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Analysis of the climatic trends and heat stress periods for ruminants rearing in Bangladesh

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A R T I C L E I N F O

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A B S T R A C T

The production of ruminant livestock is greatly impacted by climate change, as it is anticipated to jeopardise food security due to the increasing heat stress experienced by the animals, which can be measured using the Temperature Humidity Index (THI). The objective of our study was to analyze climatic patterns, identify influential variables and evaluate heat stress episodes through the utilization of the THI to establish a rearing system for ruminants in Bangladesh. The THI value was determined by analyzing meteorological station data spanning from 1995 to 2022 across various climatic zones in Bangladesh. The Mann–Kendall evaluation was used to analyze the THI patterns throughout the study. Our findings indicated that heat stress problems are expected to occur in Bangladesh when THI for ruminant rearing exceeds 74, particularly from February to December. The severity of heat stress in $THI_{ruminant}$ 71–90 varied significantly, ranging from normal to extremely severe. We observed that June (90) was the hottest month in the west central region, while January (71) was the coldest in the northwest area. When examining the impact of climatic factors on the THI, we found that air temperature has the highest influence, while relative humidity had the second-highest influence on THI in all areas of Bangladesh. Sunlight length and wind speed influenced the yearly THI marginally but not seasonally. Our findings highlighted a seasonal threat associated with heat stress in the climatic conditions of Bangladesh. It is essential to identify heat stress in ruminants, especially considering the continuing global warming issue. Our results recommend the implementation of heat stress mitigation strategies for ruminant farmers in Bangladesh.

1. Introduction

Livestock production and well-being are susceptible to the effects of climate change as well as global warming (Godde et al., 2021). Meteorologists predict that the world is expected to warm more in the future, which could lead to an increase in farm animals experiencing heat stress (HS). In warmer areas, animals may gradually depart their thermal neutral zone, also referred to as the comfort zone—if appropriate cooling strategies are not taken (Sake et al., 2023). Thermal comfort is a significant concern in animal welfare and is crucial role for maximizing the production of grazing animals (Andréa do et al., 2022). Climatic factors such as air temperature, relative humidity, sun radiation, and wind speed have a strong correlation with thermal comfort (de Oliveira et al., 2018). Bangladesh is located in tropical climatic region and has hot in summer, heavy rainfall with humidity, and mild in winter season (Mahmud et al., 2018). The country experiences a variety of weather phenomena, including heat waves, heat stress, drought, cold waves, dense fogs, tornadoes, tropical cyclones with associated storm surge, heavy rains, floods, and flash floods etc. (Karmakar & Das, 2020). The climate in this area is influenced by its geographical location, with the Bay of Bengal to the south, India to the west, as well as Myanmar to the southeast. Weather phenomena have a significant impact on humans

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and livestock as well as natural ecosystems (Karmakar & Das, 2020).

In the globe all livestock animals are categorized as homeothermic animals due to their capacity to regulate body temperature at a relatively constant level, which fluctuates within a small range (de Oliveira et al., 2018). Animals are in stress when they are directly and indirectly affected by intense sun radiation, elevated temperatures, and heightened relative humidity, these animals experience a physiological condition referred to as HS (Bhateshwar et al., 2023). Heat stress is still a big problem for ruminant production because it lowers feed intake and weight gain, limits meat and milk production, damages the intestinal wall, interfering with nutrient absorption and digestion, and lowers the quality of meat. Multiple factors that directly or indirectly affect both vectors and vertebrate hosts can drive vector-borne disease dynamics (de Souza & Weaver, 2024). Heat stress also indirectly affects ruminants' productivity by enhancing the spread of new vector-borne illnesses (Chauhan et al., 2023). Heat stress may cause hyperthermia, tachypnea, shade-seeking, and reduced activity in ruminants (da Silva et al., 2023). Heat stress also impacts the hormones that govern thermoregulation as well as the immunological response in ruminants (Bernabucci et al., 2010). Thermal comfort in ruminant production in different climates is measured using indices that correspond with physiological and behavioral traits (da Silva et al., 2023).

The temperature-humidity index (THI), heat stress index (HSI), and various thermal index reports were used as tools for the measurement of heat stress. The temperature humidity index (THI) is a good indicator of heat stress (HS) in livestock. It is a value that shows the discomfort, or is a combined assessment of the ambient temperature and relative humidity which has the objective to examine the contrast in climatic conditions (Bhateshwar et al., 2023). Among these indices, the THI initially established through Thom (1958) to evaluate the comfort for people, has been extensively utilized to assess the heat welfare of different animal species, including ruminant livestock (Lallo et al., 2018). The THI has been demonstrated to be a valuable instrument for assessing the relationship between livestock productivity and climate (Ravagnolo et al., 2000; Dikmen & Hansen, 2009). The measure is determined by considering the air temperature and relative humidity, with varying degrees of importance assigned to various classes (Hahn et al., 2009). It serves as the indication of combined external factors that influence the deviation of body temperature from its desired level (Tao & Xin, 2003). Some formulations of THI include an additional component to include the cooling impact of air movements (Lallo et al., 2018), or include factors for both the velocity of the wind and the intensity of solar radiation (Silva et al., 2007).

Season and meteorological stress has a significant role for animal physiology and their behavior (Friday et al., 2015). Environmental temperature, air moisture, and direct sunlight are the primary determinants that require animals to adopt to maintain thermal balance. Neglecting these measures can lead to a decline in production performance (da Silva et al., 2022). Environmental variables greatly impact the thermal comfort indices, along with other related factors exhibit temporal variations in specific locations due to climate change. Studies examining patterns in climatic variables over time employ both parametric as well as non-parametric statistical tests. A study (Zhu et al., 2018) found that parametric evaluations are known for their efficiency, but they need both information independence and normal distribution. Non-parametric tests, in contrast, are robust to data independence and unaffected by variations from normal distribution. The Mann–Kendall (MK) evaluation is a widely used non-parametric test for identifying patterns in time series data. It has been used to identify trends in several climate factors, including temperature, evapotranspiration, and rainfall (da Silva et al., 2022).

Considering increasing concerns about climate change, it is essential for farmers and constructors of farm animal facilities to prioritize heat stress as a significant issue in their sustainable practices. While the use of THI to assess heat stress in ruminants is not new, applying it to the specific climatic zones of Bangladesh over an extended period (1995–2022) provides us with a comprehensive understanding of how heat stress affects various regions and seasons. This understanding can assist us in developing effective strategies to alleviate the adverse impact of heat stress on ruminant productivity in Bangladesh. Despite the importance of ruminant production in the agricultural sector of Bangladesh, there has been a lack of research on measuring THI values in associated with ruminants reared under the environmental circumstances. Therefore, our study aims to analyze climatic patterns, identify influential variables, as well as evaluate heat stress episodes using THI to develop a raising framework for ruminants in Bangladesh. Additionally, we suggest ruminant producers in Bangladesh to adopt strategies for reducing the impact of HS.

2. Materials and methods

2.1. Study area and data

The geographical location of Bangladesh is the eastern part of the South Asian sub-continent with lies between latitudes 20°34′ & 26°38′ North, and longitudes 88°01′ & 92°41′ East. The climatic situation of Bangladesh has subtropical humid climate with wide seasonal rainfall variation along with high humidity (Shahid, 2010). This study was carried out in the four selected regions of Bangladesh namely: Northwest (NW) region, Northeast (NE) region, West Central (WC) region, and East Central (EC) region (Fig. 1). For this study, we obtained meteorological station data from the Climate Information Management System (CIMS) database in Bangladesh (CIMS, 2022). The climate data of CIMS were collected from 1995 to 2022 at 17 different meteorological stations (Fig. 1). The weather stations are located in various regions of Bangladesh are Bogra, Dinajpur, Rangpur, and Syedpur in the northwest; Mymensingh, Srimongal, and Sylhet in the northeast; Chuadanga, Faridpur, Ishurdi, Jessore, Rajshahi, and Tangail in the western central region; and Chandpur, Comilla, Dhaka, and Madaripur in the eastern central region (Bosu et al., 2020; CIMS, 2022). This study utilized monthly online data on temperature (T, °C), relative humidity (RH, %), sunshine time (SD, h), as well as wind speed (W, m s^{-1}) collection from 1995 to 2022 from 17 different meteorological stations. The seasons comprised winter (November–February), summer (March–June) and rainy (July–October) in Bangladesh (Al Mahmud et al., 2015).

2.2. Estimation of THI for ruminants

The THI was utilized in this study to evaluate the effects of heat stress on ruminant livestock in Bangladesh. The THI was chosen for its straightforward methodology and the accessibility of the meteorological information used in its development. The meteorological factors required for its computation, namely temperature and relative humidity, are more easily accessible compared to other data necessary for calculating other indices. THI criteria, such as the Livestock Meteorological Safety Index (NOAA, 1976), have been used for a long time by US extension agencies to provide livestock farmers with information about potential heat stress caused by the environment (Eirich et al., 2015). According to Hahn et al. (2009), the stress levels classified as THI based for ruminants (cattle, sheep, and goats) are as follows: normal ≤74; moderate = 75–78; severe = 79–83; and extremely severe (emergency) ≥84.

The following formulas are used for the $THI_{ruminant}$ calculation, with temperatures measured in degrees Celsius and RH represented as a percentage (Lallo et al., 2018).

$$THI_{ruminant} = (1.8T\max + 32) - ((0.55 - 0.0055RH)(1.8T\max - 26.8))$$

2.3. Trend calculation

The THI was initially introduced by Thom (1958) to measure heat stress in humans. Currently, it is employed to evaluate heat stress in

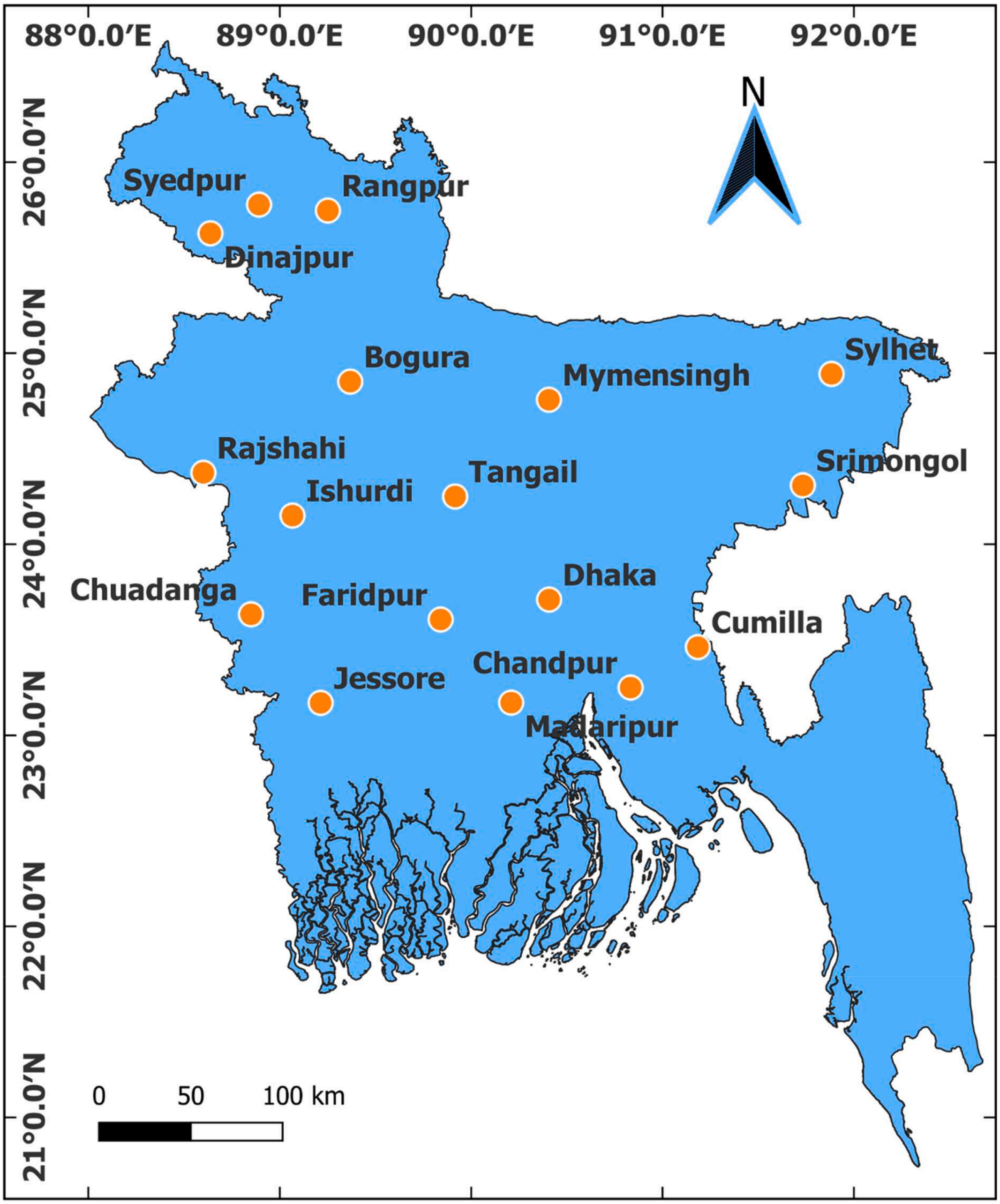

Fig. 1. Displays the geographical positions of the areas under investigation.

several animal species (Lallo et al., 2018) along with to measure the influence of climatic conditions on animal well-being (da Silva et al., 2022).

$$\mathrm{THI} = T + 0.36 \times \mathrm{Td} + 41.5 \quad (1)$$

T represents the dry-bulb temperature, while Td represents the dew point temperature, both measured in degrees Celsius. The dew point temperature (Td) was estimated using the dry-bulb temperature and relative humidity calculation from Hossain et al. (2022).

$$\mathrm{Td} = T - (100 - \mathrm{RH})/5 \quad (2)$$

T represents the dry-bulb temperature (°C), while RH stands for relative air humidity (%)

The Mann–Kendall (MK) test (Mann, 1945; Kendall, 1957) was utilized to identify significant patterns (Z) in the THI series. This test can detect both linear as well as non-linear patterns. In the MK test, the null hypothesis (H_0) signifies the lack of a discernible pattern in a collection of raw data, while the alternative hypothesis (H_1) suggests the existence of a pattern. The following equation, adopted from Alam et al. (2023) was used to determine the MK test:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} Sign(X_j - X_i) \quad (3)$$

$$Sign(X_j - X_i) = \begin{cases} +1se(X_j - X_i) > 0 \\ 0 + 1se(X_j - X_i) = 0 \\ -1 + 1se(X_j - X_i) < 0 \end{cases} \quad (4)$$

$$\mathrm{VAR(S)} = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i(t_i - 1)(2t_i + 5)}{18} \quad (5)$$

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{VAR(S)}} se S > 0 \\ 0 se S = 0 \\ \dfrac{S+1}{\sqrt{VAR(S)}} se S < 0 \end{cases} \quad (6)$$

S represents the statistical evaluation, VAR represents the variance of S, Z represents the standardized statistical assessment, n represents the duration of time series, x_i as well as x_j represent the order of the data of the series of time values in years i as well as j, and t represents the amount of extension for any given moment in time.

The application of Sen's method (Sen, 1968) was used to figure out the amount (β) of the trend slope in the series. This strategy has the advantage of minimizing the influence of outliers below the slope. It is determined using the following equation, adopted from da Silva et al. (2022):

$$\beta = median\left(\frac{(X_j - X_i)}{(j - i)}\right), \forall j > i \quad (7)$$

The tests were conducted at 1% and 5% levels of significance and assessed the presence (or absence) of an annual trend throughout the seasons under study.

2.4. Influence of variables

In addition to temperature and humidity, the present study also examined the influence of other climatic factors on the THI. Thus, wind speed (W) and solar duration (SD) were examined as potential influences on THI, along with *T* as well as RH. The calculation of the proportional contributions of every climate variable followed a prescribed method by da Silva et al. (2022).

The methodology utilizes multiple linear regression to determine the relative impact as a percentage of every independent factor (SD, *T*, RH, as well as W) in that clarify the dependent factor (THI). Before applying the method, the original THI information as well as the independent factors had been normalized employing the following equation:

$$X_{in} = \frac{X_i - X_{i\ mim}}{X_{i\ max} - X_{i\ mim}} \quad (8)$$

In the historical series, the value sequences are represented by xi, xi max, and xi min (present value, maximum value, as well as lowest value, respectively). Xin denotes the normalized variable.

$$Y_i = aX_{i1} = bX_{i2} + cX_{i3} + dX_{i4} \ldots nX_{in} \quad (9)$$

X_{i1}, X_{i2}, X_{i3}, X_{i4}, and X_{in} represent independent factors, while a, b, c, d, and n denote the regression coefficients in this scenario. The variable Y_i is the dependent factor.

The following equation may be used to determine the impact percentage (η, %) of each variable (X_{in}) on the values of the THI (Y_i) based on the regression coefficients:

$$\eta_{1,2,3,\ldots,n} = \left(\frac{|a_{1,2,3\ldots,n}|}{|a_{1,2,3\ldots,n}| + |b_{1,2,3\ldots,n}| + |c_{1,2,3\ldots,n}| + |n|}\right) \times 100 \quad (10)$$

The meteorological components' % contribution to the THI was computed for the annual period, as well as for the summer, rainy, as well as winter seasons.

2.5. Statistical analysis

All analysis was performed using software R studio (Version 4.3.1).

3. Results

3.1. Evaluation of heat stress using $THI_{ruminant}$

Table 1 demonstrates the annual variations of HS indicators in $THI_{ruminant}$ across all study areas in Bangladesh from 1995 to 2022. For most of the year, there has been an increase in the number of data points when the $THI_{ruminant}$ value is more than 74. The HS index ranges from 79 to 86, signifying a severe to extremely severe degree for ruminants. During the entire study period, the west central area had the largest variance (86) in 2016, while the northwest area had the smallest variation (79) in 1997. In addition, $THI_{ruminant}$ has consistently experienced extremely high levels of heat stress for most of the years.

Fig. 2 illustrates the presence of HS from February to December, as indicated by $THI_{ruminant}$ levels exceeding the critical value of 74. These values ranged between 75.5 and 90.0, suggesting that they experienced different levels of HS, ranging from moderate to highly severe. In contrast, the months of January indicate periods of time during which ruminants were exposed to thermally comfortable temperatures throughout all research locations. Between 1995 and 2022, the west central area encountered the highest $THI_{ruminant}$ level, with June (90) being the hottest month. Similarly, the northwest area experienced the smallest values, with January (71) becoming the coldest month for ruminants.

Fig. 3 illustrates the seasonal fluctuations of HS experienced by $THI_{ruminant}$ over the summer, rainy, and winter seasons. During all three seasons, the northwest region had the smallest $THI_{ruminant}$ value of 76, whereas the west central region had the highest $THI_{ruminant}$ values of 88. The winter season showed a moderate stress level, while the summer and rainy seasons exhibited an extremely severe degree of HS.

Fig. 4 depicts the fluctuations in the $THI_{ruminant}$ across four study zones in Bangladesh and the differences observed in these regions during various time periods. Additionally, the study indicates that the largest $THI_{ruminant}$ was consistently observed in the west central area from 2014

Table 1
Annual temperature humidity index (THI) values for ruminants in the northwest (NW), northeast (NE), west central (WC), as well as east central (EC) regions of Bangladesh from 1995 to 2022.

Year	$THI_{ruminant}$			
	NW	NE	WC	EC
1995	83	83	84	84
1996	83	84	85	85
1997	79	83	84	84
1998	83	84	85	84
1999	84	85	86	85
2000	83	83	85	84
2001	84	84	85	84
2002	83	84	85	84
2003	82	83	85	84
2004	83	83	85	84
2005	83	84	85	84
2006	84	84	86	85
2007	83	83	85	84
2008	83	83	85	84
2009	84	85	86	85
2010	84	84	86	85
2011	83	84	85	84
2012	83	84	84	84
2013	83	84	85	84
2014	83	84	85	84
2015	83	84	85	84
2016	84	85	86	85
2017	83	84	85	85
2018	83	84	85	84
2019	84	84	85	85
2020	83	84	85	84
2021	84	85	86	85
2022	84	85	85	85

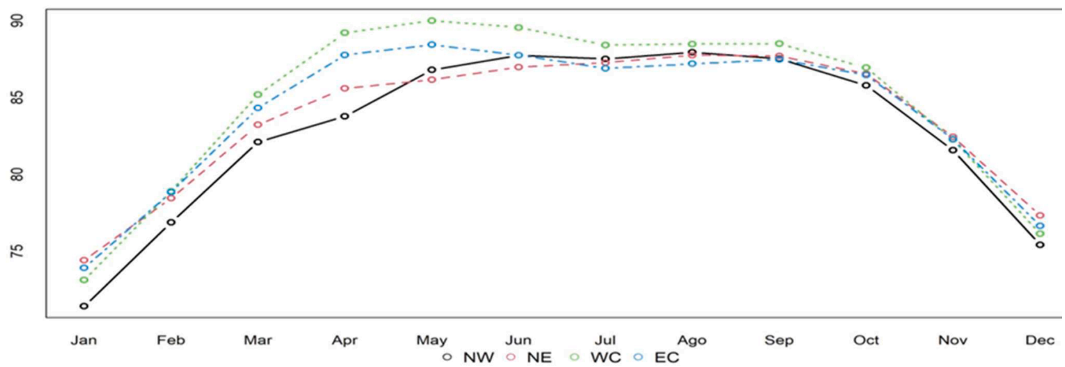

Fig. 2. Monthly temperature humidity index (THI) values for ruminants in the northwest (NW), northeast (NE), west central (WC), as well as east central (EC) areas of Bangladesh from January to December, spanning the years 1995 to 2022.

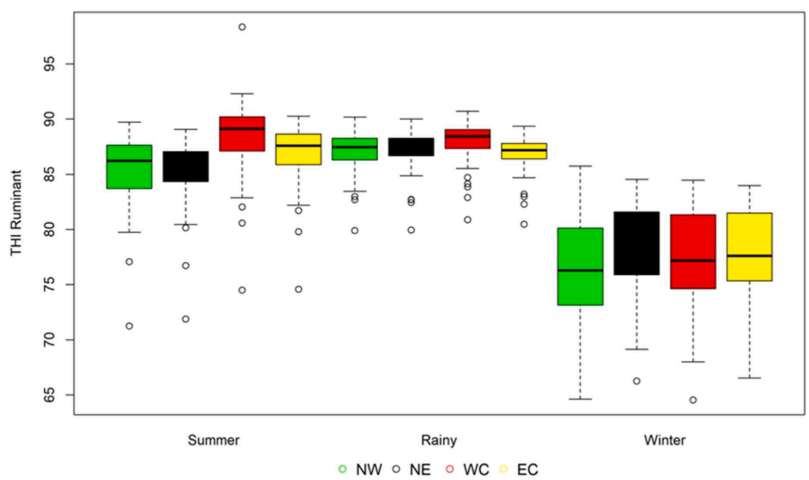

Fig. 3. Seasonal temperature humidity index (THI) values for ruminants in the West Central (WC), East Central (EC), Northwest (NW), and Northeast (NE) regions of Bangladesh from 1995 to 2022.

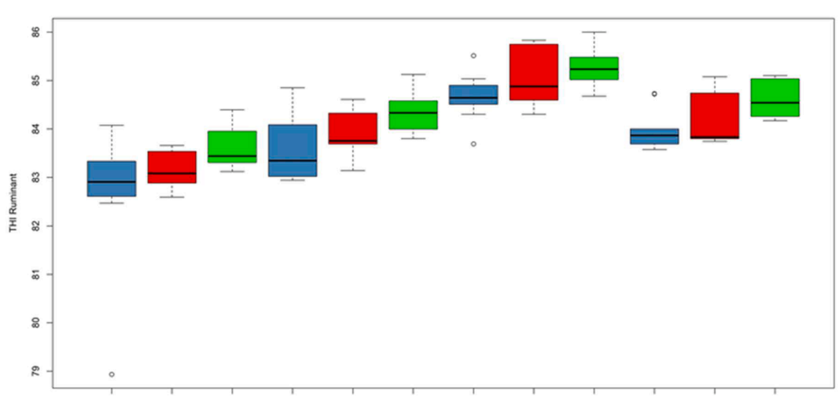

Fig. 4. Box plot showing the average $THI_{ruminant}$ in different regions (NW, Northwest; NE, Northeast; WC, West Central; EC, East Central) during three periods (P1 = 1995 to 2004; P2 = 2005 to 2013; P3 = 2014 to 2022).

to 2022. Conversely, the northwest area experienced the smallest $THI_{ruminant}$ values from 1995 to 2004. The regional average $THI_{ruminant}$ during each period is consistently between 82.8 and 85.5.

3.2. Trend and slope of THI

When the yearly THI trend for each area of Bangladesh is examined, it is feasible to found that there was no statistically significant rise trend for all locations (Table 2). The study areas of north west zones grew by 0.133, northeast by 0.167, west central by 0.003, and east central by 0.133. Thus, the THI thresholds in these places have not seen a substantial rise throughout the years. Furthermore, the summer season's THI patterns as well as its corresponding slope are illustrated in Table 2. The THI exhibited a trend of growth that was not statistically significant across all regions. Individual increases for those situated in the northwest, northeast, west central and east central regions were 0.047, 0.127,

Table 2
Patterns of THI in the yearly period, summer, rainy, as well as winter seasons, where Z stands for the trend as well as β representing the slope for every area of Bangladesh.

Regions	Annual		Summer		Rainy		Winter	
	Z	*β*	*Z*	*β*	*Z*	*β*	*Z*	*β*
Northwest	0.911	0.133	0.304	0.047	2.40*	0.347	−0.21	−0.03
Northeast	1.144	0.167	0.864	0.127	1.98**	0.287	0	0
West central	0.163	0.003	0.397	0.06	2.125**	0.31	−1.238	−0.18
East central	0.911	0.133	0.677	0.1	2.032**	0.29	−0.117	−0.02

* Significant at 1%.
** Significant at 5%.

0.06, and 0.1, respectively. The THI trend was statistically significant during the rainy season. The northwest, northeast, west central and east central areas demonstrated a positive trend, with increases of 0.347, 0.287, 0.31, and 0.29, respectively. The THI trend was statistically insignificant during the winter season. The index showed no development in any region except for the northeast, which has no trend. The index declined by −0.03, −0.18, and −0.02 in the northwest, west central, as well as east central areas, respectively, because of a reduction in temperature as well as relative humidity over the time.

3.3. Influencing variables of THI

Table 3 shows the results of the annual & seasonal multiple linear regression evaluation of normalized information to assess the influence of environmental variables on the THI. The calculation of the proportion of effect of climatic factors on the THI was performed by using the coefficients derived from a multiple linear regression analysis, as outlined in Eq. (10). This analysis was conducted for all areas within the country of Bangladesh.

Fig. 5 depicts the yearly trend of THI as well as the percentage effect of each climatic variable on THI. The THI was found to be 90.7% influenced by *T* in the northwest region, followed by RH 8%, W 0.30%, and SD1%. In the northeast region, *T* influence 88.8%, RH 11.2%, while SD and W have no visible influence. The influence of *T* at west central region was 89.7%, 7% of RH, 1.7% of SD and 1.6% of W. In east central region, *T* influence the THI by 88.5%, followed by RH with 9.7%, SD with 1.3% and W with 0.5%. There was a strong linear association across regions, with R^2 values of 0.977 in the northwest region, 0.931 in the west central area, as well as 0.993 in the east central area (Table 3).

Fig. 6 illustrates the temporal pattern and proportional impact of climatic factors on the THI during the summer season. In the northwest during the summer, *T* was found to influence the THI by 89.1%, followed by RH at 10.9%, with no visible influence from SD or W. Similarly, in the northeast region, *T* influence 87.9%, RH 12.1%, while SD and W have no visible influence. The influence of *T* at west central region was 87.5%, RH with 12.5%, with no visible influence from SD or W. Lastly, in the east central region, *T* influence the THI by 87.9%, followed by RH with 12.1%, while SD and W have no visible influence (Table 3).

In the northwest during the rainy season, *T* was found to influence the THI by 87.5%, followed by RH at 12.5%, with no visible influence from SD or W, as demonstrated in Fig. 7 and Table 3. Similarly, in the northeast region, *T* influence 87.8%, RH 12.2%, while SD and W have no visible influence. The influence of *T* at west central region was 86.7%, RH with 13.3%, with no visible influence from SD or W. Lastly, in the east central region, *T* influence the THI by 88%, followed by RH with 12%, while SD and W have no visible influence.

In the northwest during the winter season, *T* was found to influence the THI by 89%, followed by RH at 11%, with no visible influence from SD or W, as demonstrated in Fig. 8. Likewise, in the northeast region, *T* influence 88.7%, RH 11.3%, while SD and W have no visible influence. The influence of *T* at west central region was 92.1%, RH with 7.9%, with no visible influence from SD or W. Finally, in the east central region, *T* influence the THI by 89.3%, followed by RH with 10.7%, while SD and W have no visible influence.

4. Discussion

4.1. Assessment of heat stress episodes using $THI_{ruminant}$

The THI is widely used to assess HS in livestock by considering the combined impact of relative humidity and ambient temperature (North et al., 2023). The THI formulations selected for this investigation were effective in classifying historical and prospective HS experienced by ruminants rearing in Bangladesh. Our study revealed that ruminants raised in natural environmental circumstances are exposed to prolonged periods of HS throughout the year, which poses a current and increasing threat to their well-being (Table 1).

Heat stress is affected by climate, THI formulation, as well as HS management strategies, which detect micro-climates (Lallo et al., 2018; Dikmen & Hansen, 2009), and the breed of the animal, how well adopted it is to the climate, as well as its physiological condition (Dikmen & Hansen, 2009; Tao & Xin, 2003; Ajakaiye et al., 2011). Based on the studies conducted by Lallo et al. (2018); Hahn et al. (2009) our findings indicate that ruminants rearing in Bangladesh faced HS ranging from severe to extremely severe levels (Table 1). Notably, there were yearly variations in THI values for ruminants, which varied from 77 to 86. In 1997, the northwest area had the lowest number of year-to-year fluctuations in $THI_{ruminant}$. Similarly, the west central and east central regions had the greatest interannual fluctuations in specific years (Table 1). Therefore, the duration of ruminants HS periods may differ based on local weather conditions.

The identification of HS has been related to THI rate threshold (Aditya et al., 2023). In 2006, Mader et al. discovered that cattle may experience HS when exposed to environmental circumstances with a THI ranging from 70 to 74. THI increases between 65 and 73 reduce milk output by 2.2 kg each day and increasing THI from 68 to 78 decreased milk output through 21% along with feed intake by 9% (Zimbelman et al., 2011). Other study by Theusme et al. (2021) found that milk production declines after 3 days of HS and requires 3 to 4 days to recover. Furthermore, studies have reported a decline in conception rate when the THI reaches a threshold of 72 or 73 (Pinto et al., 2020). Additionally, a decrease in ruminating time has been seen when the THI reaches 76 (Pinto et al., 2020). During the months of July and August in the valley zone of Mexico, the hours of high HS make it necessary to use cooling systems for milking cows, as they are unable to adequately recover during this period (Theusme et al., 2021). According to our study, January corresponds to the month in Bangladesh when $THI_{ruminant}$ exhibits thermal comfort (Fig. 2). One case study found that highest average THI value in dairy cow was reported in the month of July in a specific region of Bangladesh (Al Reyad et al., 2016). Other studies in Bangladesh examined the THI of dairy farms discovered that the highest THI was in the month of May (Chanda et al., 2018) and June (Hossain et al., 2022). Our study revealed that the west central area had the greatest $THI_{ruminant}$ level, with June becoming the hottest month. In contrast, the northwest region had the smallest values, with January becoming the coolest month for ruminants rearing from 1995 to 2022

Table 3
The coefficients derived from the yearly & seasonally multivariate regression analysis of the normalized information pertaining to the climate factors in northwest (NW), northeast (NE), west central (WC) and east central (EC) regions of Bangladesh.

Variables	Yearly				Seasonally											
					Summer				Rainy				Winter			
	NW	NE	WC	EC	NW	NE	WC	EC	NW	NE	WC	EC	NW	NE	WC	EC
SD (h)	−0.017	$-2.948e^{-10}$	0.031	0.036	$-6.216e^{-11}$	$4.899e^{-10}$	$2.840e^{-10}$	$-3.229e^{-14}$	$4.114e^{-15}$	$2.186e^{-10}$	$-1.707e^{-10}$	$6.077e^{-15}$	$3.984e^{-11}$	$3.618e^{-10}$	$-1.914e^{-10}$	$-1.038e^{-10}$
T (°C)	1.384	1.36	1.321	1.348	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36
RH (%)	0.044	0.072	0.052	0.071	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072	0.072
W (m/s)	0.007	$-8.460e^{-10}$	−0.038	−0.012	$-1.014e^{-10}$	$-9.198e^{-11}$	$-3.308e^{-10}$	$9.649e^{-15}$	$1.528e^{-15}$	$-6.317e^{-12}$	$-1.409e^{-09}$	$-1.454e^{-14}$	$-4.793e^{-11}$	$-8.824e^{-10}$	$5.886e^{-10}$	$-3.150e^{-11}$
Int.	35.614	34	36.357	34.133	34	34	34	34	34	34	34	34	34	34	34	34
R^2	0.977	1	0.931	0.994	1	1	1	1	1	1	1	1	1	1	1	1
Adjusted R^2	0.973	1	0.917	0.993	1	1	1	1	1	1	1	1	1	1	1	1
P-value	$2.979e^{-16}$	$<2.2e^{-16}$	$2.492e^{-11}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$	$<2.2e^{-16}$

SD sunshine duration, *T* air temperature, RH relative humidity, W wind speed, Int. intercept.

(Fig. 2). The observed differences in the THI level for ruminants may be attributed to the specific formula used for its calculation along with the utilization of various study regions.

The monthly variations of the ruminants exhibited various trends, as depicted in (Fig. 2). These trends generally followed the typical temperature pattern in Bangladesh and were influenced by seasonal changes. Likewise, $THI_{ruminant}$ experienced varying degrees of HS throughout all three seasons, ranging from moderate to extremely severe. Indeed, our study concluded that there is a seasonal risk observed in ruminants rearing. Based on the HS levels established for ruminants (Lallo et al., 2018), the $THI_{ruminant}$ values showed thermal stress level, even in the winter season (Fig. 3), which aligns with findings from prior research (Lallo et al., 2018; Hossain et al., 2022; Al Reyad et al., 2016; Chanda et al., 2018). A study (Lallo et al., 2018) found that ruminants THI increased more rapidly at Montego Bay compared to the other two areas after the cooler winter season.

The differences among the four study zones of Bangladesh suggesting the presence of severe to extremely severe HS (Fig. 4), which negatively impacts the overall health of animals (da Silva et al., 2023).Even when the temperature and season are good, some authors (da Silva Costa et al., 2010; Polli et al., 2020) found that the wind speed is very important for thermal comfort because it helps the Santa Inês sheep lose heat by convection. Additionally, da Silva Costa etal. (2010) also observed that significant heat stress for animals subjected to the sun during specific times of day, which may be caused by high humidity as well as low wind speed, decreasing herd productivity. According to Habeeb et al. (2018), animals need to modify their daily behaviors to cope with stress caused primarily by environmental factors.

4.2. Trends and variables that influence the THI during the interannual, summer, rainy, and winter seasons

Table 2 demonstrates the results indicating that the annual, summer, and winter season trends of THI, as well as its slope, lack statistical significance across all regions. However, during the rainy season, these trends become significant. Apart from the winter season, a positive trend is observed annually, during the summer, and during the rainy season. Conversely, negative trends are observed in the northwest, east central, and west central regions, and no trend is detected in the northeast region. In 2022, da Silva et al. conducted a similar study in the northeastern region of Brazil's state of Paraíba. The researchers found statistical significance and an annual trend increase for all sites except Monteiro, which dropped. The trend and slope of the THI were statistically significant for every meteorological station that showed an increase during the rainy and dry seasons, except Monteiro, which declined.

At all studies areas on an annual basis, our study found that temperature had the most influence in the northwest and the smallest effect in the east central region. The second most important component was relative humidity. Nevertheless, the impact of wind speed and sunshine duration on the THI was negligible (Fig. 5). However, statistically significant differences were noted across different areas ($P < 0.001$) (Table 3). The annual behavior of the climatic variable's temperature, relative humidity, solar duration, and wind speed in our study region was comparable to that of Purswell et al. (2012); Li et al. (2017, 2018).

Throughout the rainy season, the primary factors that significantly affected the trend level of the THI were temperature and relative humidity. These variables increased, which had an impact on the THI index (da Silva et al., 2022). Our study found that temperature had the largest influence in the east central area and the lowest in the west central area of all study sites during the rainy season. The THI was not influenced by wind speed and sunlight throughout the rainy period (Fig. 7). Research (da Silva et al., 2022) found that sunlight duration and wind speed affected the THI index more in dry periods than rainy periods. The THI pattern was most influenced by temperature and relative humidity. Similarly, the present study found that during the summer and winter

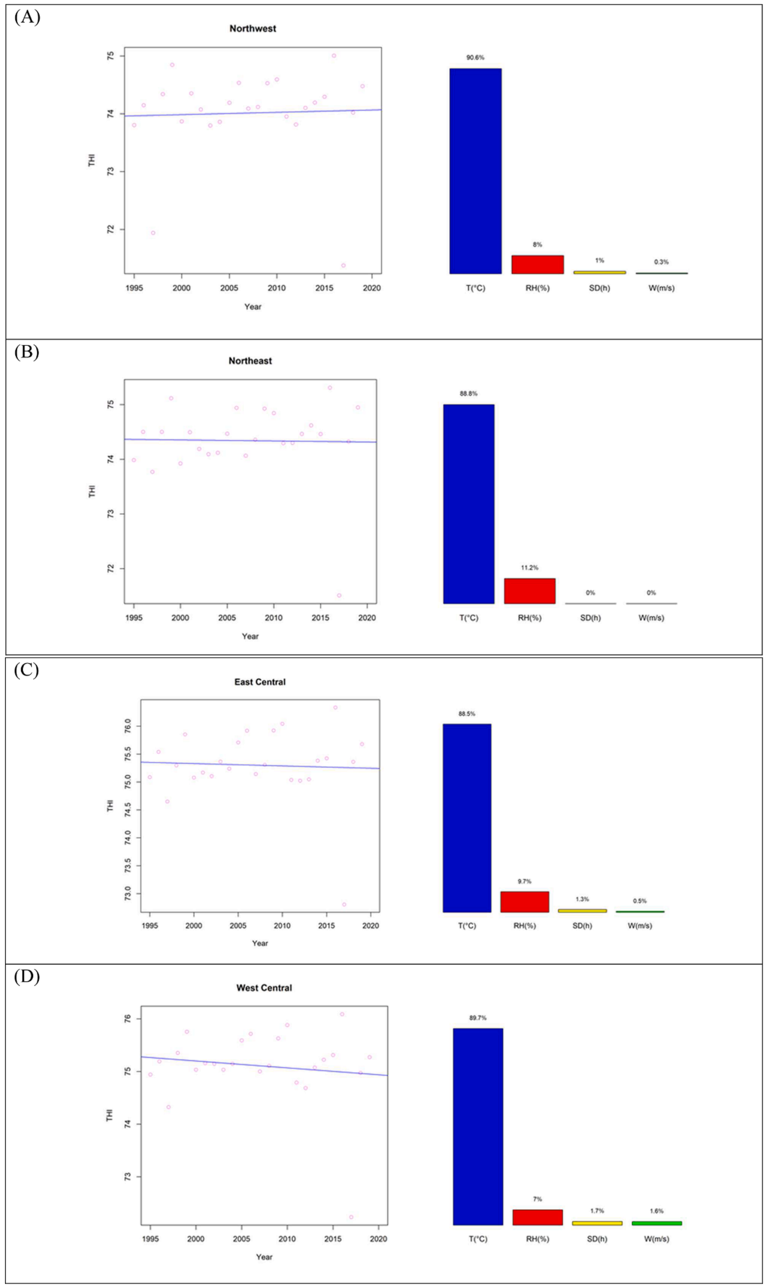

Fig. 5. The yearly pattern as well as the proportionate impact of climatic factors on the THI in every season in the Northwest (A), Northeast (B), Eastcentral (C) and West central (D) regions of Bangladesh.

seasons, temperature had the greatest influence in the northwest as well as west central regions and the least in the west central as well as east central regions at all study sites. The second most important component was relative humidity. However, wind speed and sunlight did not influence THI in summer or winter (Figs. 6 and 8).

The present study demonstrated that temperature as well as relative humidity are the two most important seasonal climatic factors that exert the most significant influence on the THI across all the study locations of Bangladesh (Figs. 6–8). Therefore, as demonstrated in THI, increased temperature and humidity may have a detrimental impact on feed intake and disrupt hormone levels, which in turn adversely affects the performance of livestock in terms of productivity and reproduction (Habeeb et al., 2018).

4.3. Heat stress mitigating strategies for ruminant livestock

It is crucial to adapt ruminant animals farming systems to minimize the consequences of HS is of utmost importance. Offering extensive awareness and training initiatives to livestock farmers and extension staff in Bangladesh and surrounding areas to enhance their knowledge of HS mitigation. This encompasses the correct use of HS metrics, such as the THI, and determining the most efficient method for prioritizing adaptive capacity using these indices. Possible mitigation options involve implementing proactive measures to reduce heat load and improve heat dissipation in the environment. These measures may include providing shade, enhancing ventilation, and utilizing fogging devices and fans. Implement suitable pasture management techniques, like pasture rotation. Additional strategies include reducing metabolic heat production by adjusting feeding schedules and altering the composition of the feed. Regular monitoring of ruminant health is

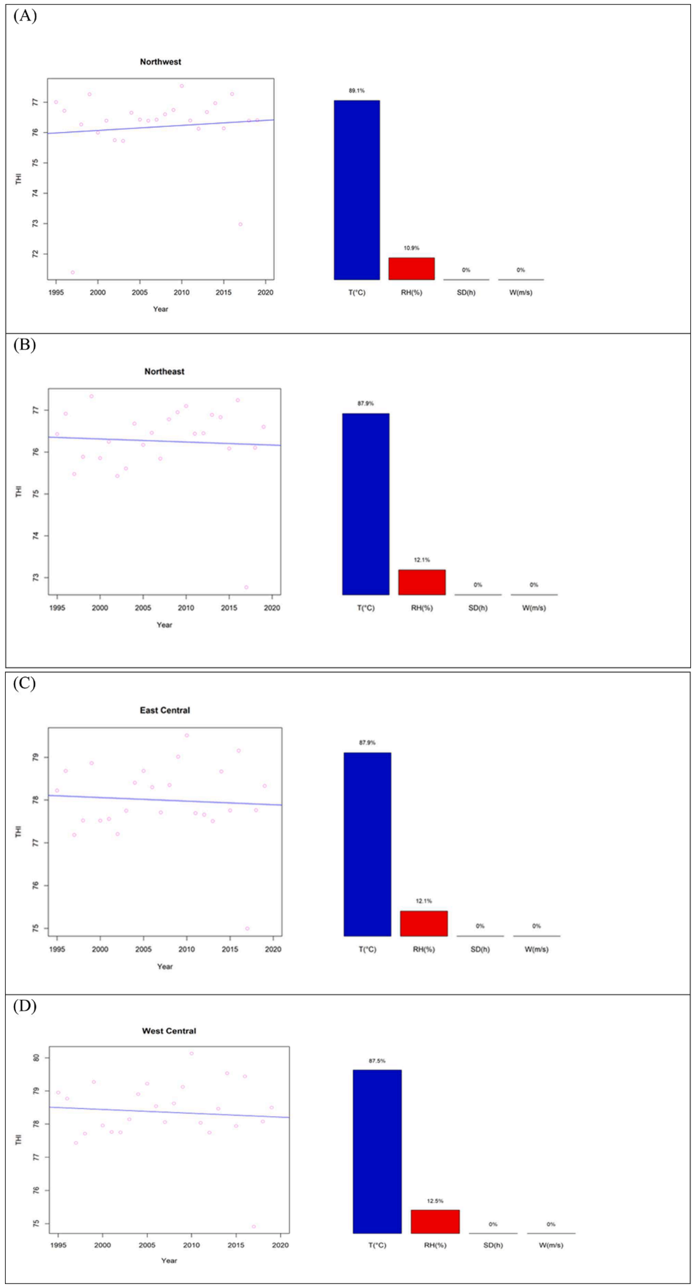

Fig. 6. The trend as well as proportion of climatic factors that influence THI in the Northwest (A), Northeast (B), East central (C) and West central (D) regions of Bangladesh during the summer season.

crucial to identify signs of HS, which may manifest as various symptoms. Utilizing selective breeding for heat resistance and implementing seasonal management for calving are both highly effective strategies. In addition, it may be worth considering the use of cattle breeds that are better adapted to heat or exploring the possibility of using alternative livestock species such as goats. However, opting for heat-tolerant breeds or species has certain disadvantages when it comes to production. Research has indicated that choosing for higher output of milk may have a negative impact on heat tolerance (da Silva et al., 2023; Lallo et al., 2018; North et al., 2023).

4.4. Limitations of the study and future aspects

There are some limitations to our study. Firstly, the THI values in this investigation were computed based on the highest daily values, without considering the influence of diurnal fluctuations on heat stress. The factors that contribute to the actual heat stress experienced by ruminant livestock include the time of day, duration of heat stress, accumulated heat stress (referred to as THI hours), correlation with animal behavior, and the length of recovery periods. Secondly, we have not considered the specific species of ruminants, the age of the animals, and how the heat stress affects their productive and reproductive performance. Despite its limitations, this study offers valuable initial data that can enhance our understanding of heat stress risk for ruminants. By utilizing meteorological parameters, this research can contribute to the development of mitigation strategies and forecasting methods. Ultimately, these findings can lead to improved food security and accessibility for the affected population.

5. Conclusions

The examination of the heat stress experienced by ruminants rearing

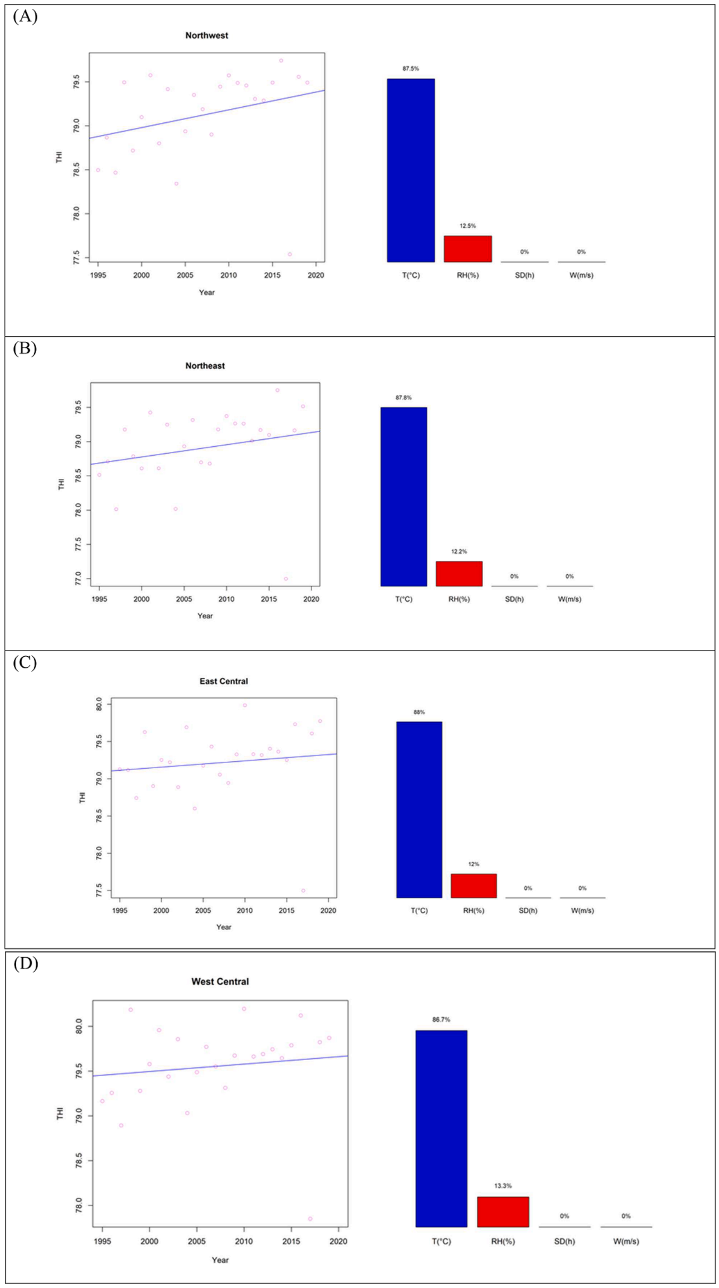

Fig. 7. The trend as well as proportion of climatic factors that influence THI in the Northwest (A), Northeast (B), East central (C) and West central (D) regions of Bangladesh during the rainy season.

throughout several parts of Bangladesh during the 27-year study revealed significant fluctuations in $THI_{ruminant}$. These fluctuations indicate varying degrees of HS, ranging from moderate to highly severe levels. The winter season showed a moderate HS level, while the summer and rainy seasons exhibited an extremely severe degree of HS for ruminants. The study of climatic factors on THI in different seasons in Bangladesh indicates that temperature has the most influence on THI across all observed regions. Additionally, relative humidity had the second greatest contribution to the THI. Sunlight length and wind speed affected the yearly THI marginally but not seasonally. Therefore, ruminants' rearing in this region is hampered by heat stress, which negatively impacts the production as well as reproduction characteristics of these animals. Thus, incorporating trees, supplying shade, ensuring sufficient air circulation, access to clean water, implementing cooling systems, modifying feeding habits, and exploring specific breeding for heat tolerance are important strategies to mitigate thermal stress in ruminants raised in this region. There is limited research on THI in Bangladesh. The proposed strategy is anticipated to enhance ruminant livestock rearing in Bangladesh, hence benefiting farmers.

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Ethical approval

Not applicable.

CRediT authorship contribution statement

Md. Sodrul Islam: Conceptualization, Methodology, Formal analysis, Writing – original draft, Project administration. **Apurbo Kumar**

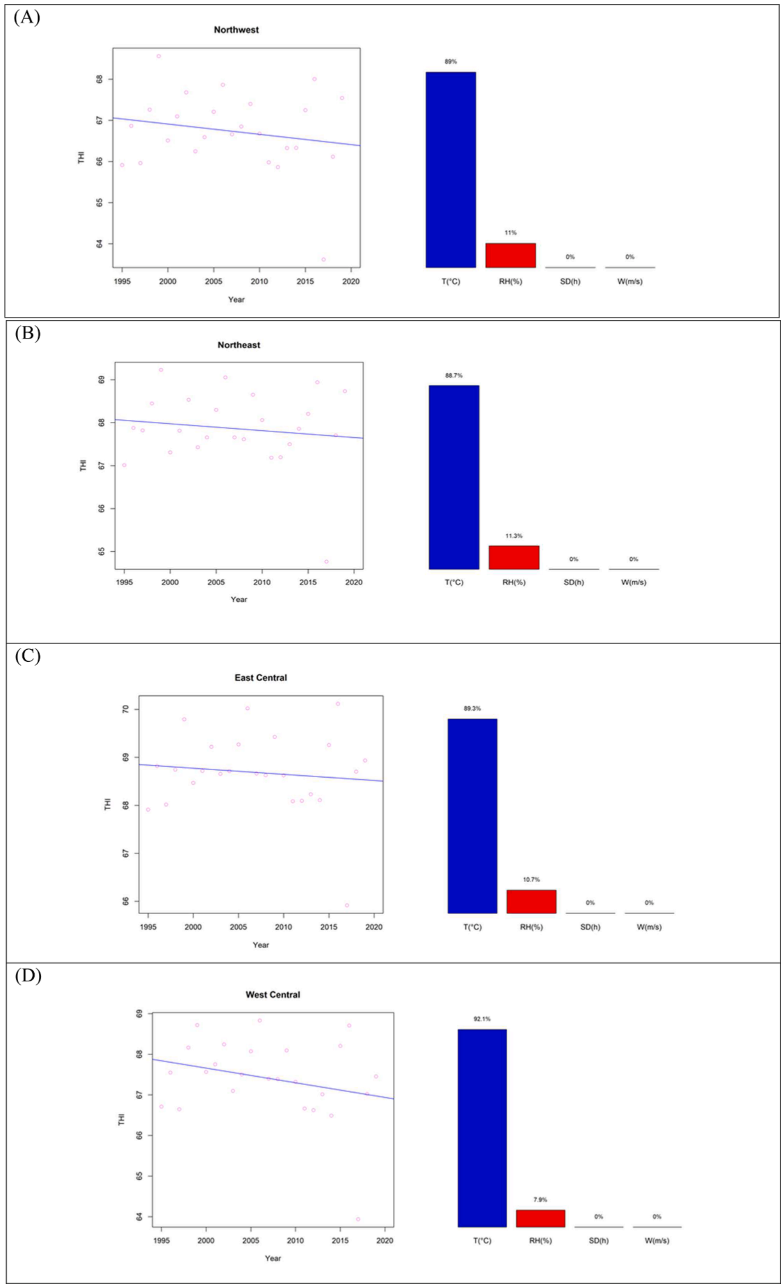

Fig. 8. The trend as well as proportion of climatic factors that influence THI in the Northwest (A), Northeast (B), East central (C) and West central (D) regions of Bangladesh during the winter season.

Mondal: Writing – original draft, Project administration, Methodology, Formal analysis, Conceptualization. **Md. Rabiul Auwul:** Formal analysis, Project administration. **S. H. M. Faruk Siddiki:** Writing – review & editing, Investigation. **Md. Ashraful Islam:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets utilized in this study are available from the corresponding author upon request.

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