REGULAR ARTICLES

Analysis of the effects of thermal stress on milk production in a humid tropical climate using linear and non-linear models

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Abstract

The decline of milk production in crossbred cattle during the onset of summer was evaluated using lactation records of the cows ($n = 48$) maintained at the Livestock Research Station, Thiruvazhamkunnu, for the period between January 2019 and March 2019. Climate data were obtained from an automatic weather station maintained on the campus. The temperature-humidity index (THI) was used to assess the thermal stress on animals. Values varied between 70.78 and 83.93 during the study period, indicating that the cows were exposed to mild and moderate stress. Highly significant negative correlations ($p < 0.01$) were observed between the average temperature, THI, and milk production. Linear, logarithmic, power, and polynomial models linking milk production and THI were used to fit the data. The coefficient of determination (R^2) in general exceeded 0.85 and these equations could be used to model the drop in milk production or predict production loss due to thermal stress. The rate of decline in daily milk production observed in the study was 2.13% per unit increase in THI. A general linear model that included THI, parity, and the stage of lactation as independent variables, and milk production as a response variable, was also tested. Parity and stages of lactation were observed to influence forenoon and afternoon milk production significantly ($p < 0.01$). The temperature-humidity index also had a significant effect on forenoon milk production ($p < 0.05$) and afternoon milk production ($p < 0.01$).

Keywords Cattle · Milk Production · Thermal stress and THI

Introduction

Milk production in bovines is a complex biochemical process regulated by neuroendocrine mechanisms. The different processes which regulate the development of mammary glands and lactation have been reviewed by Akers (2017) and Bhimte et al. (2018), among others. Milk production is also influenced by a range of genetic factors and certain non-genetic factors such as the plane of nutrition, the season, and the different stages of lactation, parity, etc. and these are outlined by Boro et al. (2016).

Tropical dairy production systems are exposed to problems that include thermal stress, inadequate nutrition, poor infrastructure, and competition with imports from temperate countries (Hernández-Castellano et al. 2019). Published research indicates that milk production is adversely affected by warm and humid conditions (Todorović et al. 2011; Yano et al. 2014; Liu et al. 2019). Heat or thermal stress develops when the ability of animals to dissipate heat becomes compromised by a combination of environmental factors such as high relative humidity (RH), ambient temperature, solar radiation, and lack of air movement. Some of the common manifestations include general discomfort, polypnea, exhaustion, heat syncope, and heat stroke (Todorović et al. 2011). Reports indicate that certain coat characteristics such as hair angle and hair length (Anzures et al. 2019) and diet regimen (Gonzalez-Rivas et al. 2018) can also contribute to thermal stress in cattle.

Heat stress in dairy bovines needs to be assessed in the context of global warming and climate change. 'Global warming' here refers to the warming of oceans and near-surface air due to human activity, which became evident in the latter part of the twentieth century. The average temperature rose by 0.74 ± 0.18 °C in the last century and is projected to rise much further, by 1.1 to 6.4 °C, in the twenty-first century (IPCC 2007). Simulation studies predict that an

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increase in temperature of more than1.8 °C will negatively affect livestock production in Southeast Asian countries such as Malaysia, Thailand, Vietnam, Cambodia, and the Philippines (Darwin 2001). Analysis of weather data during the three decades from 1981 to2012 indicates that the mean temperature for March had increased by 1.2 to 2.4 °C and that the effects of climate change were evident in the major urban centres of Kerala, India(Anie 2012).

Thermal stress in cattle is assessed using the temperature-humidity index (THI), which combines the effects of temperature and relative humidity on animals (Habeeb et al. 2018). Even though most studies agree that milk production falls as a result of thermal stress, relatively few studies have examined the rate of decline. Such studies are essential to anticipating production loss and developing appropriate strategies, especially in the context of climate change (Kumar and Gautam 2014). The present investigation was carried out to determine the nature and rate of change in milk production due to an increase in ambient temperature and find out an efficient model to predict a decline in dairy output in a humid tropical climate. This study will help to focus on ameliorating measures to reduce the impact of thermal stress on milk production.

Materials and methods

Milk production records from crossbred dairy cows ($n = 48$) maintained at the Livestock Research Station, Thiruvazhamkunnu, were used for the study. The study period is from January to March 2019. The average parity (mean ± SE, number) of the selected animals was 2.44 ± 1.10. The days in milk (mean ± SE, days) of the group were 79.29 ± 8.45 at the beginning of the study. Selected animals were reared under uniform management conditions and had continuous milk production during the period of the study ($n = 90$ days).

The animals were housed in an open, double-row tie-stall with a full monitor type of roof, in the tail-to-tail orientation. The east and west sides of the stall were devoid of walls except for the outer curb of the manger (height = 70 cm), which facilitated the free movement of air. Air circulation was further ensured with six fans, which were switched on between 12.00 PM and 5.00 PM, Indian standard time (IST). Concentrated feed and mineral mixtures were prepared as per the specifications of the Bureau of Indian Standards and were used for feeding the animals. Roughage, concentrate, and the mineral mixture were fed according to the package of practices and recommendations published by Kerala Veterinary and Animal Sciences University (KVASU 2016). Pelleted concentrates were fed twice daily at 4.00 AM and 12.30 PM (IST) before milking. Each cow was fed with 30kgof hybrid napier grass per day as green fodder. Water was provided ad libitum. Cows were grouped based on the number of days in milk, as early-stage or stage I (between 1 and 100 days), mid-stage or stage II (101–200 days), and later stage or stage III, when lactation exceeded 200 days (Vijayakumar et al. 2017). Animals were classified into four groups based on parity. Cows with first, second, third, and fourth parities formed these groups.

Data on weather parameters such as the daily average temperature, average relative humidity, and maximum and minimum temperatures, were obtained from an automatic weather station maintained on the campus (CR 800, Campbell Scientific, the USA). Pearson correlation coefficients were calculated between the weather parameters and the periods of morning, evening, and daily milk production. Livestock and poultry heat stress indices developed by Clemson University were calculated using the following formula: $\text{THI} = T_{air} - (0.55 - [0.55 \times RH/100]) \times (T_{air} - 58)$, where THI = temperature humidity index, T_{air} = average air temperature in Fahrenheit, RH = average relative humidity percentage (LPHSI 1990). Forenoon and afternoon milk production data obtained from 48 animals over 90 days ($n = 4320$) were used for statistical analysis.

Temperature, relative humidity, THI, and milk production were grouped according to the weeks of study and were analysed using ANOVA and Duncan's multiple range tests. Univariate and general linear models were fitted with morning, afternoon, daily and weekly milk production data. Univariate models (linear, logarithmic, power, and polynomial functions) were prepared using the excel spreadsheet application of Microsoft Office. Root mean square error (RMSE) was calculated using the equation given below, where O_i is the observed value, P_i is the predicted value and n is the number of observations.

$$\text{RMSE} = \sqrt{\dfrac{1}{n \sum\limits_{i=1}^{n} (O_i - P_i)^2}}$$

Linear functions were differentiated with respect to THI to ascertain the rate of change in milk production. A general linear model connecting morning, evening, or total milk yields with THI, parity, and stage of lactation, taken as fixed effects, were prepared using SPSS (version 24). The model used along with the Bonferroni test (post hoc) was $Y_{ijk} = \mu + T_i + P_j + S_k + \varepsilon_{ijk}$, where Y_{ijk} = milk production (kg); μ = overall mean; T_i = effect of THI ($i = 1$ to 3); P_j = effect of parity ($j = 1$ to 4); S_k = effect of stage of lactation ($k = 1$ to 3); ε_{ijk} = residual error.

Results

The lactation length (mean ± SE, days) of the group was 79.29 ± 8.45 at the beginning of the study, which increased

to 169.29 ± 8.45 at the end of the experiment. The temperature-humidity index, calculated from the average day temperature and RH during the period of study, varied from 70.78 to 83.93. Significant differences were noted in weather and production variables as the season changed from colder January to hotter March. The summary of observations is presented in Table 1.

The days in milk of the group (mean $\pm$ SE, days) increased to 169.29 ± 8.45 at the end of the experiment. The temperature-humidity index, calculated from the average day temperature and RH during the period of study, varied from 70.78 to 83.93. Significant differences were noted in weather and production variables as the season changed from colder January to hotter March. The summary of observations in this regard is presented in Table 1.

Pearson correlation coefficients between milk production, weather variables, and THI are presented in Table 2. Highly significant negative correlations ($p < 0.01$) were observed between the average day temperature, as well as the daily maximum and daily minimum temperatures, and milk production. Average relative humidity was also negatively correlated with total milk production ($p < 0.05$). The resulting THI values were also negatively correlated ($p < 0.01$) with milk production.

The plot of average weekly THI values throughout the study (13 weeks) against milk production is presented in chronological order in Fig. 1.

The equations of trend lines fitted in Microsoft Excel using exponential, linear, logarithmic, polynomial, and power

Table 2 Pearson correlations between weather variables and milk production

Parameter	Milk production		
	Morning	Evening	Daily
Temperature (average)	-0.887^{**}	-0.889^{**}	-0.904^{**}
Temperature (maximum)	-0.825^{**}	-0.832^{**}	-0.843^{**}
Temperature (minimum)	-0.744^{**}	-0.727^{**}	-0.752^{**}
Relative humidity (average)	-0.208	-0.207	-0.211^{*}
Relative humidity (maximum)	-0.106	-0.063	-0.092
Relative humidity (minimum)	0.011	0.007	0.010
THI (maximum)	-0.842^{**}	-0.838^{**}	-0.856^{**}
THI (average)	-0.878^{**}	-0.874^{**}	-0.893^{**}

$^{**}p < 0.01$
$^{*}p < 0.05$

functions are presented in Table 3. The rate of change in milk production along with the unit change in THI observed in the present study is presented in Table 4. The general linear model connecting total milk production with THI, parity, and stage of lactation, indicates that all independent variables have a highly significant effect ($p < 0.01$) on afternoon and daily milk production levels. A similar highly significant effect ($p < 0.01$) of independent variables was noticed in the case of forenoon milk production, except for THI, which had only a significant effect ($p < 0.05$). These results are presented in Table 5.
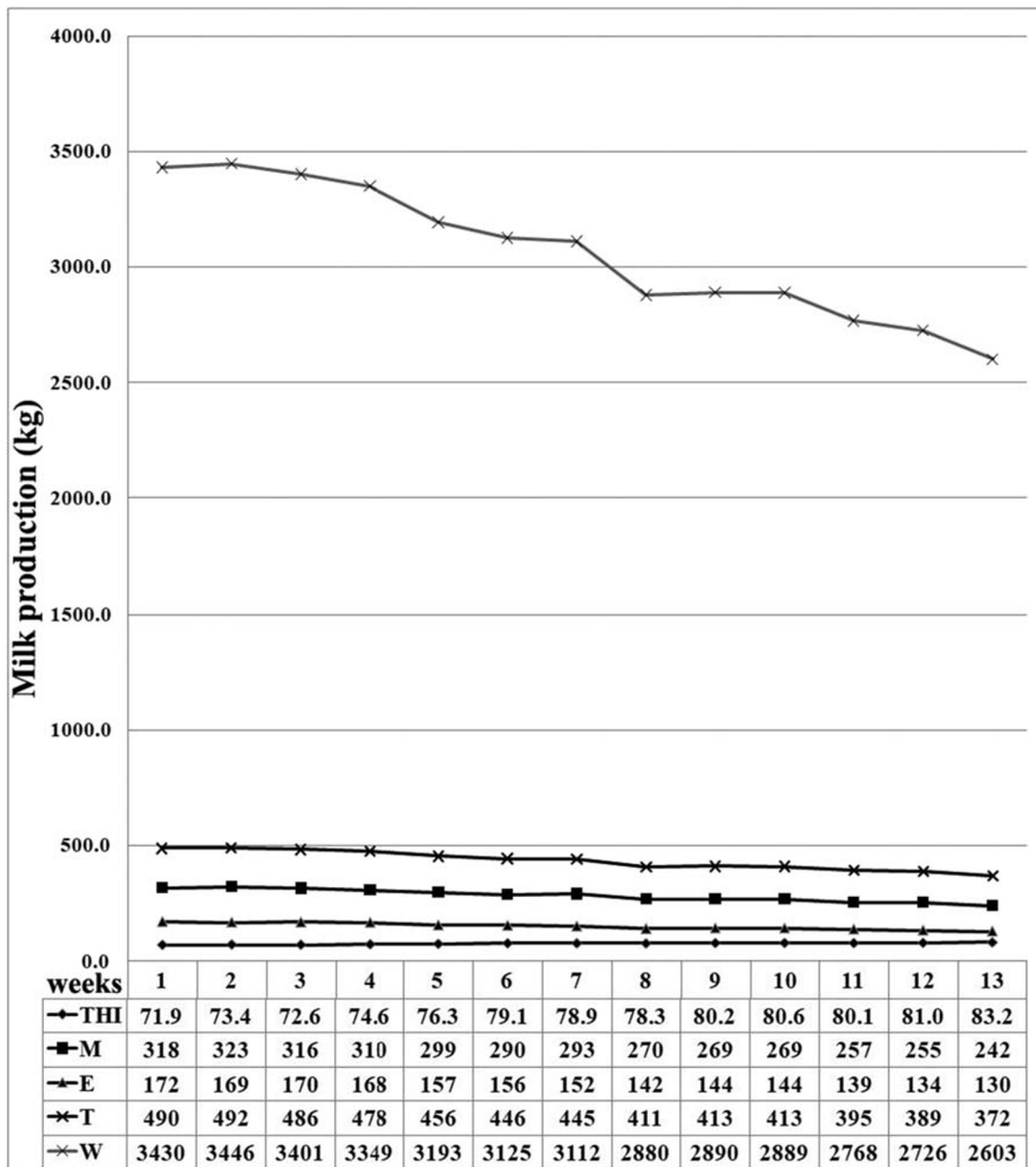
Table 1 Variations in weather and production parameters

Weeks	Parameters (mean $\pm$ SE)			Daily milk production (mean $\pm$ SE, kg)		
	T (°C)	RH (%)	THI	Forenoon	Afternoon	Total
1	23.67 ± 0.31^{a}	$70.17 \pm 3.58^{a,b}$	71.88 ± 0.56^{a}	$317.93 \pm 4.67^{a,b}$	172.07 ± 2.65^{a}	490.00 ± 4.29^{a}
2	$24.22 \pm 0.17^{1a,b}$	$77.44 \pm 2.09^{a,b,c,d}$	$73.41 \pm 0.30^{b,c}$	323.21 ± 2.28^{a}	169.00 ± 1.31^{a}	492.21 ± 3.18^{a}
3	$24.08 \pm 0.08^{a,b}$	$71.60 \pm 3.65^{a,b,c}$	$72.63 \pm 0.37^{a,b}$	$316.07 \pm 3.06^{a,b}$	169.79 ± 1.93^{a}	$485.86 \pm 3.87^{a,b}$
4	24.67 ± 0.46^{b}	81.91 ± 0.68^{d}	74.58 ± 0.79^{c}	310.07 ± 2.07^{b}	168.29 ± 1.66^{a}	478.36 ± 2.05^{b}
5	26.10 ± 0.16^{c}	$77.15 \pm 1.15^{a,b,c,d}$	76.34 ± 0.21^{d}	298.71 ± 4.79^{c}	157.43 ± 2.16^{b}	456.14 ± 6.38^{c}
6	27.50 ± 0.26^{d}	81.40 ± 2.41^{d}	$79.07 \pm 0.25^{e,f}$	290.36 ± 2.41^{d}	156.07 ± 1.88^{b}	$446.43 \pm 3.37^{c,d}$
7	$28.11 \pm 0.17^{d,e}$	$72.27 \pm 4.39^{a,b,c}$	$78.85 \pm 0.65^{e,f}$	$292.57 \pm 1.87^{c,d}$	151.93 ± 3.03^{b}	444.50 ± 4.33^{d}
8	$27.98 \pm 0.31^{d,e}$	70.01 ± 4.81^{a}	78.31 ± 0.63^{e}	269.64 ± 2.99^{e}	141.79 ± 2.29^{c}	411.43 ± 5.06^{e}
9	$28.29 \pm 0.17^{e,f}$	$79.77 \pm 1.04^{c,d}$	$80.16 \pm 0.35^{f,g}$	268.79 ± 2.23^{e}	144.07 ± 1.52^{c}	412.86 ± 2.50^{e}
10	$28.18 \pm 0.16^{d,e}$	84.71 ± 1.16^{d}	80.64 ± 0.23^{g}	269.07 ± 1.75^{e}	143.57 ± 1.42^{c}	412.64 ± 2.84^{e}
11	$28.48 \pm 0.12^{e,f}$	$76.87 \pm 1.08^{a,b,c,d}$	$80.05 \pm 0.28^{f,g}$	256.71 ± 1.21^{f}	$138.71 \pm 1.06^{c,d}$	395.43 ± 1.16^{f}
12	28.93 ± 0.16^{f}	$78.58 \pm 1.48^{b,c,d}$	81.10 ± 0.37^{g}	255.00 ± 0.98^{f}	$134.43 \pm 1.39^{d,e}$	389.43 ± 1.93^{f}
13	30.07 ± 0.13^{g}	81.13 ± 0.58^{d}	83.21 ± 0.20^{h}	241.83 ± 1.95^{g}	130.00 ± 1.15^{e}	371.83 ± 2.11^{g}

Means with different superscripts across a column differ significantly ($p < 0.01$)

T, average temperature; RH, average relative humidity

Weeks 1–4 = January; Week 5 = January–February; Weeks 6–8 = February; Week 9 = February–March; Weeks 10–13 = March

weeks	1	2	3	4	5	6	7	8	9	10	11	12	13
THI	71.9	73.4	72.6	74.6	76.3	79.1	78.9	78.3	80.2	80.6	80.1	81.0	83.2
M	318	323	316	310	299	290	293	270	269	269	257	255	242
E	172	169	170	168	157	156	152	142	144	144	139	134	130
T	490	492	486	478	456	446	445	411	413	413	395	389	372
W	3430	3446	3401	3349	3193	3125	3112	2880	2890	2889	2768	2726	2603

Fig. 1 Variation in total milk production with THI. X axis: period of study in weeks; Y axis: milk production (kg). Series labels: THI, temperature humidity index; M, morning; E, evening; T, daily milk production; W, weekly milk production

Discussion

Palakkad district lies between 10° 21′ N and 11° 14′ N latitudes, and 76° 02′ E and 76° 54′ E longitudes, and has an area of 4476 km². The region experiences a humid and sub-humid climate with an average rainfall of 2171 mm per year (Premakumar et al. 2015). The maximum day temperature ranged between 32.27 °C and 41.05 °C during the period of study. During these same 3 months, the average relative humidity varied between 44.1 and 92.3%. Subramanyam et al. (2017) reported a similar range of RH during this period in the

Palakkad district, with a slightly different range of maximum day temperatures from 33.1 °C to 38.6 °C.

The variables of average temperature (T) and THI during the 13 weeks of study were classified by a post hoc test into ten subgroups. However, only four groups were observed in the case of relative humidity, which implied that variations in RH were lower than that of temperature during the period. Therefore, it could be concluded that an increase in temperature contributes more to the development of heat stress in dairy cattle than RH does. It was observed that temperature ($p < 0.01$), THI ($p < 0.01$), and relative humidity ($p < 0.05$)

Table 3 Equations for forenoon, afternoon, daily and weekly milk production

Time/period of lactation	Type of function	Function*	R square	RMSE (kg)
Forenoon	Exponential	$y = 1954.e^{-0.02x}$	0.874	129.12
	Linear	$y = -7.072x + 834.9$	0.886	8.75
	Logarithmic	$y = -543.\ln(x) + 2649.$	0.880	8.96
	Polynomial-2nd degree	$y = -0.327 \times^2 + 43.43x - 1108.$	0.903	8.62
	Power	$y = 1E+06x^{-1.90}$	0.868	29.59
Afternoon	Exponential	$y = 1070.e^{-0.02x}$	0.891	74.81
	Linear	$y = -3.839x + 450.4$	0.901	4.37
	Logarithmic	$y = -295.\ln(x) + 1436.$	0.898	4.43
	Polynomial-2nd degree	$y = -0.095 \times^2 + 10.89x - 116.3$	0.906	5.26
	Power	$y = 68,481x^{-1.93}$	0.887	5.30
Daily	Exponential	$y = 3025.e^{-0.02x}$	0.885	204.05
	Linear	$y = -10.91x + 1285.$	0.896	12.79
	Logarithmic	$y = -838.\ln(x) + 4086$	0.892	13.15
	Polynomial- 2nd degree	$y = -0.422 \times^2 + 54.32x - 1225$	0.908	13.18
	Power	$y = 2E+06x^{-1.91}$	0.879	57.30
Weekly	Exponential	$y = 21187e^{-0.02x}$	0.885	1430.94
	Linear	$y = -76.39x + 8998.$	0.896	89.52
	Logarithmic	$y = -5870\ln(x) + 28,606$	0.892	91.41
	Polynomial-2nd degree	$y = -2.966 \times^2 + 381.1x - 8609.$	0.908	84.14
	Power	$y = 1E+07x^{-1.91}$	0.879	607.46

*y = milk production; x = THI

were correlated significantly with milk production. Averages of temperature and relative humidity had a higher correlation with milk production than either the maxima or minima of these variables.

Since THI integrates both temperature and relative humidity, it was selected as the predictor in a univariate setting and was included in the general linear model. A temperature-humidity value of between 72 and 79 exposed the dairy cattle to mild thermal stress, which increased to a moderate level of stress when the THI value rose to between 79 and 89, beyond which the cows experienced severe thermal stress (West 1993; Kohli et al. 2014).

During the present study, animals exhibited milk symptoms of stress when the THI was between 72 and 79 in weeks 1 to 5. Stress increased to a moderate level after the fifth week

and remained so until the end of the study. By the time thermal stress had progressed from a mild to a moderate level, a production loss of 9% was observed.

Production losses of as much as 4 kg per cow per day have been recorded in China due to thermal stress, as assessed using THI (Ranjitkar et al. 2020). A loss in milk production due to heat stress has also been reported in Nili Ravi buffaloes reared under subtropical conditions (Ahmad et al. 2018). Therefore, the production losses due to thermal stress observed in the present study could be interpreted as a hallmark of tropical dairy production systems. A decline in milk production due to heat stress has also been reported in Holstein cows raised in temperate regions (Kino et al. 2018).

The coefficient of determination (R^2) is a measure of the extent to which the model explains variations in the data

Table 4 Rate of change in milk production with respect to THI

Type of lactation	Function	Rate of change (dy/dx)	% change
Forenoon	$y = -7.072x + 834.9$	-7.072 kg	-2.15
Afternoon	$y = -3.839x + 450.4$	-3.839 kg	-2.10
Daily	$y = -10.91x + 1285.$	-10.91 kg	-2.13
Weekly	$y = -76.39x + 8998.$	-76.39 kg	-2.31

Table 5 ANOVA table from GLM procedure

Source of variation	Forenoon production			Afternoon production			Daily production		
	df	F	Sig.	df	F	Sig.	df	F	Sig.
Corrected model	7	417.7	0.000[a]	7	360.1	0.000[a]	7	434.1	0.000[a]
Intercept	1	14,358.5	0.000[a]	1	15,193.8	0.000[a]	1	15,962.1	0.000[a]
THI	2	4.26	0.014[b]	2	7.5	0.001[a]	2	5.7	0.003[a]
Stage	2	887.1	0.000[a]	2	709.2	0.000[a]	2	899.6	0.000[a]
Parity	3	248.1	0.000[a]	3	237.9	0.000[a]	3	268.6	0.000[a]
Error	4312			4312			4312		
Total	4320			4320			4320		
Corrected total	4319			4319			4319		

[a]($p < 0.01$) $R^2 = 0.404$ (adjusted $R^2 = 0.403$) $R^2 = 0.369$ (adjusted $R^2 = 0.368$) $R^2 = 0.413$ (adjusted $R^2 = 0.412$)
[b]($p < 0.05$)

(Schneider et al. 2010). A model with R^2 equal to one indicates that it explains all variations; therefore, the reliability of a model increases as its R^2 approaches one. Here, the R^2 values of the general linear models range from 0.37 to 0.41 and are lower than that of simpler models which consider THI alone to explain variations in milk production. Therefore, simpler models are seen to be more efficient in approximating production loss due to thermal stress.

In general, models using an exponential, linear, logarithmic, polynomial (second degree), and power functions have R^2 values exceeding 0.85. Polynomials of higher degrees also fit well with the data but have a higher root mean square error (RMSE). Exponential and power models have a high RMSE and so were found to be unsuitable for modelling the effect of thermal stress on milk production. In general, second-degree polynomial models have the highest R^2, which exceeded 0.90, and a lower RMSE. Linear and logarithmic models also fit well with the data and have similar R^2 and RMSE values. The high R^2 observed in univariate models could be because of the elimination from the analysis of animals with incomplete records due to disease or the end of lactation. The linear functions are differentiated with respect to x (THI) to obtain the rate of change in milk production (y), as the coefficient of determination is high. Since explanatory models and predictive models are conflated (Shmueli 2010), these models can be used to predict variations in milk production with THI.

The lactation curve is generally triphasic with an ascending phase, a static or persistent phase, and a descending phase. Different models explaining variations in milk production with time have been reviewed by Dongre et al. (2011). A linear mixed model was used to analyse long term milk production of Holstein Frisian and Jersey cows under harsh environmental conditions prevailing in Oman (Alqaisi et al. 2019). An adaptive dynamic model was used by researchers in the Netherlands, which estimated that the loss due to thermal stress was 31.4 ± 12.2 kg of milk per cow per annum (André et al. 2011). Logarithmic functions integrating lactation days, parity, calving month, and day length along with environmental parameters were used to model the milk production of individual cows (Yano et al. 2014).

Modelling the production of individual cows is not an objective of the present study, however; rather, it focuses on the dynamics of total milk production of the herd in response to thermal stress. A linear decrease in milk production with thermal stress has also been reported in cattle by Kino et al. (2018), which directly supports the results of this study. The linear nature of the milk production graph (Fig. 1) could be due to the averaging of the effects of parity and stage of lactation. Uniform management and the relatively short duration of the study, considering standard lactation length, are other possible factors to consider.

Conclusion

A highly significant negative correlation ($p < 0.01$) was observed between milk production and variables such as average temperature and average relative humidity, as well as THI. Parity ($p < 0.01$), stage of lactation ($p < 0.01$), and THI ($p < 0.05$) had a significant effect on milk production. Linear, logarithmic, power, and polynomial models had an R^2 of above 0.85 and a reasonable RMSE. Therefore, these functions could be used to model or predict the drop in milk production due to thermal stress under tropical conditions. The rate of decline in daily milk production due to thermal stress observed in the study was 2.13% for every unit increase in THI.

Compliance with ethical standards

Conflict of interest   The authors of this manuscript do not have any financial or non-financial interest concerning to the contents discussed therein and are not associated with any entity or organization which may have such interests.

Statement of animal rights   The study was performed using lactation records and data collection did not involve painful procedures. The cows were milked using milking machines supplied by competent manufacturers and standard procedures were followed.

Ethical standards   The manuscript does not contain clinical studies or patient data.

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