi, R. and Izhboldina, O. (2025). An Integrated Approach Using Temperature-Humidity Index, Productivity, and Welfare Indicators for Herd-Level Heat Stress Assessment in Dairy Cows. Animals, 15(22), 3341. https://doi.org/10.3390/ani15223341.

Nascimento, B.M. et al. (2025). Impact of heat stress on dry matter intake and residual feed intake in mid-lactation dairy cows. *Journal of Dairy Science*, 108 (7), 7345-7353. https://doi.org/10.3168/jds.2025-26574.

Ndakize, S.J. et al. (2022). Rainfall variability and trends over Rwanda. *Journal of Climate Change and Sustainability* - JCCS. 4(1), 26-34. https://doi.org/10.20987/jccs.04.06.2022.

Oliveira, C.P. et al. (2025). Impacts, Identification, and Mitigation Strategies: A Review. Animals, 15(2), 249. https://doi.org/10.3390/ani15020249.

Rakib, M.R.H. et al. (2024). Graduate Student Literature Review: Potential use of HSP70 as an indicator of heat stress in dairy cows - A review. *Journal of Dairy Science*, 107(12), 11597-11610. https://doi.org/10.3168/jds.2024-24947.

Roche, J.R. et al. (2026). Considerations for Dairy Cow Nutrition in Pasture-Based Systems. *Journal of Dairy Science Communications*, https://doi.org/10.3168/jdsc.2025-0992.

Roche, S.M. et al. (2023). Invited review: Prevalence, risk factors, treatment, and barriers to best practice adoption for lameness and injuries in dairy cattle - A narrative review. Journal of Dairy Science, 107 (6), 3347-3366. https://doi.org/10.3168/jds.2023-23870.

Rwema, M. (2024). Statistical analysis of climate variability in Rwanda. Dissertation for the degree of Doctor of Science (Technology) presented at Lappeenranta-Lahti University of Technology – LUT (Finland). Accessible via the URL: https://lutpub.lut.fi/bitstream/handle/10024/168525/Michel%20Rwema_A4.pdf?sequence=1 . Accessed 18/05/2026.

Safari, B. and Sebaziga, J.N. (2023). Trends and Variability in Temperature and Related Extreme Indices in Rwanda during the Past Four Decades. *Atmosphere*, 14 (9), 1449. https://doi.org/10.3390/atmos14091449.

Slayi, M. and Jaja, I.F. (2025). Strategies for mitigating heat stress and their effects on behavior, physiological indicators, and growth performance in communally managed feedlot cattle. *Frontiers in Veterinary Science: Animal Behavior Welfare*, Vol.12. https://doi.org/10.3389/fvets.2025.1513368.

Souza, V.C. et al. (2023). Modeling the effects of heat stress in animal performance and enteric methane emissions in lactating dairy cows. *Journal of Dairy Science*, 106(7), 4725-4737. https://doi.org/10.3168/jds.2022-22658.

Tu, P.A. et al. (2025). Stage-specific milk yield losses and associated sweating, respiration, and rectal temperature responses under varying temperature-humidity index thresholds in lactating and dry cows. *Journal of Dairy Science*, 108, 2023 - 2035. https://doi.org/10.3168/jds.2024-25392.

Tucker, C.B. et al. (2021). Invited review: Lying time and the welfare of dairy cows. *Journal of Dairy Science*, 104 (1), 20–46. https://doi.org/10.3168/jds.2019-18074.

Uwizewe, C. et al. (2024). Investigation of the Historical Trends and Variability of Rainfall Patterns during the March–May Season in Rwanda. *Atmosphere*, 15(5), 609. https://doi.org/10.3390/atmos15050609.

Zhang, Q. et al. (2025). Heat stress affects dairy cow performance via oxidative stress, hypothalamic–pituitary–adrenal axis, gut microbiota, and multi-dimensional mitigation. *Frontiers in Veterinary Science: Animal Behavior Welfare*, Vol.12. https://doi.org/10.3389/fvets.2025.1686241.