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Evaluation of Phule Amrutkal mobile application for estimation of Temperature Humidity Index (THI) in cattle

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Abstract

The present investigation entitled “Evaluation of Phule Amrutkal mobile application for estimation of Temperature Humidity Index (THI) in cattle” was conducted at Indigenous Cattle Research cum Training Centre, Division of Animal Husbandry and Dairy Science, College of Agriculture, Pune to assess the correlation between THI values and physiological responses of animals. Thirty clinically healthy cattle, comprising animals of Indigenous and Crossbreed, maintained under uniform feeding and management conditions, were monitored across summer, monsoon, and winter seasons. Open-source data was obtained by Mobile application “Phule Amrutkal”. Physiological responses demonstrated breed-specific variation. Indigenous cattle exhibited stable morning respiration rates (RR 17-21 breaths/min) with weak or negative THI correlations ($r=-0.17$ to 0.15), reflecting greater thermotolerance. Crossbreeds, however, showed stronger positive correlations (morning $r=0.33-0.57$, afternoon $r=0.82$) with elevated RR (up to 43.33 breaths/min in summer), indicating higher sensitivity to thermal load. Rectal temperature (RT) and pulse rate (PR) correlated moderately with THI in crossbreeds during mornings, but weaker in afternoons due to adaptive thermoregulation. Non-invasive indicators such as muzzle temperature (MT) and skin temperature (ST) displayed strong afternoon correlations with THI ($r=0.67-0.71$), confirming their reliability in field assessment. In afternoon Body temperature (BT) showed consistently strong associations (Indigenous $r=0.40$, Crossbreed $r=0.50$), establishing it as a robust heat stress biomarker. Pulse rate (PR) and rectal temp (RT) showed less sensitivity while Respiration rate (RR), Ear temp (ET), Muzzle temp (MT), Body temp (BT), Skin temp (ST) showed greater sensitivity and more fluctuations. Indigenous cattle showed better adaptability than crossbred cattle.

Seasonal analysis revealed that summer (March-May) imposed the highest thermal stress, with crossbreeds recording peak physiological strain. Monsoon reduced heat load due to rainfall, but humidity stress persisted. Post-monsoon and late winter showed residual or diurnal heat stress effects, particularly in crossbreeds. Overall, indigenous cattle demonstrated superior heat resilience, while crossbreeds were more vulnerable, with THI derived from IMD and sensors proving more reliable for assessing diurnal stress dynamics.

The THI values derived from the Phule Amrutkal mobile application provide reliable estimates of actual temperature and humidity, thereby enabling accurate calculation of THI. These accurate estimations are instrumental in adopting timely adaptive measures to mitigate the impact of heat stress in livestock management.

Keywords: THI, ambient temperature, relative humidity, physiological parameters

Introduction

Climate change, predicted to raise global temperatures by about 0.2°C per decade, poses a major challenge to livestock production worldwide. Rising temperature, humidity, and solar radiation directly affect animal growth, productivity, and welfare, with heat stress being the most critical factor in tropical and subtropical regions. When exposed to excessive heat, cattle struggle to maintain thermal balance, leading to elevated body temperature, increased respiration and pulse rate, reduced feed intake, and higher water consumption.

Once environmental temperatures exceed the upper critical limits (24-26 °C for crossbred/exotic cattle, 33 °C for Zebu cattle, and 36 °C for Water buffalo), their evaporative cooling mechanisms fail, causing hyperthermia.

The combined effect of air temperature and humidity on thermal stress is expressed as the Temperature-Humidity Index (THI). THI values below 72 indicate no stress, 73-77 mild, 78-89 moderate, and ≥ 90 severe stress. Elevated humidity further reduces heat dissipation through evaporation, aggravating thermal load. Heat stress impairs immunity, lowers feed intake and milk yield, and disrupts reproductive efficiency, with crossbred and *Bos taurus* cattle being more vulnerable than indigenous *Bos indicus* breeds, which have lower metabolic rates and better heat tolerance but lower productivity.

THI is widely used to assess livestock thermal comfort (Yousef, 1985; Thom, 1959; Mader, 2006; Berman, 2016) [36, 34, 30, 9]. Understanding physiological, haematological, and biochemical responses such as changes in rectal temperature, respiration, sweating, blood flow, hormones, and metabolites helps explain heat adaptation mechanisms and their impacts on productivity (Silanikove *et al.*, 1997; Ganaie *et al.*, 2013) [32, 23].

To address rising heat stress risks, the Phule Amrutkal mobile application has been developed as a climate-smart advisory tool. Using open-source weather data and THI models (National Research Council [NRC], 1971; Mader, 2006; Berman, 2016) [30, 9, 31, 30], it estimates THI in real time and issues automatic livestock management advisories on feeding, watering, housing, and health. With a simple, multilingual interface and color-coded stress categories (Normal, Alert, Danger, Emergency), it enables farmers to take timely preventive measures. The app's integration of meteorological data and threshold-based advisories promotes climate-resilient livestock farming by safeguarding cattle health and productivity. In this study, ambient temperature and relative humidity data from the India Meteorological Department observatory were used to compute THI (NRC 1971; Mader

2006; Berman 2016) [31, 30, 9] across summer, rainy, and winter seasons. These values validated the THI outputs from the Phule Amrutkal app and were compared with real-time sensor data from the experimental farm.

Materials and Methods

The present study entitled "Evaluation of Phule Amrutkal mobile application for estimation of Temperature-Humidity Index (THI) in Cattle" was carried out during 2024-2025 at the Indigenous Cattle Research cum Training Centre (ICRTC), Division of Animal Husbandry and Dairy Science, College of Agriculture, Pune, under Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri. The site is located at 18.5447° N latitude and 73.8496° E longitude, at an elevation of 530-570 m above sea level. The region experiences temperatures ranging from 5 °C to 46 °C (mean 24.3 °C), relative humidity averaging 60-63% (up to 81-83% in monsoon), and annual rainfall averaging 722 mm, mostly during June-September.

Thirty clinically healthy cattle (five animals from each of six breeds, including indigenous and crossbred types) of similar age and managed under uniform housing, feeding, and watering conditions were selected.

The Phule Amrutkal mobile application uses open-source meteorological data to provide temperature and relative humidity, computing THI to assess livestock heat stress and offering weather-based advisories. Data was collected during morning (8 AM) and afternoon (2 PM) in summer, rainy, and winter seasons.

THI Estimation: THI was calculated using model

National Research Council (NRC, 1971) [31]:

$$\text{THI} = (1.8 \times T + 32) - [(0.55 - 0.0055 \times \text{RH}/100) \times (1.8 \times T - 26)]$$

Physiological Parameters

The physiological parameters respiration rate, rectal temperature, pulse rate, skin temperature and thermographic image was recorded in every week of interval in adhering to standard clinical procedure.

Table 1: Standard clinical procedures to record physiological parameters

Parameters	Standard method
Respiration Rate (Breaths /Min)	Record by visual observation of inward and outward flank movement.
Rectal Temperature (°C)	By using digital Thermometer
Pulse Rate (Beats / Min)	By observing the pulsation of middle coccygeal artery at the base of tail.
Skin Temperature (°C)	By Infrared Flir thermograph Therma CAM. Model-FLIR E5xt (incl.Wi-Fi)
Body Temperature (°C)	By Infrared Flir thermograph Therma CAM. Model-FLIR E5xt (incl.Wi-Fi)
Ear Temperature (°C)	By Infrared Flir thermograph Therma CAM. Model-FLIR E5xt (incl.Wi-Fi)
Muzzle Temperature (°C)	By Infrared Flir thermograph Therma CAM. Model-FLIR E5xt (incl.Wi-Fi)

Thermographic Camera

A thermographic camera (also called an infrared camera or thermal imager) is a device that detects infrared radiation (heat) emitted from objects and converts it into a visible image (called a thermogram). Measures body surface temperature (Eye, Ear, Muzzle, Flank and Udder) to evaluate how animals respond to environmental heat. Helps in determining Thermal Comfort Index and adjusting housing, cooling, or feeding strategies. In this study Thermographic camera, Infrared Flir thermograph Therma CAM. Model-FLIR E5xt (incl.Wi-Fi) has been used to measure Physiological parameters like Skin temp, Body temp, Muzzle temp and Ear temperature. It was measured in morning 8 am and in the afternoon 2 pm.

Statistical Analysis: Seasonal data were analyzed using correlation analysis, to evaluate variations and relationships among THI values and Physiological data.

Results and Discussion

The above table shows the correlation analysis between respiration rate of cattle and THI values revealed distinct patterns among Indigenous and crossbred cattle during morning and afternoon periods. The average Temperature Humidity Index (THI) during the study period was 66.86±0.61 in the morning and 71.26±0.87 in the afternoon, indicating a moderate rise in thermal load as the day progressed.

Effect of THI on Respiration Rate (Breaths/Min) of cattle in morning and afternoon (Ideal range of respiration rate in cattle 10-30 Breaths/min)

Respiration Rate (Breaths/min)						
Months	Morning			Afternoon		
	THI	Indigenous	Crossbreed	THI	Indigenous	Crossbreed
March	66.54±0.4	18.59±0.48	25.33±0.33	74.52±0.3	22.91±0.0	43.33±0.53
April	70.32±0.4	18.94±0.55	25.53±0.55	76.37±0.3	25.20±0.58	42.40±0.58
May	70.37±0.5	17.76±0.79	20.60±0.26	76.44±0.3	23.31±0.52	32.87±0.56
June	67.75±0.4	15.01±0.39	20.20±0.22	71.25±0.4	16.29±0.37	35.00±0.32
July	66.34±0.3	16.04±0.33	20.40±0.23	67.46±0.3	16.42±0.34	24.60±0.34
Aug	67.64±0.3	15.63±0.60	19.20±0.20	69.22±0.4	20.51±0.28	25.00±0.0
Sept	67.00±0.4	16.66±0.20	20.00±0.45	69.33±0.4	21.10±0.33	24.60±0.51
Oct	67.76±0.4	19.51±0.22	22.20±0.58	69.12±0.4	24.26±0.21	30.80±0.58
Nov	64.77±0.6	17.43±0.39	18.80±0.37	69.32±0.3	20.99±0.28	26.20±0.37
Dec	64.01±0.6	17.71±0.22	21.20±0.37	69.80±0.2	22.11±0.22	26.00±0.37
Jan	63.88±0.5	20.17±0.31	20.80±0.49	69.97±0.4	25.14±0.21	26.20±0.37
Feb	65.90±0.5	20.17±0.41	21.20±0.20	72.33±0.2	27.48±0.41	31.20±0.86
AVG	66.86±0.61	17.80±0.50	21.29±0.62	71.26±0.87	22.14±0.97	30.68±1.93
Correlation		-0.17	0.33		0.46	0.82

The mean Respiration Rate (RR) of indigenous cattle was 17.80±0.50 breaths/min in the morning and 22.14±0.97 breaths/min in the afternoon, while crossbred cattle exhibited comparatively higher values of 21.29±0.62 breaths/min in the morning and 30.68±1.93 breaths/min in the afternoon. In the morning, Indigenous cattle exhibited a weak negative correlation with THI ($r=-0.17$), indicating that respiration rate was not strongly influenced by thermal load during the morning hours. Conversely, crossbred cattle showed a weak positive correlation ($r=0.33$), suggesting a slightly higher sensitivity to rising THI in the morning hours. In the afternoon, the association became more pronounced, with Indigenous cattle demonstrating a moderate positive correlation ($r=0.46$), while crossbred cattle exhibited a strong positive correlation ($r=0.82$). These findings highlight that crossbred cattle are more responsive to increasing heat load during afternoon hours as compared to Indigenous cattle, indicating their greater susceptibility to thermal stress.

During the summer months (March-May), the afternoon THI ranged between 74.52±0.3 and 76.44±0.3. Under these conditions, the respiration rate of crossbred cattle was considerably higher (32.87±0.56-43.33±0.53 breaths/min) compared to Indigenous cattle (22.91±0.0-25.20±0.58 breaths/min). In the morning, the respiration rate of Indigenous cattle remained relatively stable at 17.76±0.79 to 18.94±0.55 breaths/min, whereas crossbred cattle exhibited higher values ranging from 20.60±0.26 to 25.53±0.55 breaths/min. In the monsoon season (June-September), the afternoon respiration rate of crossbreds remained elevated (24.60±0.51 to 35.0±0.32 breaths/min), while Indigenous cattle recorded moderate values (16.29±0.37-21.10±0.33 breaths/min). Morning THI values during this period were relatively stable (66.34±0.3 to 67.75±0.4), yet crossbred cattle continued to show higher sensitivity compared to Indigenous cattle. In the post-monsoon season (October-November), the afternoon THI remained around 69.12±0.4 to 69.32±0.3, which corresponded with an increase in respiration rate of Indigenous cattle (20.99±0.28 to 24.26±0.21 breaths/min), indicating the onset of thermal load build-up. Crossbred cattle, however, continued to record higher respiration rates (26.20±0.37-30.80±0.58 breaths/min). During the winter months (December-February), the afternoon THI values ranged between 69.80±0.2 and 72.33±0.2. A distinct rise in respiration rate was observed, particularly in February, when Indigenous cattle reached 27.48 breaths/min and crossbred

cattle recorded 31.20±0.86 breaths/min. Morning respiration rates also increased to approximately 20-21 breaths/min, suggesting recovery from cold stress in the early hours followed by increased heat load during clear-sky afternoons.

In Indigenous cattle, the morning respiration rate was largely independent of THI ($r=-0.17$), whereas the afternoon respiration rate showed a stronger positive correlation with THI ($r=0.46$). This indicates that Indigenous cattle are less responsive to morning fluctuations but exhibit a more pronounced response during afternoon heat stress. In crossbred cattle, both morning ($r=0.33$) and particularly afternoon respiration rates ($r=0.82$) demonstrated significant positive correlations with THI, thereby highlighting their higher susceptibility to thermal stress throughout the year.

Indigenous cattle displayed a negative correlation with THI in the morning, which suggests effective thermoregulatory adaptation during the early hours when ambient heat stress is relatively low. However, the moderate positive correlation observed in the afternoon indicates that these animals become more susceptible once the thermal load accumulates. In contrast, crossbred cattle exhibited a consistent positive correlation with THI, which was more pronounced during the afternoon period. The strong correlation observed in the afternoon ($r=0.82$) emphasizes their heightened vulnerability to heat stress.

During the summer season, the peak in afternoon respiration rate indicates that heat stress is most severe during this period, particularly in crossbred cattle. In the monsoon season, although THI levels moderate slightly, the persistently high humidity continues to impose stress on crossbreds, while Indigenous breeds demonstrate better adaptability with relatively stable respiration rates. In the post-monsoon and winter seasons, afternoon respiration rates increase again, particularly in February, suggesting the influence of seasonal transition stress. Indigenous cattle exhibit resilience and adaptive thermoregulation, maintaining comparatively stable respiration rates across THI fluctuations. Crossbred cattle, however, show a stronger physiological response, making them not only more reliable bio-indicators of heat stress but also more vulnerable to its effects. These results suggest that afternoon monitoring of respiration rate provides a more reliable indication of heat stress, especially in crossbred cattle. While Indigenous cattle may require minimal intervention, crossbreds demand targeted cooling strategies during summer and late winter afternoons to mitigate heat stress.

Similar finding was given by Srikanthakumar *et al.*, (2003) that respiratory rate significantly increased in sheep when THI increased from 72 to 93, showing a strong link between THI and RR, and also highlighting breed differences in heat tolerance. Demonstrated that exotic cattle (Frisian) developed high thermal polypnea under heat stress, while native breeds tolerated heat better, indicating that crossbred/exotic breeds are more vulnerable to heat load. Found that respiration rate in crossbred (Holstein Friesian $\times$ Indigenous) cows increased significantly with unit rises in temperature, humidity, and THI. This aligns with the higher RR observed in crossbreds compared to indigenous cattle. Reported that during summer, young Punganur cattle exhibited higher respiration rates than adults, supporting the idea that sensitivity to heat stress varies with breed and age. Observed that Karan Fries (crossbred) cattle showed a marked increase in RR during summer afternoons, with strong correlations between THI and RR, indicating their higher susceptibility compared to indigenous breeds. Reported that indigenous Sahiwal cows had lower respiration rates across seasons compared to Karan Fries crossbreds, which showed sharp increases in RR during high THI conditions, confirming greater resilience of indigenous breeds. Showed that cooling interventions significantly reduced RR in crossbred cows under high THI, demonstrating that management strategies are especially necessary for

crossbreds. Found that Tharparkar (indigenous) cows had lower increases in RR at high THI compared to Karan Fries, reaffirming indigenous resilience and crossbred vulnerability. Reported that RR increased progressively with THI categories (70-75, 76-81, and 82-87), confirming that increasing THI is directly linked to higher RR, particularly in dairy cattle. Concluded that physiological parameters like RR are highly sensitive to climatic stress, with crossbred cows showing significantly higher values in summer than indigenous breeds. Murrah buffaloes and Karan fries cattle and in their studies they observed that average maximum temperature was (40.8°C) at 2 pm and THI at that time was 85, the physiological responses like RT, RR, PR were increased significantly ($p < 0.01$) at 2 pm as compared to the respective values at 2 am. They reported that different indices have been used to measure the impact of heat stress but the most widely used indicator is THI. Studied eight Hereford $\times$ Angus $\times$ Simmental steers were exposed to 24 h cyclic hot conditions (24°C to 39°C). It concluded Respiration rate (RR) can be used as an indicator of heat stress in cattle, provided animal condition, prior exposure, ambient conditions (increasing or decreasing T_a) and previous cooling strategies are considered. Reported Physiological responses showed a diurnal pattern, being lower in the mornings than the afternoons.

Effect of THI on Rectal Temperature (°C) of cattle in morning and afternoon (Ideal range of Rectal temp. in cattle 36-39°C)

Rectal Temperature (°C)						
Months	Morning			Afternoon		
	THI	Indigenous	Crossbred	THI	Indigenous	Crossbred
March	66.54 $\pm$ 0.4	38.12 $\pm$ 0.06	38.45 $\pm$ 0.11	74.52 $\pm$ 0.3	38.40 $\pm$ 0.06	38.73 $\pm$ 0.06
April	70.32 $\pm$ 0.4	38.45 $\pm$ 0.09	38.69 $\pm$ 0.08	76.37 $\pm$ 0.3	38.15 $\pm$ 0.06	38.62 $\pm$ 0.09
May	70.37 $\pm$ 0.5	38.15 $\pm$ 0.07	38.80 $\pm$ 0.08	76.44 $\pm$ 0.3	38.50 $\pm$ 0.11	38.54 $\pm$ 0.12
June	67.75 $\pm$ 0.4	38.35 $\pm$ 0.07	38.49 $\pm$ 0.16	71.25 $\pm$ 0.4	38.37 $\pm$ 0.06	38.64 $\pm$ 0.08
July	66.34 $\pm$ 0.3	38.26 $\pm$ 0.05	38.38 $\pm$ 0.05	67.46 $\pm$ 0.3	38.42 $\pm$ 0.05	38.59 $\pm$ 0.03
Aug	67.64 $\pm$ 0.3	37.12 $\pm$ 0.07	38.38 $\pm$ 0.04	69.22 $\pm$ 0.4	37.58 $\pm$ 0.07	38.68 $\pm$ 0.03
Sept	67.00 $\pm$ 0.4	38.15 $\pm$ 0.08	38.55 $\pm$ 0.03	69.33 $\pm$ 0.4	38.58 $\pm$ 0.02	37.64 $\pm$ 0.01
Oct	67.76 $\pm$ 0.4	38.12 $\pm$ 0.06	38.27 $\pm$ 0.10	69.12 $\pm$ 0.4	38.40 $\pm$ 0.04	37.50 $\pm$ 0.02
Nov	64.77 $\pm$ 0.6	38.12 $\pm$ 0.07	37.27 $\pm$ 0.03	69.32 $\pm$ 0.3	38.41 $\pm$ 0.09	38.63 $\pm$ 0.10
Dec	64.01 $\pm$ 0.6	38.02 $\pm$ 0.05	38.29 $\pm$ 0.15	69.80 $\pm$ 0.2	37.56 $\pm$ 0.06	38.66 $\pm$ 0.03
Jan	63.88 $\pm$ 0.5	38.15 $\pm$ 0.05	38.48 $\pm$ 0.03	69.97 $\pm$ 0.4	38.55 $\pm$ 0.03	38.63 $\pm$ 0.05
Feb	65.90 $\pm$ 0.5	37.68 $\pm$ 0.24	37.98 $\pm$ 0.17	72.33 $\pm$ 0.2	38.44 $\pm$ 0.04	38.37 $\pm$ 0.10
AVG	66.86 $\pm$ 0.61	38.06 $\pm$ 0.10	38.33 $\pm$ 0.11	71.26 $\pm$ 0.87	38.28 $\pm$ 0.10	38.44 $\pm$ 0.12
Correlation		0.15	0.57		0.14	0.28

The above table shows the correlation analysis between rectal temperature and THI values revealed distinct patterns among Indigenous and crossbred cattle. The average THI during the study was 66.86 $\pm$ 0.61 in the morning and 71.26 $\pm$ 0.87 in the afternoon. The mean rectal temperature (RT) of indigenous cattle was 38.06 °C in the morning and 38.28 $\pm$ 0.10 °C in the afternoon, while crossbred cattle recorded slightly higher averages of 38.33 $\pm$ 0.11 °C in the morning and 38.44 $\pm$ 0.12 °C in the afternoon. In the morning, Indigenous cattle exhibited a weak positive correlation with THI ($r=0.15$), whereas crossbred cattle showed a moderate positive correlation ($r=0.57$). During the afternoon, Indigenous cattle again demonstrated a weak positive correlation ($r=0.14$), while crossbreds displayed a weak positive association ($r=0.28$).

During the summer season (March-May), the morning rectal temperature in crossbred cattle increased steadily with increasing THI (38.45 $\pm$ 0.09-38.80 $\pm$ 0.08 °C), reflecting their greater sensitivity to heat stress. In contrast, Indigenous cattle maintained relatively stable rectal temperatures within the

range of 38.12 $\pm$ 0.06-38.45 $\pm$ 0.11 °C. In the afternoon, rectal temperatures in both groups fluctuated slightly without showing a consistent pattern in relation to THI, ranging from 38.15 $\pm$ 0.06 to 38.50 $\pm$ 0.11 °C in Indigenous cattle and 38.54 $\pm$ 0.12 to 38.73 $\pm$ 0.06 °C in crossbreds.

During the monsoon season (June-September), the morning rectal temperature remained relatively consistent, ranging from 38.12 $\pm$ 0.06 to 38.35 $\pm$ 0.07 °C in Indigenous cattle and 38.38 $\pm$ 0.04 to 38.55 $\pm$ 0.03 °C in crossbreds, showing a mild positive alignment with THI. In the afternoon, rectal temperature also remained stable, averaging between 38.37 $\pm$ 0.06 and 38.58 $\pm$ 0.02 °C in Indigenous cattle and 38.59 $\pm$ 0.03 to 38.68 $\pm$ 0.03 °C in crossbreds, with only weak correlations observed with THI.

During the post-monsoon season (October-November), the morning rectal temperature remained around 38.12 $\pm$ 0.06 °C in Indigenous cattle and 37.27 $\pm$ 0.03-38.27 $\pm$ 0.10 °C in crossbreds, showing alignment with THI values. In the afternoon, rectal temperature ranged from 38.40 $\pm$ 0.04 to

38.41±0.09 °C in Indigenous cattle and 37.50±0.02 to 38.63±0.10 °C in crossbreds, indicating only a weak correlation with THI. In the winter season (December-February), the morning rectal temperature showed a slight decline in February, reaching 37.68±0.24 °C in indigenous cattle and 37.98±0.17 °C in crossbreds, reflecting the influence of cooler conditions. However, in the afternoon, rectal temperature increased again (38.44±0.12 °C in Indigenous cattle and 38.37±0.10 °C in crossbreds), even at a moderate THI of 72.33±0.2, suggesting diurnal heat accumulation despite relatively low ambient stress.

In the morning period, Indigenous cattle exhibited an almost negligible association with THI ($r=0.15$), whereas crossbred cattle showed a moderate positive correlation ($r=0.57$), reflecting their greater thermal sensitivity during the early hours of the day. In the afternoon period, both Indigenous cattle ($r=0.14$) and crossbred cattle ($r=0.28$) demonstrated weak positive correlations, suggesting that rectal temperature in the afternoon is less directly governed by THI, likely due to compensatory physiological adjustments that moderate internal body temperature under elevated thermal load.

In the morning, rectal temperature exhibited stronger alignment with THI, particularly in crossbred cattle. This finding suggests that morning rectal temperature reflects the accumulation of overnight heat load and serves as a reliable early indicator of thermal stress. In the afternoon, the correlations weakened for both Indigenous and crossbred cattle, highlighting the influence of adaptive physiological responses such as increased respiration rate and sweating, which help to maintain rectal temperature within a narrow range despite elevated THI levels.

During the summer season, both crossbred and indigenous cattle exhibited a gradual rise in rectal temperature, with morning values showing a relatively higher sensitivity to increasing THI levels. In the monsoon season, the combined effect of elevated humidity and moderate ambient temperatures contributed to maintaining rectal temperatures within a narrow range, with only weak correlations observed between THI and afternoon rectal temperature. In the post-monsoon period, rectal temperature patterns remained largely stable, indicating a possible acclimatization of cattle to the prevailing moderate THI conditions. During winter, morning rectal temperature tended to decline, particularly in February, while afternoon rectal temperature showed a slight increase, reflecting the influence of diurnal thermal variations even under comparatively mild THI conditions.

Crossbred cattle were consistently more responsive to changes in THI during the morning ($r=0.57$), whereas Indigenous cattle exhibited minimal fluctuations, indicating their higher adaptive thermotolerance.

Morning rectal temperature in crossbred cattle serves as a reliable indicator of thermal load and is useful for identifying animals that are more vulnerable to heat stress. In contrast, afternoon rectal temperature alone is not sufficient for accurate heat stress assessment, as compensatory physiological mechanisms tend to dampen its correlation with THI. Under such conditions, respiration rate (RR) emerges as a more sensitive and reliable indicator during the afternoon period.

Similar finding was also given by Bhan *et al.*, (2013) [12] found that RT in Karan Fries cattle increased by ~0.8 °C during summer afternoons compared to spring, with strong

positive correlations between RT and THI, indicating that crossbreds are more affected by seasonal heat load than indigenous breeds. Observed that RT values in Sahiwal (indigenous) cows remained lower across seasons than in Karan Fries (crossbreds), which recorded significantly higher RT under summer THI (~87), reflecting indigenous resilience versus crossbred sensitivity. reported that cooling systems (foggers + fans) reduced RT significantly in crossbred cows compared to control groups, further validating that crossbreds are more susceptible to high THI and require intervention. concluded that RT, alongside other physiological traits, varied significantly across seasons, with higher summer values in Karan Fries compared to indigenous breeds, reinforcing breed-based thermotolerance differences. Found that RT increased progressively across THI categories (70-75, 76-81, 82-87), showing that RT aligns positively with THI, particularly in dairy cattle during morning periods. Jun Sik Woo *et al.* (2024) experimentally demonstrated that RT increased significantly ($p<0.05$) as THI levels rose from mild (77-79) to severe (85-86), confirming the direct relationship between RT and THI under controlled conditions. Murrah buffaloes and Karan fries cattle and in their studies they observed that average maximum temperature was (40.8°C) at 2 pm and THI at that time was 85, the physiological responses like RT, RR, PR were increased significantly ($p<0.01$) at 2 pm as compared to the respective values at 2 am.

Also some findings related to Rectal temperature by that Holstein, Jersey, and Zebu cows exposed to cool (THI 72) and hot (THI 93) conditions exhibited a significant increase in rectal temperature under high THI, confirming the adverse effect of THI on RT. McManus *et al.*, (2009) reported significantly higher RT values in Brazilian cattle breeds during afternoon compared to morning, aligning with your observation of afternoon RT fluctuations due to diurnal heat accumulation. Abdelatif & Alameen (2012) [2, 3] demonstrated that crossbred cows in tropical climates recorded significantly higher RT in summer (THI ~80.9) compared to winter (THI ~65.7). Reported that RT in crossbred cows increased significantly with rises in air temperature, humidity, and THI, emphasizing their greater vulnerability to thermal stress compared to indigenous breeds. The temperature-humidity index (THI) of the same and the previous day on morning (a.m.) and afternoon (p.m.) rectal temperatures (RT). Physiological responses showed a diurnal pattern, being lower in the mornings than the afternoons. The objective of this study was to evaluate relationships between measurements of Temperature-Humidity Index (THI) and rectal temperatures in lactating cows exposed to Heat Stress (HS). It showed increase in rectal temperature with increasing THI.

Effect of THI on Pulse Rate (Beats/Min) of Cattle in Morning and Afternoon (Ideal range of Pulse rate in cattle 60-80 Beats/min)

The above table shows the correlation analysis of pulse rate (PR) with THI values revealed distinct breed-specific responses. The average THI during the study was 66.86±0.61 in the morning and 71.26±0.87 in the afternoon. The mean pulse rate (PR) of indigenous cattle was 58.34 beats/min in the morning and 63.40±0.66 beats/min in the afternoon, whereas crossbred cattle recorded higher averages of 62.27±1.20 beats/min in the morning and 65.29±0.86 beats/min in the afternoon.

Months	Pulse Rate (Beats/min)					
	Morning			Afternoon		
	THI	Indigenous	Crossbreed	THI	Indigenous	Crossbreed
March	66.54±0.4	60.79±0.26	63.00±0.58	74.52±0.3	65.43±0.48	68.33±0.87
April	70.32±0.4	61.40±0.58	65.44±0.63	76.37±0.3	64.91±0.60	67.78±0.56
May	70.37±0.5	63.04±0.52	64.44±0.29	76.44±0.3	62.16±0.27	61.56±0.45
June	67.75±0.4	55.07±0.77	59.33±0.30	71.25±0.4	61.60±0.75	66.67±0.55
July	66.34±0.3	55.07±0.77	59.33±0.50	67.46±0.3	62.07±0.53	62.21±0.53
Aug	67.64±0.3	53.87±0.72	63.67±0.40	69.22±0.4	58.73±0.72	64.25±0.51
Sept	67.00±0.4	61.60±0.24	70.67±0.29	69.33±0.4	67.07±0.43	68.67±0.59
Oct	67.76±0.4	54.67±0.51	65.33±0.40	69.12±0.4	63.13±0.45	66.67±0.33
Nov	64.77±0.6	57.67±0.58	57.00±0.58	69.32±0.3	62.33±0.52	59.33±0.73
Dec	64.01±0.6	62.27±0.23	62.33±0.40	69.80±0.2	65.80±0.40	65.00±0.58
Jan	63.88±0.5	61.60±0.56	61.33±0.40	69.97±0.4	64.73±0.54	65.00±0.33
Feb	65.90±0.5	53.00±0.59	55.33±0.45	72.33±0.2	62.80±0.74	68.00±0.33
AVG	66.86±0.61	58.34±1.09	62.27±1.20	71.26±0.87	63.40±0.66	65.29±0.86
Correlation		0.05	0.44		0.16	0.23

During the morning, Indigenous cattle showed no significant association with THI ($r=0.05$), whereas crossbred cattle demonstrated a moderate positive correlation ($r=0.44$). In the afternoon, Indigenous cattle exhibited a weak positive correlation ($r=0.16$), while crossbred cattle also displayed a weak positive correlation ($r=0.23$). In summer (March-May), the morning pulse rate (PR) of Indigenous cattle ranged between 60.79 ± 0.26 and 63.04 ± 0.52 beats/min, showing little association with THI. In contrast, crossbred cattle exhibited higher values (63.00 ± 0.58 - 65.44 ± 0.63 beats/min), indicating greater sensitivity to thermal stress. Afternoon PR remained elevated, particularly in March and April, with crossbreds reaching 67.8 ± 0.56 beats/min, reflecting a strong thermal load.

During the monsoon season (June-September), morning PR showed notable fluctuations. Indigenous cattle recorded a decline as low as 53.87 ± 0.72 beats/min in August, while crossbreds rose to 70.67 ± 0.29 beats/min in September, in line with higher THI values. Afternoon PR in crossbreds peaked in September (68.67 ± 0.59 beats/min), whereas Indigenous cattle also showed an increase (67.07 ± 0.43 beats/min), suggesting seasonal stress effects. In the post-monsoon season (October-November), morning PR in Indigenous cattle remained moderate (54.67 ± 0.51 - 57.67 ± 0.58 beats/min), while crossbreds recorded values ranging from ~ 57 to 65 beats/min. Afternoon PR continued to remain elevated, with Indigenous cattle showing ~ 62 - 63 beats/min and crossbreds ranging from ~ 59 to 67 beats/min. During winter (December-February), morning PR in Indigenous cattle stayed relatively high (61 - 62 beats/min), whereas crossbreds showed a decline to 55.3 beats/min in February. Afternoon PR peaked again in February, reaching 62.80 ± 0.74 beats/min in Indigenous cattle and 68.00 ± 0.33 beats/min in crossbreds, indicating increased diurnal stress despite the presence of moderate THI values.

In Indigenous cattle, the morning pulse rate (PR) showed minimal association with THI ($r=0.05$), while the afternoon correlation was slightly higher ($r=0.16$). In crossbred cattle, the morning PR exhibited a moderate positive correlation ($r=0.44$), indicating higher thermal sensitivity, whereas the afternoon correlation remained weak ($r=0.23$).

Morning PR in Indigenous cattle showed weak dependency on THI, indicating greater thermotolerance and adaptive stability. In contrast, crossbred cattle exhibited a moderate positive correlation ($r=0.44$), suggesting that morning PR serves as a reliable stress indicator in this group. During the afternoon, both breeds showed weaker correlations with THI, as adaptive mechanisms such as increased respiration and peripheral blood flow helped modulate the cardiovascular

response. Nevertheless, afternoon PR values remained elevated, particularly during summer and late winter, reflecting the accumulation of diurnal stress.

During summer, afternoon Pulse Rate (PR) was highest, particularly in crossbred cattle, highlighting the peak of heat stress, while Indigenous cattle remained relatively stable but still exhibited mild increases. In the monsoon season, despite moderate THI values, high humidity contributed to elevated PR, with crossbreds showing a distinct peak in September. In the post-monsoon period, PR values stabilized, with Indigenous cattle displaying comparatively less variation. During winter, afternoon PR increased again, particularly in February, suggesting that bright sunny days induced transient thermal stress despite lower THI levels.

Indigenous cattle maintained relatively stable pulse rates (PR) across varying THI ranges, reflecting higher adaptability and thermotolerance. In contrast, crossbred cattle consistently exhibited higher PR values with stronger correlations to THI, indicating a greater cardiovascular response to heat stress and comparatively lower thermal resilience.

Morning Pulse Rate (PR) in crossbred cattle can serve as a sensitive physiological marker of thermal stress. Although afternoon PR is less reliable as a standalone indicator due to adaptive regulatory mechanisms, its assessment in combination with respiration rate (RR) offers valuable insight into the overall stress load.

Similar trend was observed by Joshi *et al.*, (1982) moderate increases in pulse rate (PR) in Murrah buffalo heifers exposed to hot arid and humid ambiances, establishing PR as a sensitive heat stress indicator. Reported a positive correlation between THI and heart rate in Holstein-Friesian cows under Mediterranean conditions, with PR increasing by 6 beats/min as THI rose from 68 to 78, supporting the positive THI-PR association in crossbreds. Found that PR in Karan Fries cattle rose significantly during hot-humid and summer seasons compared to spring, with strong positive correlation with THI, confirming your finding of higher PR in crossbreds under summer and monsoon stress. Demonstrated a highly significant positive correlation between THI and PR in both buffalo ($r=0.921$) and crossbred calves ($r=0.925$) under Kerala's hot-humid climate, consistent with your results showing moderate positive correlations for crossbreds. Reported that crossbred cows housed with cooling (foggers + fans) exhibited significantly lower PR compared to control cows under high THI, highlighting the cardiovascular stress of crossbreds during summer. Aggarwal *et al.*, (2019) ^[5] observed significant seasonal variations in PR across Sahiwal, Tharparkar, Gir, and Karan Fries breeds, with crossbreds

showing higher PR in summer compared to indigenous breeds, validating breed-based differences in cardiovascular sensitivity. Found that PR increased markedly during summer compared to winter in both Sahiwal and Karan Fries, with crossbreds showing a stronger rise, supporting your seasonal trend of elevated afternoon PR. documented that exposure of Tharparkar (indigenous) and Karan Fries (crossbreds) to THI 91 increased PR significantly more in Karan Fries (+14 beats/min) than Tharparkar (+13 beats/min), affirming crossbred vulnerability. Determined THI thresholds for PR in goats, with values between 71-79 depending on breed, showing that PR responds early to thermal stress and confirming its role as a reliable physiological marker,

especially in more sensitive breeds. Reported that high summer THI values in Bulgarian dairy goats significantly elevated PR ($p<0.001$), supporting the general principle that PR is a strong indicator of heat stress across livestock species. Murrah buffaloes and Karan fries cattle and in their studies they observed that average maximum temperature was (40.8 °C) at 2 pm and THI at that time was 85, the physiological responses like RT, RR, PR were increased significantly ($p<0.01$) at 2 pm as compared to the respective values at 2 am. They reported that different indices have been used to measure the impact of heat stress but the most widely used indicator is THI.

Effect of THI on muzzle temperature (°C) of cattle in morning and afternoon (Ideal range of Muzzle temp in cattle 32-35°C)

Muzzle Temperature (°C)						
Months	Morning			Afternoon		
	THI	Indigenous	Crossbred	THI	Indigenous	Crossbred
March	66.54±0.4	34.24±0.01	34.55±0.02	74.52±0.3	35.56±0.01	35.66±0.02
April	70.32±0.4	34.47±0.07	34.33±0.15	76.37±0.3	35.31±0.06	35.99±0.17
May	70.37±0.5	34.86±0.09	34.79±0.12	76.44±0.3	36.08±0.03	35.94±0.42
June	67.75±0.4	34.57±0.25	33.93±0.25	71.25±0.4	34.10±0.32	34.45±0.52
July	66.34±0.3	33.14±0.56	33.96±0.12	67.46±0.3	34.10±0.70	34.59±0.49
Aug	67.64±0.3	33.09±0.51	33.63±0.51	69.22±0.4	33.09±0.42	33.68±0.49
Sept	67.00±0.4	33.59±0.62	33.87±0.34	69.33±0.4	35.11±0.29	34.88±0.34
Oct	67.76±0.4	34.17±0.24	34.28±0.26	69.12±0.4	35.12±0.43	35.58±0.44
Nov	64.77±0.6	33.85±0.56	33.95±0.26	69.32±0.3	34.70±0.44	34.72±0.59
Dec	64.01±0.6	34.32±0.60	33.76±0.59	69.80±0.2	34.52±0.39	34.98±0.52
Jan	63.88±0.5	34.10±0.87	33.76±0.46	69.97±0.4	34.04±0.34	33.90±0.56
Feb	65.90±0.5	34.31±0.45	34.40±0.93	72.33±0.2	35.10±0.48	35.65±0.28
AVG	66.86±0.61	34.06±0.16	34.10±0.10	71.26±0.87	34.74±0.23	35.00±0.22
Correlation		0.29	0.57		0.69	0.71

The above table shows the correlation of muzzle temperature (MT) recorded by thermographic camera the THI values exhibited distinct seasonal variations. The average THI recorded during the study was 66.86±0.61 in the morning and 71.26±0.87 in the afternoon. The mean muzzle temperature (MT) of indigenous cattle was 34.06±0.16 °C in the morning and 34.74±0.23 °C in the afternoon, while crossbred cattle exhibited slightly higher averages of 34.10±0.10 °C in the morning and 35.00±0.22 °C in the afternoon. In the morning, Indigenous cattle ($r=0.29$) and crossbred cattle ($r=0.57$) exhibited weak-to-moderate correlations with THI, suggesting that morning MT is only partially influenced by ambient heat load due to the effect of overnight cooling. In the afternoon, Indigenous ($r=0.69$) and crossbred cattle ($r=0.71$) showed strong correlations with THI, indicating that afternoon MT serves as a more reliable physiological marker of heat stress. During summer (March-May), morning THI ranged from 66.54±0.4 to 70.37±0.5, with MT values recorded between 34.24±0.01 and 34.86±0.09 °C in Indigenous cattle and 34.33±0.15 to 34.79±0.12 °C in crossbreds. Afternoon THI peaked between 74.52±0.3 and 76.44±0.3, accompanied by higher MT values in both breeds (Indigenous: 35.31±0.06-36.08±0.03 °C; Crossbreds: 35.66±0.02-35.99±0.17 °C). Crossbred cattle consistently showed higher afternoon MT, indicating greater susceptibility to thermal load. In the monsoon season (June-September), morning THI values (66.34±0.3-67.75±0.4) coincided with relatively lower MTs (Indigenous: 33.09±0.51-34.57±0.25 °C; Crossbreds: 33.63±0.51-33.93±0.25 °C). Afternoon THI (67.46±0.3-71.25±0.4) corresponded to reduced MT values (Indigenous: 33.09±0.42-35.11±0.29 °C; Crossbreds: 33.68±0.49-

34.88±0.34 °C). The cooling effects of rainfall and cloud cover during this period helped reduce muzzle heat load in both breeds.

In the post-monsoon season (October-November), moderate THI values (64.77±0.6-67.76±0.4) were associated with an increase in morning MT (Indigenous: 33.85±0.56-34.17±0.24 °C; Crossbreds: 33.95±0.26-34.28±0.26 °C). Afternoon MT also increased (Indigenous: 34.70±0.44-35.12±0.43 °C; Crossbreds: 34.72±0.59-35.58±0.44 °C), suggesting delayed heat dissipation even under moderate ambient stress conditions.

During winter (December-February), morning THI dropped to its lowest values (63.88±0.5-65.90±0.5), with stable MTs observed in Indigenous (34.10±0.87-34.32±0.60 °C) and crossbred cattle (33.76±0.59-34.40±0.93 °C). Afternoon THI ranged between 69.80±0.2 and 72.33±0.2, with MT values moderately elevated (Indigenous: 34.04±0.34-35.10±0.48 °C; Crossbreds: 33.90±0.56-35.65±0.28 °C). A noticeable rise was recorded in February, aligning with pre-summer warming trends.

In summer, afternoon muzzle temperature (MT) showed a strong correlation with THI ($r \approx 0.70$), particularly in crossbred cattle, indicating the accumulation of heat load during peak stress hours. Morning correlations were comparatively weaker ($r \approx 0.29-0.57$). During the monsoon season, both morning and afternoon correlations weakened due to rainfall-induced cooling and reduced solar radiation. Although MT values fluctuated, their dependence on THI was less pronounced. In the post-monsoon period, afternoon MT values increased disproportionately to THI, reflecting residual heat stress and humidity effects, with moderate positive

correlations being recorded. In winter, morning MT exhibited weak correlations with THI ($r < 0.40$), whereas afternoon correlations were stronger, particularly in February, when THI values rose sharply.

The results clearly demonstrate that muzzle temperature responds more sensitively to afternoon THI than morning values, confirming that afternoon hours are the most critical for assessing thermal load. Indigenous cattle and Crossbreds showed relatively stable MT.

Similar finding was given by Bhan *et al.*, (2013) [12] seasonal variability in Karan Fries cattle and found that physiological parameters, including skin temperature, increased significantly during summer and hot-humid seasons compared to spring. They also reported strong positive correlations between Temperature Humidity Index (THI) and surface temperatures, confirming that peripheral indicators such as muzzle or skin temperature reflect heat load. found that cooling interventions (foggers and fans) significantly reduced physiological responses such as respiration rate, rectal temperature, and pulse rate in crossbred cows during high

THI, further indicating that crossbreds exhibit higher peripheral heat stress markers like muzzle temperature unless managed. Reported strong correlations between surface/muzzle temperatures and THI, highlighting the reliability of peripheral temperatures as non-invasive heat stress indicators. showed that indigenous Tharparkar cattle recorded smaller rises in surface body temperature at THI 91 compared to crossbred Karan Fries, who exhibited sharper increases. Indigenous breeds show stable MT, while crossbreds are more sensitive. highlighted seasonal effects on peripheral temperatures and blood flow in multiple indigenous (Sahiwal, Tharparkar, Gir) and crossbred (Karan Fries) breeds. Crossbreds showed significantly higher thermal load indicators during summer, confirming the breed-based differences in muzzle/surface temperature. Studied on goat in high summer THI (32-33 °C inside barns) significantly elevated peripheral body temperatures ($p < 0.001$). Their findings support the broader principle that muzzle and skin temperatures rise proportionally with THI under tropical heat stress.

Effect of THI on ear temperature (°C) of cattle in morning and afternoon (Ideal range of Ear temp. in cattle 35-38°)

Ear Temperature (°C)						
	Morning			Afternoon		
Months	THI	Indigenous	Crossbreed	THI	Indigenous	Crossbreed
March	66.54±0.4	36.22±0.01	36.24±0.02	74.52±0.3	36.25±0.01	36.97±0.02
April	70.32±0.4	36.19±0.07	36.49±0.15	76.37±0.3	36.98±0.10	37.49±0.28
May	70.37±0.5	36.45±0.09	36.78±0.12	76.44±0.3	37.37±0.03	37.97±0.09
June	67.75±0.4	35.23±0.22	34.73±0.64	71.25±0.4	36.59±0.16	36.73±0.26
July	66.34±0.3	36.21±0.31	36.05±0.29	67.46±0.3	35.51±0.64	35.65±0.25
Aug	67.64±0.3	35.97±0.39	34.03±0.50	69.22±0.4	35.10±0.52	35.94±0.78
Sept	67.00±0.4	35.38±0.57	35.26±0.92	69.33±0.4	35.45±0.33	35.76±0.33
Oct	67.76±0.4	36.10±0.26	36.51±0.36	69.12±0.4	37.42±0.33	37.69±0.34
Nov	64.77±0.6	35.09±0.52	35.97±0.45	69.32±0.3	36.02±0.30	35.62±0.92
Dec	64.01±0.6	36.21±0.68	35.29±0.92	69.80±0.2	35.36±0.23	35.80±0.45
Jan	63.88±0.5	36.11±0.68	35.61±0.56	69.97±0.4	35.16±0.23	35.94±0.57
Feb	65.90±0.5	35.10±0.59	35.23±0.58	72.33±0.2	36.14±0.23	36.58±0.68
AVG	66.86±0.61	35.86±0.14	35.68±0.23	71.26±0.87	36.11±0.24	36.51±0.25
Correlation		0.27	0.32		0.61	0.75

The above table shows the correlation of ear temperature (ET) recorded by thermographic camera the THI values demonstrated clear seasonal variations. The mean THI during the study was 66.86±0.61 in the morning and 71.26±0.87 in the afternoon. The average ear temperature (ET) of indigenous cattle was 35.86±0.14 °C in the morning and 36.11±0.24 °C in the afternoon, whereas crossbred cattle recorded slightly lower morning averages (35.68±0.23°C) but higher afternoon averages (36.51±0.25 °C). Morning correlations of ear temperature (ET) with THI in Indigenous ($r=0.27$) and crossbred cattle ($r=0.32$) showed weak positive associations, indicating that morning ET is less sensitive to thermal fluctuations. In the afternoon, correlations strengthened, with Indigenous cattle ($r=0.61$) and crossbreds ($r=0.75$) exhibiting moderate to strong associations with THI. This suggests that afternoon ET is more responsive to rising THI, particularly in crossbred cattle, confirming their higher vulnerability to environmental heat load.

In the summer months (March-May), morning THI was highest in April and May (70.32±0.4-70.37±0.5), with corresponding ET values ranging from 36.19±0.07 to 36.45±0.09 °C in Indigenous cattle and 36.49±0.15 to 36.78±0.12 °C in crossbreds. Afternoon THI also peaked (> 76), which was reflected in elevated ET values (37.37±0.03-37.97±0.09 °C in crossbreds and 36.98±0.10-37.97±0.09 °C

in Indigenous cattle). This indicates that ET increases in response to rising heat load, particularly in crossbred cattle. During the monsoon months (June-September), THI values remained moderate (66.34±0.3-67.75±0.4). Morning ET dropped noticeably, especially in June, with Indigenous cattle recording 35.23±0.22 °C and crossbred's 34.73±0.64 °C. Afternoon ET values were comparatively stable (35.10±0.52-36.59±0.16 °C), suggesting that cloudy and humid conditions during this season reduced the direct impact of heat load.

In the post-monsoon period (October-November), afternoon ET increased again, particularly in October (Indigenous: 37.42±0.33°C; Crossbred: 37.69±0.34 °C), despite only moderate THI levels (69.12±0.4). This reflects the transition season, during which animals may still experience thermal stress due to higher radiant heat and humidity. In the winter months (December-February), morning THI was lowest (63.88±0.5-65.90±0.5), with ET values stabilizing around 35.09±0.52-36.51±0.36 °C in both breeds. Afternoon ET also remained low (35.16±0.23-36.58±0.68 °C), except in February, when a rise in THI (72.33±0.2) led to a modest increase in ET (36.14±0.23-36.58±0.68 °C).

In summer (March-May), THI had a strong influence on ear temperature (ET), with higher afternoon elevations observed in both breeds. Crossbred cattle consistently recorded higher ET values, reflecting greater susceptibility to thermal stress.

During the monsoon season (June-September), ET values were lower in the mornings despite moderate THI, likely due to rainfall and reduced solar radiation, while afternoon ET values were stabilized by environmental humidity. In the post-monsoon period (October-November), ET increased again despite relatively moderate THI, indicating a lagged effect of heat stress. In winter (December-February), ET values were the lowest overall, with minimal variation between Indigenous and crossbred cattle, although afternoon values showed a slight rise in February.

The analysis demonstrates that afternoon ET is a more reliable physiological indicator of heat stress than morning ET, as it closely aligns with peak THI conditions. Crossbred cattle consistently showed higher ET values and stronger correlations with THI compared to Indigenous breeds, highlighting their reduced adaptability to tropical climatic stressors. Seasonally, summer and post-monsoon periods posed the greatest heat load, while monsoon and winter provided relief. The weak morning correlations suggest that animals dissipate accumulated heat stress overnight, making morning ET less reflective of immediate climatic conditions.

These findings align with earlier reports Bhan *et al.*, (2013) ^[12] reported that Karan Fries cattle. Rise in ET with higher

THI, especially in summer. Observed that Tharparkar (indigenous) and Karan Fries (crossbred) cows exposed to increasing THI (72.2-91.0) showed higher surface body temperatures in crossbreds than indigenous cattle, confirming crossbreds' greater susceptibility. reported that physiological responses such as skin surface temperature and blood flow varied significantly across seasons and were higher in Karan Fries compared to indigenous Sahiwal, Gir, and Tharparkar cows, corroborating the stronger ET-THI correlation in crossbreds. Reported that THI thresholds for physiological responses (including respiration rate and rectal temperature) were lowest in early-lactation cows and varied with parity. They emphasized that peripheral indicators like ET are sensitive to THI changes, especially in high-yielding or crossbred animals. Kadirvel *et al.*, (2022) used infrared thermal imaging to validate eye and ear temperatures as substitutes for rectal temperature in pigs, showing strong correlations. This supports your interpretation that ET is a reliable proxy for thermal stress in field conditions. Demonstrated that high summer THI (32-33 °C indoors) significantly elevated body surface temperatures in dairy goats ($p<0.001$), further reinforcing the role of ET and similar peripheral measures as robust thermal stress indicators.

Effect of THI on skin temperature (°C) of cattle in morning and afternoon (Ideal range of Skin temp in cattle 35-38°C)

Skin Temperature (°C)						
Months	Morning			Afternoon		
	THI	Indigenous	Crossbred	THI	Indigenous	Crossbred
March	66.54±0.4	36.10±0.01	36.24±0.02	74.52±0.3	36.71±0.03	36.68±0.04
April	70.32±0.4	36.11±0.05	36.32±0.42	76.37±0.3	36.86±0.02	38.91±0.28
May	70.37±0.5	36.45±0.12	37.38±0.15	76.44±0.3	37.14±0.01	38.70±0.11
June	67.75±0.4	35.20±0.26	35.77±0.34	71.25±0.4	36.66±0.22	37.65±0.81
July	66.34±0.3	36.45±0.59	36.51±0.08	67.46±0.3	35.87±0.42	36.67±0.49
Aug	67.64±0.3	36.12±0.41	36.45±0.58	69.22±0.4	35.23±0.39	35.56±0.42
Sept	67.00±0.4	35.72±0.65	36.04±0.39	69.33±0.4	36.06±0.54	35.58±0.51
Oct	67.76±0.4	36.18±0.65	36.49±0.13	69.12±0.4	37.54±0.46	38.19±0.20
Nov	64.77±0.6	35.46±0.64	35.47±0.53	69.32±0.3	35.97±0.55	35.88±0.54
Dec	64.01±0.6	36.00±0.44	36.61±0.94	69.80±0.2	35.39±0.21	36.86±0.52
Jan	63.88±0.5	36.13±0.60	36.43±0.47	69.97±0.4	34.71±0.31	35.83±0.13
Feb	65.90±0.5	35.38±0.46	35.94±0.60	72.33±0.2	36.52±0.30	38.05±0.60
AVG	66.86±0.61	35.94±0.12	36.30±0.14	71.26±0.87	36.22±0.24	37.05±0.35
Correlation		0.27	0.39		0.52	0.67

The above table shows the correlation of Skin Temperature (ST) recorded by thermographic camera the THI values exhibited clear seasonal and breed-specific variations. The mean THI during the study was 66.86±0.61 in the morning and 71.26±0.87 in the afternoon. The average skin temperature (ST) of indigenous cattle was 35.94±0.12 °C in the morning and 36.22±0.24 °C in the afternoon, while crossbred cattle recorded higher averages of 36.30±0.14 °C in the morning and 37.05±0.35 °C in the afternoon. In the morning, Indigenous ($r=0.27$) and crossbred cattle ($r=0.39$) exhibited weak positive correlations between skin temperature (ST) and THI, suggesting that morning ST is less influenced by ambient thermal load. In the afternoon, Indigenous ($r=0.52$) and crossbreds ($r=0.67$) showed moderate to strong correlations with THI, with crossbred cattle consistently recording higher ST values and stronger associations.

During summer (March-May), morning THI ranged from 66.54±0.4 to 70.37±0.5, with Indigenous cattle recording ST values of 36.10±0.01-36.45±0.12 °C and crossbreds slightly higher at 36.24±0.02-37.38±0.15 °C. Afternoon THI increased markedly (74.52±0.3-76.44±0.3), with crossbreds reaching peaks of 38.91±0.28 °C in April and 38.70±0.11 °C

in May, compared to Indigenous cattle (36.71±0.03-37.14±0.01 °C), demonstrating a stronger thermal load impact on crossbreds.

In the monsoon season (June-September), morning THI remained moderate (66.34±0.3-67.75±0.4), with Indigenous ST ranging from 35.20±0.26-36.45±0.59 °C, lower than summer values, while crossbreds maintained slightly higher ST (35.77±0.34-36.51±0.08 °C). Afternoon THI (67.46±0.3-71.25±0.4) corresponded to Indigenous ST values of 35.23±0.39-37.54±0.46 °C and crossbreds ranging from 35.56±0.42-38.19±0.20 °C. The highest post-monsoon spike occurred in October, with crossbreds reaching 38.19 °C, indicating residual heat load. During the post-monsoon period (October-November), despite moderate THI (64.77±0.6-67.76±0.4), afternoon ST in crossbreds remained elevated (38.19±0.20 °C in October and 35.88±0.54 °C in November), whereas Indigenous cattle showed relatively stable ST (35.97±0.55-37.54±0.46 °C), reflecting lingering effects of environmental humidity and radiant heat.

In winter (December-February), morning THI was lowest (63.88±0.5-65.90±0.5), with Indigenous ST stabilizing around 35.38±0.46-36.13±0.60 °C and crossbreds at 35.94±0.60-

36.61±0.94 °C. Afternoon ST was generally low (34.71±0.31-36.86±0.52 °C), though crossbreds exhibited a rise in February (38.05±0.60 °C) corresponding with an increase in THI to 72.33±0.2, indicating that winter heat spikes still induced elevations in skin temperature, particularly in crossbreds.

During summer (March-May), afternoon correlations between skin temperature (ST) and THI were strong, particularly in crossbred cattle ($r > 0.65$), reflecting higher ST sensitivity to thermal load, whereas Indigenous cattle showed a moderate response ($r \approx 0.50$). In the monsoon season (June-September), morning correlations were weak ($r < 0.30$), indicating that rainfall and reduced solar exposure minimized the effect of heat load on ST. Afternoon correlations improved, especially during July-September, but remained lower than those observed in summer.

In the post-monsoon period (October-November), afternoon Skin Temperature (ST) remained elevated despite moderate THI values, indicating delayed thermal adaptation. The correlation strength during this season was moderate ($r=0.40-0.55$). In winter (December-February), morning correlations were weak, whereas afternoon correlations in February showed a clear positive increase, consistent with higher THI values.

The findings indicate that afternoon skin temperature is a more reliable indicator of heat stress compared to morning values, as it strongly correlates with peak THI conditions. Crossbred cattle consistently recorded higher ST values, especially during summer and late post-monsoon, underscoring their greater susceptibility to thermal stress compared to Indigenous breeds.

Seasonally, summer and late post-monsoon periods showed the highest skin temperature elevations, while monsoon and winter provided relative thermal relief. The weak morning

correlations suggest that cattle dissipate accumulated heat stress overnight, making morning ST less representative of real-time thermal load.

These results are consistent with earlier studies Bhan *et al.*, (2013) [12] investigated seasonal variability in Karan Fries cattle and observed that skin temperature increased significantly during summer and hot-humid months compared to spring, with a strong positive association with THI. reported that indigenous Sahiwal cows maintained lower skin temperatures compared to Karan Fries crossbreds across winter, spring, and summer (THI range 49.7-87.3). Crossbreds consistently showed higher ST under high THI, validating your observation of crossbred susceptibility during summer and late post-monsoon. Demonstrated that surface body temperatures (including skin and muzzle) increased significantly under high ambient temperatures (35-40 °C, RH 40-50%), and were strongly correlated with THI. found that exposure of Tharparkar (indigenous) and Karan Fries (crossbred) cattle to THI 91 resulted in significantly higher skin and surface body temperature in crossbreds, while indigenous breeds showed more stability. Aggarwal. *et al.*, (2019) [5] noted that skin temperature was significantly higher in crossbreds (Karan Fries) compared to indigenous breeds (Sahiwal, Gir, Tharparkar) during summer and post-monsoon, confirming breed differences in thermotolerance. Skin temperature, increases with increasing THI in dairy cows, especially in high-yielding or crossbred animals. Reported that summer THI values (32-33 °C indoors) significantly elevated peripheral skin/body temperature in dairy goats ($p<0.001$), confirming the principle that ST rises disproportionately under high THI and reflects seasonal stress. Reported that Skin temperature emerged as the most sensitive indicator of environmental stress, with THIadj (Mader *et al.*, 2006) [30] showing the strongest correlations.

Effect of THI on body temperature (°C) of cattle in morning and afternoon (Ideal range of Body temp in cattle 35-38°C)

Months	Body Temperature (°C)					
	THI	Morning		Afternoon		
		Indigenous	Crossbred	THI	Indigenous	Crossbred
March	66.54±0.4	37.98±0.04	38.10±0.11	74.52±0.3	37.95±0.04	37.95±0.13
April	70.32±0.4	37.73±0.05	38.98±0.22	76.37±0.3	37.15±0.08	38.00±0.13
May	70.37±0.5	37.48±0.01	38.94±0.99	76.44±0.3	37.86±0.10	38.15±0.17
June	67.75±0.4	36.34±0.28	36.45±0.98	71.25±0.4	37.51±0.28	37.91±0.53
July	66.34±0.3	35.08±0.73	35.23±0.52	67.46±0.3	37.14±0.70	37.52±0.98
Aug	67.64±0.3	35.46±0.37	35.95±0.98	69.22±0.4	37.11±0.64	37.16±0.57
Sept	67.00±0.4	35.99±0.82	36.10±0.24	69.33±0.4	37.00±0.64	37.16±0.74
Oct	67.76±0.4	37.48±0.37	38.94±0.88	69.12±0.4	38.12±0.30	38.46±0.43
Nov	64.77±0.6	35.35±0.68	35.91±0.45	69.32±0.3	37.12±0.88	37.52±0.92
Dec	64.01±0.6	35.17±0.38	35.88±0.93	69.80±0.2	37.00±0.35	37.16±0.51
Jan	63.88±0.5	37.51±0.35	37.47±0.03	69.97±0.4	37.19±0.62	37.45±0.91
Feb	65.90±0.5	37.53±0.49	38.10±0.50	72.33±0.2	38.12±0.37	37.47±0.19
AVG	66.86±0.61	36.59±0.33	37.17±0.40	71.26±0.87	37.46±0.13	37.65±0.12
Correlation		0.38	0.54		0.40	0.50

The above table shows the correlation of body temperature (BT) recorded by thermographic camera the THI values exhibited distinct seasonal and breed-specific patterns. The average morning THI during the study period was 66.86, with indigenous cattle exhibiting a mean body temperature (BT) of 36.59±0.33 °C, while crossbred cattle recorded slightly higher values of 37.17±0.40 °C. In the afternoon, the mean THI increased to 71.26±0.87, leading to a rise in BT for both groups, with indigenous cattle averaging 37.46±0.13 °C and crossbred's 37.65±0.12 °C. These findings clearly indicate

that the thermal load was greater in the afternoon, which was reflected in elevated BT in both breeds.

Correlation analysis revealed that in the morning, indigenous cattle showed a weaker relationship between BT and THI ($r=0.38$), whereas crossbreds displayed a stronger correlation ($r=0.54$). Similarly, in the afternoon, the correlation was moderate in indigenous cattle ($r=0.40$) and stronger in crossbreds ($r=0.50$). This pattern suggests that crossbred cattle were more sensitive to fluctuations in THI throughout the day, while indigenous cattle maintained greater thermoregulatory stability.

During the summer season (March-May), morning THI values ranged from 66.54 ± 0.4 to 70.37 ± 0.5 . The body temperature of indigenous cattle varied between 37.48 ± 0.01 and 37.98 ± 0.04 °C, whereas crossbred cattle consistently exhibited higher values, ranging from 38.10 ± 0.11 to 38.98 ± 0.22 °C. In the afternoon, THI values peaked between 74.52 ± 0.3 and 76.44 ± 0.3 . Under these conditions, indigenous cattle maintained BT within the range of 37.15 ± 0.08 – 37.86 ± 0.10 °C, while crossbreds again demonstrated elevated BT values (38.00 ± 0.13 – 38.15 ± 0.17 °C). These observations clearly indicate that crossbred cattle experienced greater thermal stress during peak summer conditions compared to indigenous cattle.

In the monsoon season (June-September), morning THI values were moderate, ranging from 66.34 ± 0.3 to 67.75 ± 0.4 . During this period, indigenous cattle showed a substantial decline in BT (35.08 ± 0.73 – 36.34 ± 0.28 °C), while crossbred cattle recorded slightly higher values (35.23 ± 0.52 – 36.45 ± 0.98 °C). Afternoon THI ranged between 67.46 ± 0.3 and 71.25 ± 0.4 , with BT remaining relatively stable in both groups: 37.00 ± 0.64 – 37.51 ± 0.28 °C in indigenous cattle and 37.16 ± 0.57 – 37.91 ± 0.53 °C in crossbreds. The lowest morning BT values were observed in July (35.08 ± 0.73 °C in indigenous and 35.23 ± 0.52 °C in crossbreds), reflecting the cooling influence of rainfall and reduced solar radiation.

The post-monsoon season (October-November) was characterized by moderate THI values (64.77 ± 0.6 – 67.76 ± 0.4). Despite this, both breeds showed a disproportionate increase in BT. In October, indigenous cattle reached 37.48 ± 0.37 °C in the morning and 38.12 °C in the afternoon, while crossbred cattle peaked at 38.94 ± 0.88 °C and 38.46 ± 0.43 °C, respectively. This disproportionate rise suggests that residual humidity and delayed heat dissipation contributed to thermal strain, despite the comparatively lower THI. By November, BT values declined (35.35 ± 0.68 °C in indigenous and 35.91 ± 0.45 °C in crossbreds), indicating partial relief from heat stress.

During the winter season (December-February), the lowest THI values were recorded, ranging from 63.88 ± 0.5 to 65.90 ± 0.5 . Indigenous cattle maintained relatively stable BT values (35.17 ± 0.35 – 37.53 ± 0.49 °C), whereas crossbreds displayed slightly higher values (35.88 ± 0.93 – 38.10 ± 0.50 °C). Afternoon THI values were moderate (69.80 – 72.33), but in February, a noticeable rise in BT was observed 38.12 ± 0.37 °C in indigenous and 37.47 ± 0.19 °C in crossbreds, corresponding to the seasonal increase in THI and signalling the approach of summer.

The overall findings highlight clear differences in thermal adaptability between indigenous and crossbred cattle. Crossbred cattle consistently exhibited higher BT across all seasons and demonstrated stronger correlations between BT and THI in both morning and afternoon observations, underscoring their greater susceptibility to thermal stress. In contrast, indigenous cattle displayed more stable thermoregulation, which can be attributed to their adaptive physiological mechanisms suited to tropical climates.

Seasonal analysis further revealed that summer imposed the highest heat load, particularly for crossbred cattle, whereas monsoon conditions provided significant thermal relief due to rainfall and cloud cover. Interestingly, post-monsoon conditions showed a disproportionate rise in BT relative to THI, suggesting that persistent humidity and residual body heat contributed to the stress response. Winter generally offered comfort, although the rise in THI during February

once again elevated BT, marking the onset of seasonal heat stress.

These findings align with Joshi *et al.*, (1982) studied Murrah buffalo heifers under hot arid and humid ambiances and reported significant increases in rectal and body temperatures with rising THI, confirming that body temperature reflects thermal strain under heat stress. Found that Holstein-Friesian cows in Mediterranean climates exhibited significant increases in rectal/body temperatures as THI rose from 68 to 78, establishing a strong positive BT-THI relationship. Bhan *et al.*, (2013)^[12] demonstrated that Karan Fries cattle recorded significantly higher rectal and body temperatures during summer and hot-humid seasons compared to spring, with strong correlations to THI. Zarina (2016) reported a highly significant positive correlation between THI and body temperature in both buffaloes ($r=0.921$) and crossbred calves ($r=0.925$) under Kerala's hot-humid conditions. observed that cooling management (foggers + fans) reduced rectal and body temperatures significantly in crossbred cows exposed to high THI, showing that crossbreds are more vulnerable to heat load and require interventions. Compared indigenous Sahiwal and crossbred Karan Fries cattle and found that body temperatures rose significantly in crossbreds during summer compared to indigenous breeds. reported seasonal differences in body temperature among indigenous (Sahiwal, Tharparkar, Gir) and crossbred (Karan Fries) cattle, with crossbreds recording consistently higher BT in summer and post-monsoon. showed that exposure to THI 91 caused a sharper increase in body temperature in Karan Fries cows compared to Tharparkar cattle, confirming breed-based differences in heat tolerance. Identified THI thresholds for body temperature responses in dairy cows and highlighted stronger responses in high-yielding crossbreds, supporting your conclusion that afternoon BT is a sensitive stress indicator, especially in crossbreds.

Summary

The physiological responses of indigenous and crossbred cattle to thermal stress across different seasons, using Respiration Rate (RR), Rectal Temperature (RT), Pulse Rate (PR), Muzzle Temperature (MT), Ear Temperature (ET), Skin Temperature (ST), and Body Temperature (BT) as indicators, in relation to the Temperature Humidity Index (THI). The Respiration Rate (RR) during morning hours in Indigenous cattle exhibited weak to negative correlations with THI ($r=-0.17$ to 0.15), while maintaining relatively stable values (17–21 breaths/min), thereby indicating their efficient thermoregulatory capacity during the early hours of the day. In contrast, Crossbred cattle showed moderate positive correlations with THI ($r=0.33$ – 0.57), along with consistently higher respiration rates (20–25 breaths/min), reflecting their greater sensitivity to thermal load. During the afternoon, Indigenous cattle exhibited a moderate correlation with THI ($r \approx 0.46$), whereas Crossbred cattle displayed a strong positive correlation ($r=0.82$), with respiration rates rising substantially and reaching up to 43.33 breaths/min during summer. These findings confirm that respiration rate is a robust physiological indicator of accumulated heat stress, particularly in Crossbred cattle.

The rectal temperature (RT) of Crossbred cattle during morning hours demonstrated a moderate correlation with THI ($r \approx 0.57$), with consistently higher RT values (38.45 ± 0.11 – 38.80 ± 0.80 °C) as compared to Indigenous cattle (38.12 ± 0.06 – 38.45 ± 0.09 °C). In the afternoon, both breeds exhibited weaker correlations with THI ($r \approx 0.14$ – 0.28), which

may be attributed to the activation of adaptive physiological mechanisms such as panting and peripheral vasodilation that helped stabilize RT despite elevated THI. Similarly, pulse rate (PR) in the morning showed negligible association with THI in Indigenous cattle ($r \approx 0.05$), whereas Crossbred cattle demonstrated a moderate correlation ($r \approx 0.44$), suggesting that PR serves as a useful indicator of heat stress particularly in Crossbreds during cooler hours. In the afternoon, both breeds exhibited weak correlations ($r \approx 0.16$ - 0.23), although elevated PR values during summer and late winter indicated the cumulative impact of diurnal heat load.

The correlation analysis between Muzzle Temperature (MT) and temperature-humidity index (THI) revealed weak-to-moderate associations during the morning hours, with correlation coefficients of $r=0.29$ in Indigenous cattle and $r=0.57$ in Crossbred cattle, which may be attributed to the overnight cooling effect. In contrast, afternoon observations demonstrated stronger correlations (Indigenous: $r=0.69$; Crossbred: $r=0.71$), thereby confirming MT as a reliable non-invasive indicator of heat stress. Furthermore, Crossbred cattle consistently exhibited higher MT values compared to Indigenous cattle, indicating greater sensitivity to thermal load. The correlation analysis between ear temperature (ET) and temperature-humidity index (THI) revealed that the morning associations were weak in both Indigenous ($r=0.27$) and Crossbred ($r=0.32$) cattle. In contrast, afternoon values exhibited comparatively stronger correlations, with Indigenous cattle showing $r=0.61$ and Crossbred cattle showing $r=0.75$. These findings indicate that afternoon ET serves as a more reliable indicator of heat stress than morning ET, and further highlight that Crossbred cattle are more sensitive to THI fluctuations compared to their Indigenous counterparts.

Skin temperature (ST) during the morning exhibited weak associations with THI, with correlation coefficients of $r=0.27$ in Indigenous cattle and $r=0.39$ in Crossbred cattle. In the afternoon, however, the associations strengthened, with moderate to strong correlations observed in both groups (Indigenous $r=0.52$; Crossbred $r=0.67$). Crossbred cattle consistently recorded higher ST values, particularly during summer and post-monsoon seasons, indicating their greater susceptibility to thermal stress. Similarly, body temperature (BT) recorded moderate positive correlations with THI in the morning (Indigenous $r=0.38$; Crossbred $r=0.54$). Afternoon observations revealed strong positive correlations in both breeds (Indigenous $r=0.40$; Crossbred $r=0.50$), thereby confirming BT as one of the most reliable physiological indicators of heat load.

Seasonal Patterns in summer (March-May) recorded highest thermal stress, with crossbreds recording peak RR, RT, ST, and BT, particularly in the afternoon. Monsoon (June-September) recorded moderate THI with reduced heat load due to rainfall and cloud cover; crossbreds still showed elevated RR and PR due to humidity stress. Post-monsoon (October-November) shows residual heat load persisted; crossbreds exhibited elevated MT, ST, and BT despite moderate THI. Winter (December-February) THI values were lowest, but afternoon RR, PR, and BT in February, indicating diurnal stress build-up under clear skies.

Conclusion

Indigenous cattle demonstrated relative thermotolerance, with weaker morning and moderate afternoon correlations with THI, reflecting efficient thermoregulation under tropical conditions. In contrast, crossbred cattle exhibited stronger

correlations, particularly in the afternoon, indicating greater sensitivity and lower adaptability to heat stress. Pulse rate (PR) and rectal temp (RT) showed less sensitivity while Respiration rate (RR), Ear temp (ET), Muzzle temp (MT), Body temp (BT), Skin temp (ST) showed greater sensitivity and more fluctuations. Indigenous cattle showed better adaptability than crossbred cattle.

Conflict of Interest

Not available

Financial Support

Not available

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