Comparison of climate data obtained from on-farm loggers and meteorological data and the effect of heat stress on production data.

1. Abstract

Background: Due to climate change, temperature increases all over the world including the Netherlands. Summer days are getting warmer and the risk of heat stress in cows becomes greater. The temperature humidity index (THI) is used as a heat stress indicator and ascertains heat load intensity by means of dry-bulb temperature and relative humidity. A period of heat stress results in general in decreased productivity, health risk and decreased welfare. Lots of research already has been done on the effects of heat stress. A paucity of data is the use of meteorological data instead of on-farm climate data in these studies, because on-farm climate loggers do have more accurate measurements in the microenvironment in the barn itself. The aim of this study was to compare on-farm climate conditions to climate conditions measured by an official meteorological station in the Netherlands and to investigate a relationship between the climate data in barns and production variables from dairy cows housed on Dutch farms.
Methods: Data from 27 climate loggers on 20 different farms was collected, as well as the same data from the nearest official meteorological station. The collected data were hourly dry-bulb temperature and relative humidity. Dewpoint temperature was calculated by means of the hourly measured dry-bulb temperature and relative humidity. The daily average THI was calculated by means of the collected data. All data was exported into Excel and statistically analyzed (paired t-tes, Chi-squared test and Pearson Correlation, depended on the experiment) in SPSS. In addition to the climate data, on 16 farms the production data was collected as well and consisted of daily milk yield, production of protein, fat, lactose, and urea. All data was exported into Excel sheets and plotted against the on-farm climate data from one day earlier than the milk deliveries.
Conclusion: The temperature, dewpoint temperature and THI was significantly higher at the barn locations compared to the official meteorological station. No significance was found between THI and average daily milk yield and lactose. The negative correlation between THI and protein and fat yield was significant. The results of this study indicate that climate data obtained from an on-farm logger is more accurate than data obtained from the nearest meteorological station. As regards to THI and milk production variables, more research is still necessary, as the results of this study are not conclusive enough. Preferably next studies will be done in standard conditions, which don’t influence the milk production variables itself.
Keywords: heat stress, THI, meteorological station, milk yield, protein, fat, lactose, urea.

2. Introduction

Climate change has become a major concern for the global dairy industry, as there has been a noticeable increase in hotter summers worldwide (Fabris et al., 2019). The Earth's average temperature has risen by approximately 0.2°C per decade since 1980, with no signs of a plateau or decline (Hansen et al., 2006). The Netherlands is not exempt from this climate change; in fact, it has experienced a temperature rise greater than the global average. Between 1951 and 2013, the average temperature in De Bilt (Netherlands) rose by 1.4°C (Timmerman et al., 2018). Additionally, since 1975, there has been a decrease in the number of cold days and an increase in the number of warm days in the Netherlands (Bresser et al., 2005). These trends highlight the impact of climate change on the country's weather patterns and have implications for the dairy sector in terms of managing heat stress and adapting to changing environmental conditions.

The productivity of agricultural animals thrives within a specific range of environmental conditions (Baumgard and Rhoads, 2012). However, when cows generate more heat than they can dissipate to their surroundings, they experience heat stress. This occurs when the upper critical temperature of the thermoneutral zone is exceeded, which typically falls between 20-25°C for Holstein cows (Timmerman et al., 2018). Heat stress is characterized by a combination of internal and external factors that cause a rise in body temperature and trigger physiological responses in the animal (Yousef, 1985). This condition directly and indirectly affects various aspects of the cow's well-being, such as milk production, reproductive efficiency, feed intake, efficiency, and overall health and welfare (Allen et al., 2013). Consequently, heat stress significantly diminishes the profitability of dairy farms.
In the United States, hot weather conditions during the summer result in substantial economic losses of approximately $897 million annually, primarily due to reduced milk yield. Particularly in regions like Florida and Texas, the economic losses per lactating cow range between $337 and $383 per year (St-Pierre et al., 2003). Similarly, estimates from Wageningen University for the Netherlands suggest that heat stress costs on a farm with 100 milk cows can vary between €3008 and €5593 per year (Timmerman et al., 2018). These numbers underscore the significant financial impact of heat stress and underscore the importance of effectively managing and mitigating its effects on dairy operations.

Typically, the negative effects of heat stress on animal performances are observed during the summer months (June, July, and August). However, these detrimental effects can persist in the months that follow (September, October, and November), even after cows are no longer experiencing direct heat stress (Becker et al., 2020). This pattern is also evident in the Netherlands. The Dutch climate experiences periods of warm temperatures during the summer, potentially leading to multiple episodes of heat stress, while tropical, subtropical, and Mediterranean climates face more prolonged and extended periods of heat stress (Becker et al., 2020). Dairy cows and other farm animals in the Netherlands may not be well-adapted to cope with heat stress conditions, and sudden episodes of heat stress can be particularly challenging for them. It can take weeks for these animals to fully adapt to heat stress conditions (Ominski et al., 2002; Perano et al., 2015). On the other hand, recovery from the negative effects of heat stress takes longer in tropical, subtropical, and Mediterranean climates, as cows in these regions are unable to recover as quickly as those in climates with shorter and less intense heat stress periods (Becker et al., 2020). To facilitate recovery from heat stress, it is crucial for animals not to be constantly exposed to such conditions. The ability to lose heat, for example during the nighttime, is essential for the recovery process, as this allows the animals to dissipate accumulated heat gained during the day.

Dairy cattle can achieve their optimal productivity within a specific temperature range known as the thermal neutral zone (Tao et al., 2018). Within this range, the metabolism does not need to expend energy to regulate the body temperature (Allen et al., 2013; Becker et al., 2020). For lactating dairy cattle, this thermoneutral zone typically spans temperatures of 5-25°C (Kadzere et al., 2002). Temperatures outside this zone, whether too cold or too hot, result in increased metabolism and a higher production of metabolic heat (Tao et al., 2018).
To assess the intensity of heat load, the Temperature Humidity Index (THI) is commonly used, taking into account dry-bulb temperature and relative humidity (Allen et al., 2013). Different equations have been utilized, with one of the most commonly employed ones being $THI = (1.8 \times Tdb + 32) - (0.55 - 0.0055 \times RH) \times (1.8 \times Tdb - 26)$ (NRC, 1971). THI is a widely used index for categorizing moderate to hot conditions.
In the past, the threshold for heat stress levels was set at a THI index above 72 (Whittier, 1993; Armstrong, 1994). However, with improvements in milk production over time, this threshold has been re-evaluated. More recent studies have suggested a new heat stress threshold at THI 68, as it better aligns with current milk production trends and lacks supporting data for the previous threshold (Whittier (1993) and Armstrong (1994) (Zimbelman et al., 2009).
Based on the current index, different THI ranges correspond to varying degrees of heat stress. THI values below 68 indicate no heat stress, while THI values between 68 and 72 represent mild heat stress. THI values ranging from 72 to 79 signify mild-moderate heat stress, while THI values from 80 to 89 indicate moderate-severe heat stress. Finally, THI values above 90 denote severe heat stress. The THI classification provides a valuable tool for understanding and managing the impact of heat stress on dairy cattle productivity and well-being.

As mentioned earlier, heat stress directly and indirectly affects production (milk yield, but also variation in milk composition). As soon as the cow's upper critical temperature is exceeded, a downwards shift in feed intake and milk production is seen. The upper critical temperature is cows dependable. High-yielding cows are more susceptible for heat stress, as their upper critical temperature is lower than that of a low-yielding cow, because of higher internal metabolism due to higher milk yield, more feed intake, and the heat production increase (Aggarwal and Upadhyay, 2013). Heat stress triggers the rostral cooling center in the hypothalamus to activate the medial satiety center, which inhibits the lateral appetite center, leading to a decrease in milk production. Heat stressed cows rely on glucose to meet their body's energy demands, causing less glucose to be directed to the mammary gland, resulting in a decline in milk production (Aggarwal and Upadhyay, 2013). At the same time, maintenance requirements increase due to temperatures above the thermoneutral zone (Allen et al., 2013). When temperatures rise above the upper limit of the thermoneutral zone, the body's cooling mechanisms are activated, which include sweating, panting, and increased blood follow to the skin's surface to dissipate heat. The energy that could have been utilized for other physiological processes, such as milk production or reproduction, is now diverted to cooling the body (Allen et al., 2013). Mild to severe heat stress in dairy cattle causes approximately an increase in maintenance requirements by 7 to 25% (NRC, 2001).

Considering that a lot of studies have been done about heat stress and its consequences, the fact is that heat stress has a negative effect on (re)production variables. But most studies about the influence of heat stress on production variables have been done in countries other than the Netherlands and with data from meteorological stations, which measure climate variables in open air situations. Schüller et al. (2013) showed that data obtained from meteorological stations differs from the data collected from 7 dairy farms in Eastern Germany. The study showed that the THI was higher in the barns than at the official meteorological station

(Schüller et al., 2013). Temperature measured in a barn can differ from measurements of a meteorological station, as they measure the outside temperature in an open grass field (wind can play its part, but the sensor is protected from sun and rainfall) (KNMI, 2023). Also, climate conditions in barns can be altered from outside climate measurements, by for example the design of the barn (ventilation, roof isolation, water atomization) or the occupation of the barn (Winsten et al., 2010; Timmerman et al., 2018). As THI measured in barns might differ from the data obtained by the meteorological stations, a more accurate image can be obtained by measuring climate data in the barn about the degree of heat stress experienced by the cows in these barns.

To my knowledge, there is no field study investigating the comparison of on-farm climate data and official meteorological data in the Netherlands as well as a comparison between on-farm climate data and production variables. Therefore, the object of this study was to compare on-farm climate conditions to climate conditions measured by an official meteorological station in the Netherlands and to investigate a relationship between the climate data in barns and production variables from Dutch farms.

3. Materials and methods

3.1 Data collection

On 20 dairy farms spread out through the Netherlands, 27 climate loggers were installed in the barns. Hence, a difference between climate conditions (roof isolation, ventilation systems, sprinklers etc.) was present between the different barns. The climate loggers recorded the dry-bulb temperate (T) and relative humidity (RH). A single logger was installed on 11 farms, where the logger was installed above the lying area of the milking cows, at a distance whereby the cows couldn't interfere with the logger. On seven different farms, a double logger was placed, one logger above the lying area of the milking cows and one logger in a different place. The place of the second logger varied from the lying area of the dry period cows, the feeding alley, the waiting area, and the old and new barn. On one farm, three loggers were placed: in two different barns above the lying area of the milking cows and one outside the barn. Dry-bulb temperature and relative humidity was recorded with an interval of 15 minutes. Hence, 4 measurements were used to calculate the average temperature and humidity per hour and 96 measurements were used to calculate the daily average temperature and humidity. The dewpoint temperature (DP) was calculated by means of the formula: $DP = (237.7 * (((17.27*T)/(237.7+T)) + LN (RH/100))) / (17.27 - ((17.27*T)/(237.7+T)) + LN(RH/100)))$, whereby T = dry-bulb temperature, LN = natural logarithm and RH = relative humidity. The DP was calculated because of the THI equation which is used in this research and the possibility to make a comparison with the measured DP of the meteorological station, which use a bulb-thermometer the measure the dewpoint accurately. The THI was calculated per hour, using the equation reported by Yousef (1985): $THI = T + 0.36 * DP + 41.2$.

Data from the meteorological stations were collected from the nearest KNMI station. Hourly measurements about temperature, relative humidity and dewpoint temperature were collected from http://projects.knmi.nl/klimatologie/uurgegevens/selectie.cgi and exported into excel sheets. The same equation about the THI as the on-farm climate loggers were used.

The first experiment is the comparison between the climate data of the on-farm climate loggers and the climate data from the nearest meteorological station (KNMI). Data was collected between the 4th of June till the 30th of September. Hence, not all on-farm loggers collected data from the 4th of June, so a later date was taken for the on-farm logger as the meteorological station in this situation. The average distance between the on-farm loggers and the nearest meteorological station was 12.65 kilometers. The closest distance between the meteorological station and the on-farm climate logger was 8.04 kilometers, the maximum distance was 20.75 kilometers.

The second experiment describes the difference between the THI during daytime and the THI during nighttime at the farm. The daytime is defined as the daily period between 6 am and 6 pm, where nighttime is the period between 6 pm and 6 am. The average THI is calculated in those periods, as well as the number of hours of heat stress and whether the average THI in the period is above 68, and thus is being categorized as a period of heat stress.

For the third experiment, the correlation between the on-farm climate data and the production, data was collected at 16 farms with a climate logger. The collected data consisted of milk deliveries of every three days for the period of June up to including September, the number of cows daily milked and the melkproductieregistratie (MPR) (milk yield, protein -, fat -, lactose yield and somatic cell count) if present. This data was used to calculate the average daily milk yield per cow and the average production of protein, fat, lactose, and urea per cow. All data was exported into Excel sheets and plotted against the on-farm climate data from one day earlier than the milk deliveries.

3.2 Statistical analysis

Data from the on-farm climate loggers, the meteorological station and from the farmers milk administration were exported into Excel spreadsheets (Office 2013, Microsoft) and statistical analyses was performed using SPSS. For experiment 1, a data map was produced to for the use of statistical analysis in SPSS. This data map concluded daily means of dry-bulb temperature, relative humidity, dewpoint temperature and THI of all 27 on-farm climate loggers as well as the matching data from the nearest meteorological station. Eventually a data map was created, consisting of:

- The number of days with heat stress
- The maximum measured THI daily
- The number of hours of heat stress per day
- The number of days with at least 3 hours of heat stress
- The number of days with at least 5 hours of heat stress
- The number of days with at least 8 hours of heat stress
- The average THI between 6am and 6pm
- The number of hours of heat stress between 6am and 6pm
- The average THI between 6pm and 6am
- The number of hours of heat stress between 6pm and 6am
- The days of THI < 68, THI 68-72 and THI > 72-79

Hence, heat stress was defined at a THI of 68 or higher. For experiment 2 and 3, the same climate calculations as in experiment 1 were used.

In experiment 1, differences and the coefficient of correlation between daily dry-bulb temperature, relative humidity, dewpoint temperature and THI of the on-farm climate loggers and the meteorological station were assessed using a paired t-test. The regression analysis has been done by means of an ANOVA. This paired t-test was also used for the assessing of the differences of the maximum measured daily THI and the average amount of hours of heat stress daily. The statistical analysis of the number of days with at least 3, 5 or 8 hours of heat stress during the day, compared between the on-farm climate logger and the nearest meteorological station, was assessed by a Chi-squared test. Figures were made using Excel.

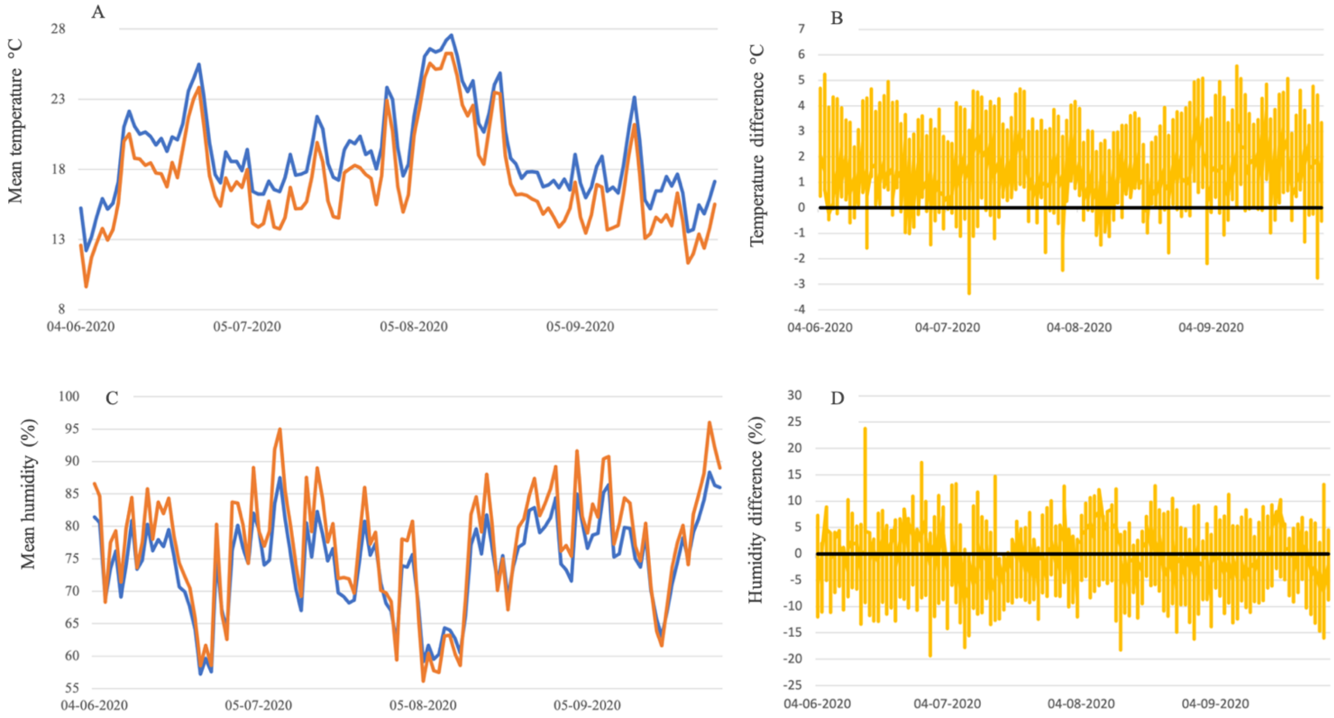
In experiment 2, difference between daily day (6 am – 6 pm) and night (6 pm – 6 am) THI were assessed between the on-farm climate data using a paired t-test. The average number of hours on a during daytime period and nighttime period were also assessed using a paired t-test. The Chi-squared test was used for the comparison between a period of heat stress during daytime and a period of heat stress during nighttime. A period of heat stress is defined as the average THI (between 6 am – 6 pm (daytime) or 6 pm – 6 am (nighttime)) above 68.

For experiment 3, the correlation between climate variables and production variables, a Pearson Correlation test was used. Milk yield, protein yield, fat yield, urea and SCC per day were plotted against de daily average THI in Excel. The assassination of different groups of THI (THI < 68, THI 68-72, THI >72) and the production variables (milk yield, protein yield, fat yield, urea) was made using a paired t-test.

4. Results

Experiment 1 – comparison between on-farm climate logger and the meteorological station

First in this experiment, the coefficient of correlation of the daily climate measurements of the on-farm climate logger and the meteorological station were calculated. The coefficient of correlation was $r = 0.95$ for daily averages of dry-bulb temperature, $r = 0.89$ for daily averages of relative humidity, $r = 0.94$ for daily averages of dewpoint temperature and $r = 0.96$ for the average daily THI ($n = 119$, $P < 0.001$). The mean temperature overall was 2.0 ± 1.1°C higher on the on-farm location (19.2 ± 3.4°C) compared to the meteorological station (17.2 ± 3.6°C, $n = 119$, $P < 0.001$). The relative humidity was 2.67 ± 4.73% higher at the meteorological station (77.0 ± 10.1%) compared to the on-farm location (74.4 ± 8.2%, $n = 119$, $P < 0.001$). Dewpoint temperature was 1.6 ± 1.0°C higher on the on-farm location (14.2 ± 2.8°C) compared to the meteorological station (12.6 ± 3.0 °C, $n = 119$, $P < 0.001$). The average THI per day was 2.6 ± 1.3 higher at the on-farm location (65.5 ± 4.2) compared to the meteorological station (62.9 ± 4.4, $n = 119$, $p < 0.001$). The difference between the on-farm climate logger and the data from the meteorological station is very constant, there are no big outliers in the differences (figure 1B, 1D, 1F). Totally, there were 768 days (24.8%) with a daily average THI > 68 at the farms and a little less day, 468 (15.1%) of the total of 3099 experimental days at the nearest meteorological station. The maximum THI at a day's moment in this experiment was 2.0 ± 1.4 higher on the on-farm location (69.8 ± 5.1) compared to the meteorological station (67.8 ± 5.3, $n = 3099$, $p < 0.001$). Figure 1 shows the mean temperature, relative humidity, dewpoint temperature and THI of both the on-farm climate logger and the meteorological station, as well as their daily differences. In the appendix a scatterplot of observed logger and predicted data (figure 6) with associated regression can be found. This associated regression showed for each parameter (temperature, DP, RH and THI) a $p < 0.001$, which tells us there is a significant difference between the observed data from the loggers and the measured data from the meteorological station (KNMI).



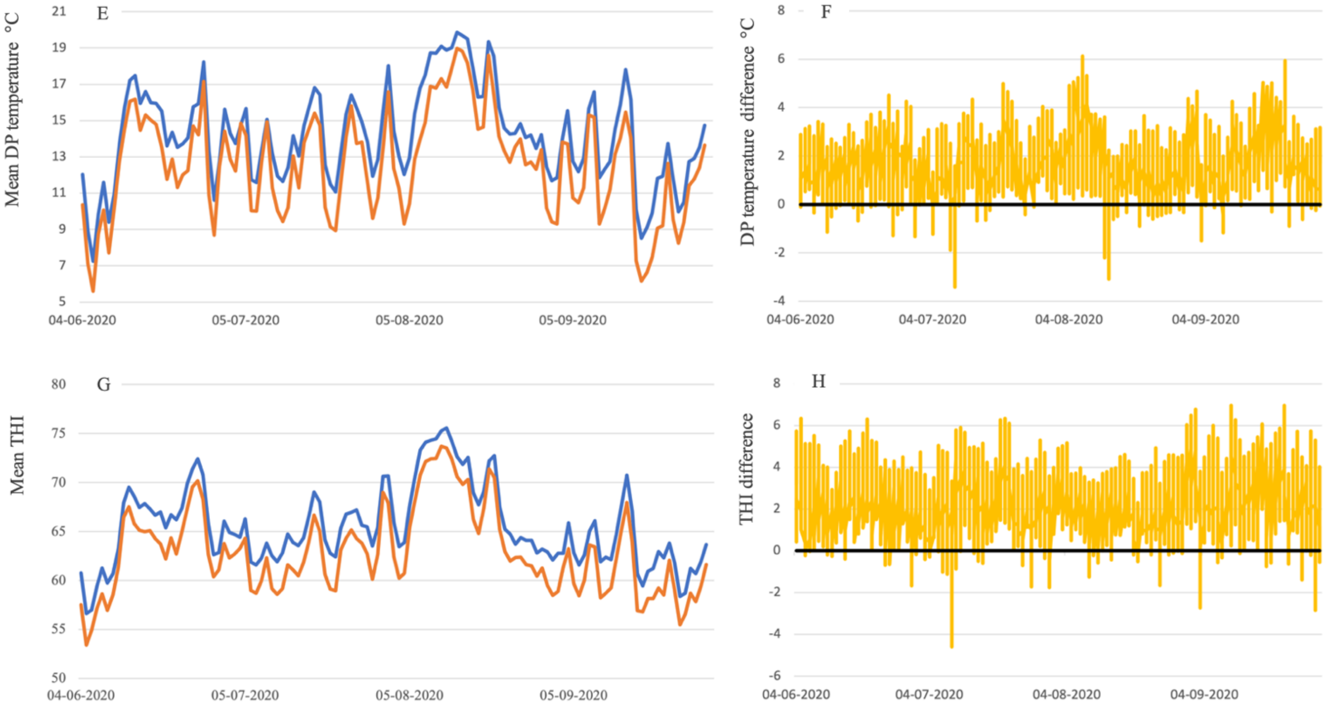


Figure 1. Mean temperature, relative humidity, dewpoint (DP) temperature and THI (figure A, C, E, G) measured at the on-farm climate logger (blue) and the meteorological station (orange) and the daily differences (figure B, D, F, H; yellow) between the on-farm climate logger and the meteorological station.

Not only a comparison was made for the average THI per day, but this experiment also included the number of hours with heat stress during a day. The average amount of hours with heat stress in the research period (June-September 2020, 27 on-farm data loggers) was 6.73 ± 7.9 hours per day measured by the on-farm loggers and 4.12 ± 6.4 (n = 119, p < 0.001) hours per day measured by the meteorological station. Per logger, the number of days with average daily THI above 68 are shown, compared to those of the nearest meteorological station (table 1).

Table 2 shows the number of days per logger with at least 3, 5 and 8 hours of heat stress during the research period. Number of days with a minimum of 3 hours of heat stress (THI > 68) were 60 (52.3%) and 39.6 (34.5%) of the 119 (mean 114.8 days, some loggers didn't collect data through the whole period) experimental days on the farm and at the meteorological station, respectively (P < 0.001). The same comparisons were made between the on-farm data and the data from the meteorological station for number of days with ≥ 5 hours THI > 68 and number of days with ≥ 8 hours THI > 68. Number of days with a minimum of 5 hours of heat stress (THI > 68) were 54.4 (47.4%) and 34.7 (30.2%) and number of days with a minimum of 8 hours of heat stress (THI > 68) were 43.5 (37.9%) and 29.5 (25.4%) of the 119 experimental days on the farm and at the meteorological station, respectively (P < 0.001).

	Days with THI > 68			
Logger number	On-farm logger	Meteoro-logical station	P-value	n
1	26	16	< 0.001	119
2	24	16	< 0.001	119
3	28	15	< 0.001	119
4	40	15	< 0.001	119
5	22	15	< 0.001	119
6	22	18	< 0.001	119
7	25	15	< 0.001	104
8	27	15	< 0.001	104
9	38	20	< 0.001	119
10	29	20	< 0.001	119
11	21	17	< 0.001	97
12	20	17	< 0.001	97
13	26	15	< 0.001	119
14	20	15	< 0.001	119
15	26	15	< 0.001	104
16	42	18	< 0.001	118
17	34	21	< 0.001	119
18	24	13	< 0.001	96
19	21	19	< 0.001	119
20	29	21	< 0.001	119
21	32	18	< 0.001	119
22	28	18	< 0.001	119
23	38	21	< 0.001	119
24	37	18	< 0.001	119
25	35	18	< 0.001	119
26	28	18	< 0.001	119
27	26	21	< 0.001	118

Table 1. Number of days between June-September 2020 with a daily THI above 68.

	Days with ≥ 3 hours THI > 68			**Days with ≥ 5 hours THI > 68**			**Days with ≥ 8 hours THI > 68**			
Logger number	On-farm logger	Meteoro-logical station	P-value	On-farm logger	Meteoro-logical station	P-value	On-farm logger	Meteoro-logical station	P-value	n
1	50	40	< 0.001	48	35	< 0.001	39	28	< 0.001	119
2	45	40	< 0.001	44	35	< 0.001	33	28	< 0.001	119
3	52	41	< 0.001	46	34	< 0.001	36	30	< 0.001	119
4	66	41	< 0.001	63	34	< 0.001	57	30	< 0.001	119
5	50	41	< 0.001	45	34	< 0.001	34	39	< 0.001	119
6	50	42	< 0.001	45	36	< 0.001	34	28	< 0.001	119
7	55	34	< 0.001	49	31	< 0.001	39	26	< 0.001	104
8	60	34	< 0.001	53	31	< 0.001	42	26	< 0.001	104
9	76	43	< 0.001	68	40	< 0.001	54	33	< 0.001	119
10	59	43	< 0.001	55	40	< 0.001	48	33	< 0.001	119
11	46	32	< 0.001	41	27	< 0.001	33	24	< 0.001	97
12	44	32	< 0.001	39	27	< 0.001	30	24	< 0.001	97
13	52	31	< 0.001	47	31	< 0.001	40	27	< 0.001	119
14	52	31	< 0.001	48	31	< 0.001	43	27	< 0.001	119
15	56	34	< 0.001	49	31	< 0.001	37	26	< 0.001	104
16	73	42	< 0.001	65	37	< 0.001	57	31	< 0.001	118
17	79	49	< 0.001	75	39	< 0.001	55	36	< 0.001	119
18	43	21	< 0.001	40	21	< 0.001	31	17	< 0.001	96
19	63	47	< 0.001	54	40	< 0.001	40	33	< 0.001	119
20	68	49	< 0.001	63	39	< 0.001	51	36	< 0.001	119
21	66	37	< 0.001	62	33	< 0.001	48	28	< 0.001	119
22	58	37	< 0.001	51	33	< 0.001	43	28	< 0.001	119
23	63	49	< 0.001	59	39	< 0.001	52	36	< 0.001	119
24	83	42	< 0.001	73	36	< 0.001	56	29	< 0.001	119
25	80	42	< 0.001	70	36	< 0.001	54	29	< 0.001	119
26	59	42	< 0.001	56	36	< 0.001	45	29	< 0.001	119
27	73	54	< 0.001	62	50	< 0.001	43	35	< 0.001	118

Table 2. Number of days between June-September 2020 with minimum of 3, 5 or 8 hours a day of heat stress.

Experiment 2 – comparison between daytime THI and nighttime THI from the on-farm climate data.

The average THI during daytime (6am – 6pm) was 0.8 ± 1.2 higher compared to the THI during nighttime (6pm – 6am), 65.9 ± 4.4 and 65.1 ± 4.2, respectively (n = 119, p < 0.001). The number of days with heat stress only during daytime were 51 compared to 45 during nighttime. The average amount of hours with heat stress during daytime was 3.7 ± 4.1 hours and 3.0 ± 3.9 (n = 3099, p < 0.001) hours during nighttime.

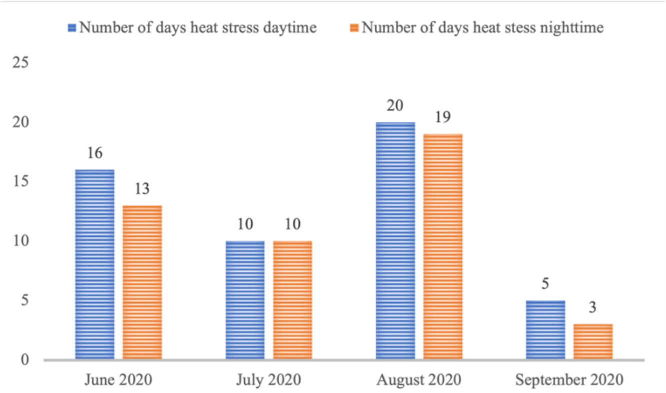


Figure 2. Number of days heat stress during daytime and nighttime per month in the period June – September 2020.

Experiment 3 – correlation between the on-farm climate data and milk production data

There is no correlation between THI and daily milk yield (p = 0.13, n = 118). The correlation coefficient r = -0.04, which tells that an increase in THI shows a decrease of 0.04 kg milk per day. Although there is no statistical significance, numeric an increase in average daily THI is followed by a decrease in milk yield (figure 3), especially when the THI increases above 70.

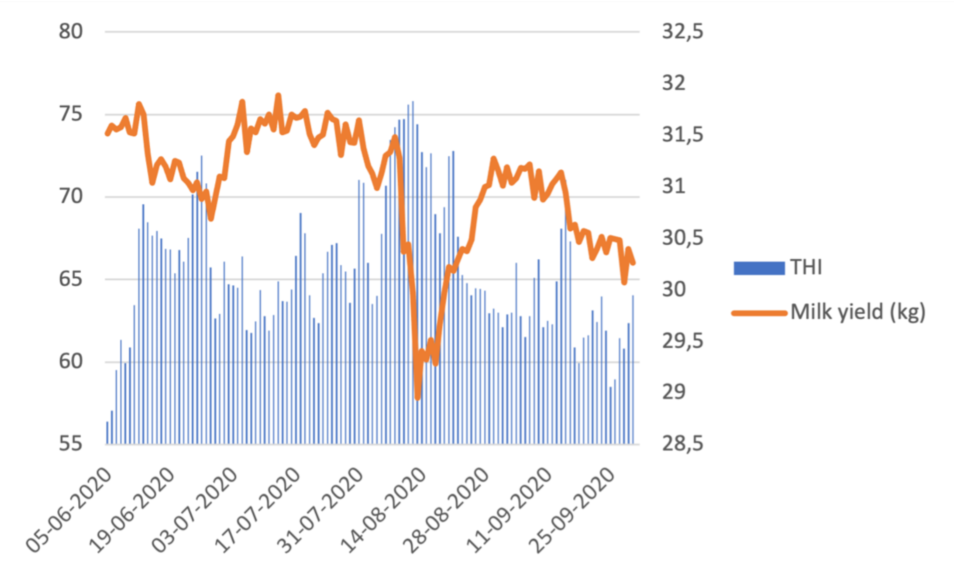


Figure 3. The relationship between daily mean THI and milk yield.

The coefficient of correlation r between THI and protein yield is -0.154 (n = 118, p < 0.001). Figure 4.A shows the same big drop in protein yield after an increase in THI above 70 (August 2020). This drop seems to be at every milk variable, looking at figure 4.B and 4.C as well. The coefficient of correlation of THI and fat yield r = -0.54 (n = 118, p < 0.001). The correlation between lactose and THI is not significant (p = 0.27), but r = - 0.26.

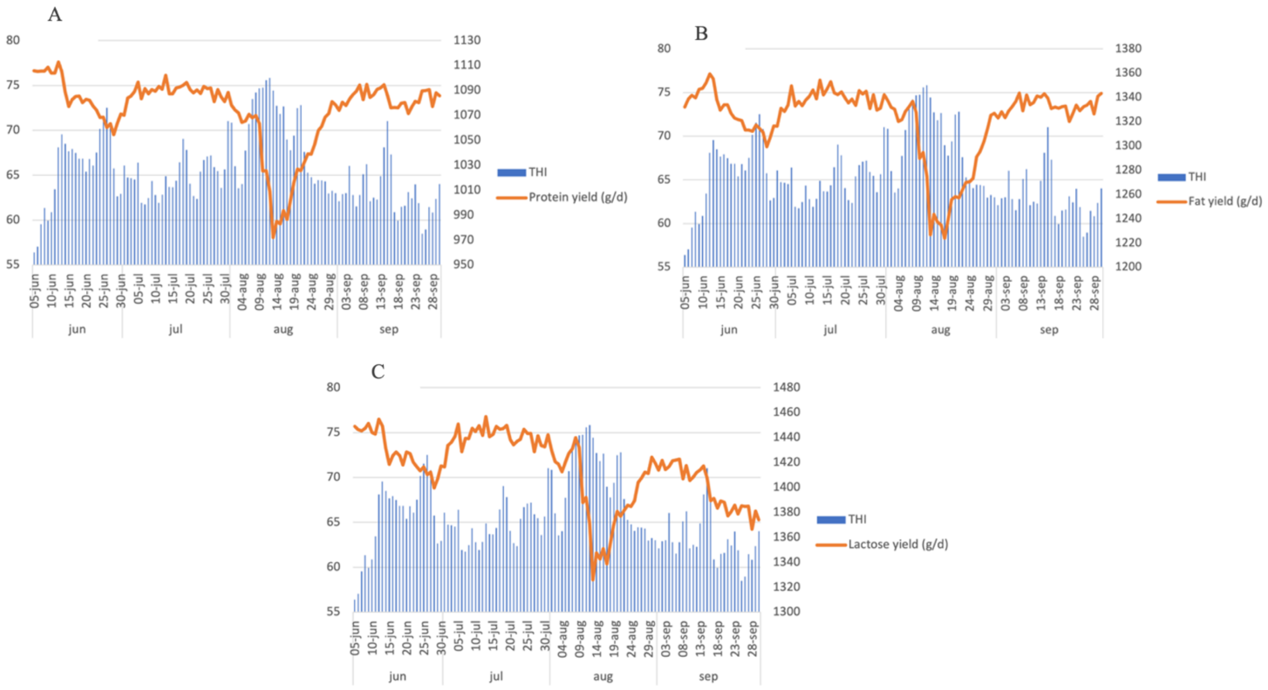


Figure 4. The relationship between daily mean THI and protein yield (A), fat yield (B), lactose yield (C).

The coefficient of correlation between urea and THI is 0.13, which is the only correlation with a positive effect. This result is significant ($p < 0.001$, $n = 118$). Figure 5 shows the relationship between THI and SCC; hence SCC is not daily monitored. After a peak in THI, a peak in SCC is noticeable in this figure.

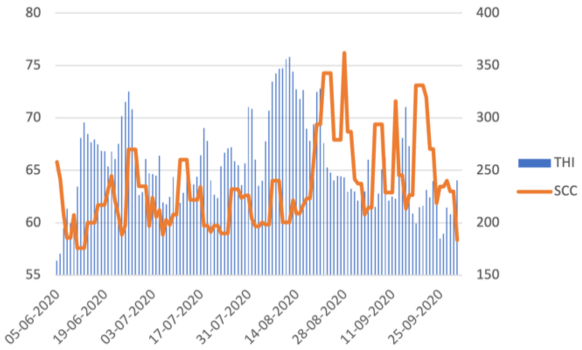


Figure 5. The relationship between daily mean THI and somatic cell count (SCC).

Table 3 shows the mean production variables (daily milk yield, protein, fat, lactose, and urea) in different groups of THI (<68, 68-72 and > 72) and the class difference in THI groups. For milk yield, the highest milk yield (31.01 ± 2.34 kg) was seen in the group with THI < 68 ($n = 61$, $P < 0.001$). The average milk yield per day was a bit lower in the group with THI 68-72, respectively 30.97 ± 2.25 kg ($n = 37$, $P < 0.001$). The lowest average milk yield per day was in the group with the highest average daily THI (THI > 72), 30.47 ± 2.33 kg ($n = 20$, $P < 0.001$). The highest protein yield was seen in group THI > 72, 1077.59 ± 84.92 g ($n = 20$, $P < 0.001$), followed by group THI < 68, respectively 1072.97 ± 80.53 g ($n = 61$, $P < 0.001$). The lowest protein yield was seen in group THI 68 -72, 1072.72 ± 86.75 g ($n = 37$, $p < 0.001$). The same can be said about fat yield, the highest protein yield was seen in group THI > 72, 1325.22 ± 88.39 g ($n = 20$, $P < 0.001$). Followed by group THI < 68, respectively 1322.51 ± 88.11 g ($n = 61$, $P < 0.001$). The lowest fat yield was seen in group THI 68 -72, 1313.08 ± 92.92 g ($n = 37$, $p < 0.001$). For lactose, the highest yield is seen in group THI > 72, 1419.89 ± 116.94 g ($n = 191$, $P < 0.001$). The group of THI < 68, showed a mean lactose yield of 1413.84 ± 112.02 g ($n = 61$, $P < 0.001$). The lowest lactose yield was seen in group THI 68 – 72, respectively 1411.20 ± 119.21 g ($n = 37$, $p < 0.001$). For urea, THI < 68 was the highest, 20.09 ± 3.7 mg ($n = 61$, $P < 0.001$). Group THI 68 – 72 had a mean urea of 19.95 ± 3.44 mg ($n = 37$, $p < 0.001$) and group THI > 72 had the lowest urea, 19.87 ± 3.74 mg ($n = 20$, $P < 0.001$).

	Daily THI < 68	Daily THI 68 - 72	Daily THI > 72	P-value
Milk yield (kg/day)	31.01 ± 2.34^b	30.97 ± 2.25^b	30.47 ± 2.33^a	< 0.001
Protein yield (g/day)	1072.97 ± 80.53^b	1072.72 ± 86.75^b	1077.59 ± 84.92^a	< 0.001
Fat yield (G/day)	1322.51 ± 88.11^a	1313.08 ± 92.92^a	1325.22 ± 88.39^a	< 0.001
Lactose (g/day)	1413.84 ± 112.02^a	1411.20 ± 119.21^a	1419.89 ± 116.94^a	< 0.001
Urea (mg/100g)	20.09 ± 3.7^b	19.95 ± 3.44^b	19.87 ± 3.74^b	< 0.001

Table 3. Mean production variables (daily milk yield, protein, fat, lactose, and urea) in different groups of THI (< 68, 68-72 and > 72) and their class differences of THI groups (^{a} = difference, ^{b} = no difference).

5. Discussion

Experiment 1

In this study, data of dry-bulb temperature, relative humidity and dewpoint temperature was collected between June and September, hence months with relatively hot climate conditions. No data was collected of the on-farm climate loggers during the cold climate conditions, during Dutch winter months. During the research period, the results were an average higher ambient temperature, lower relative humidity, higher dewpoint temperature and higher THI at the on-farm site compared to the meteorological station. These results may be caused by heat congestion and poor ventilation, due to insufficient use of sprinklers and fans or structural deficiencies (Collier et al., 2006). Because of the lack of data during the other months of the year (October – April), no comparison could be made between hot and cold climate conditions, both at the on-farm climate loggers and the difference between the loggers and the meteorological station. The expectation might be a higher ambient temperature at the on-farm site compared to the meteorological station during cold climate conditions (October – February), because of the cow's heat production and the resulting increase in temperature inside the barn (Robinson et al., 1986).

In this research, no difference was made between cows housed indoor all year and cows with access to pasture. In 2020, 82% of the Dutch farms and 74% of all Dutch cows had access to pasture during hot climate conditions (April/May – September/October). The average time on the pasture was 8.5 hours per day (CBS, 2022). Access to pasture might lower the ambient temperature at the barn, as lack of heat production described earlier in the discussion. A lower ambient barn temperature results in less heat stress experienced by the cows. On the other hand, access to pasture on days with full sunlight increases heat stress perceived by cows. Different types of housing were also not included in this research. Some barns were quite old and had no ventilation system, other barns were more modern with higher roofs and cooler climate conditions in the barn. One of the barns had an experimental climate system, which sprinkled to cows for 30 seconds (standing at the feeding place) followed by a minute of blowing air to cool the cows. These kind of systems and different barns might influence the outcome of difference between the on-farm climate logger and the nearest meteorological station. The scatterplot with associated regression (appendix 6) showed there was a significant difference between the data obtained from the logger and the data obtained from the meteorological station. This analysis shows us that data should be measured on farm and not be taken from the nearest meteorological station to have a precise knowledge of what is going on in those barns regarding the climate and the THI.

The last point of discussion is the distance between the on-farm logger data and the meteorological station. No account was taken with the difference in distance between those two. Some on-farm data loggers were closer to the meteorological station than other loggers, distances differed between 8.04 and 20.75 km. Also, the geographical location of the farms was not considered. The Netherlands is no big country, but there are still great differences in climate conditions between for example in the north and the south of the Netherlands (Wolters et al., 2011). On-farm data loggers capture temperature and humidity at specific locations on the farm. These microclimates can be influenced by various factors such as the presence of cows, (no) ventilation, or bodies of water, which can create localized variations in temperature and humidity that may differ from the broader climate conditions measured by official meteorological stations. Meteorological stations, on the other hand, are typically placed in open areas (grassfield conditions) away from obstructions to capture more representative regional climate data. These meteorological stations are influenced by wind but protected from sunlight and precipitation.

Experiment 2

In experiment 2, the only parameters researched is the difference in THI and hours during daytime and nighttime between the on-farm climate loggers. A little less hour (on average 0.7) of heat stress were observed during nighttime compared to daytime. This result is to be expected, because during nighttime on average temperatures are lower than during daytime. Direct sunlight is not present and thereby the air can cool down and reduce the ambient temperature. However, the difference between average daytime THI and nighttime THI is not that big (only 0.8). This might be due to the fact that cows are more active in cooler conditions, so they have a higher active pattern, do have a higher feed intake, go to the milking machine more often (in case of an automatic milking system) and thereby have a higher metabolism and thus a higher heat production. The higher heat production can influence the ambient temperature and thereby the THI.

Experiment 3

From previous research it is known that an increase in daily THI results in general in a decrease in milk yield (Tao et al., 2018). This decrease is attributable to a reduced feed intake, due to cows' exposure to heat stress (Allen et al. 2013). Another reason for a decrease in milk yield, when exposed to heat stress might be an increase in herd SCC (as seen in figure 5). This increase in SCC and thereby the infection rate of clinical mastitis may decrease milk yield even further (de Haas et al., 2002). Unfortunately, no data about the infection rate of clinical mastitis of the participating farms is known during this research. Although the statistical analysis showed there was no significant relationship between THI and milk yield, figure 3 showed a decrease in milk yield a few days after an increase in THI. This little delay in time is already known in other literature. One day after initiation of heat stress, a decrease in feed was noticeable according to Spiers et al. (2004). A milk decrease was seen two days after initiation of heat stress in this same research. A maximum decrease in milk yield was seen 48 hours after the first moment of heat stress according to Collier et al. (1981).

It is to be expected that a higher daily THI has a negative effect on milk yield (as discussed above) and other production variables like protein, fat, lactose, and urea. However, this research only showed a pattern of decrease (with an increase in THI) in milk yield and urea, although the decrease was very little. The highest yield of protein, fat and lactose was seen in the group with the highest THI (THI > 72 and thus heat stress). Research of Gernand et al. (2019) showed a decrease in protein yield beyond THI 68, especially for cows in the early (6 - 100 DIM) and mid lactation stage (101 – 240 DIM). An explanation for this decline in early lactation stage might be the connection between milk yield and metabolic heat production (Bilby et al., 2008). A discrepancy in results of protein yield in this research compared to previous research might be due to the smaller number of results in group THI > 72 (n = 20) compared to the group with THI < 68 (n = 61).

Literature is inconsistent about the change in fat yield in association with an increase in THI. Some research found a decrease in milk fat percentage, when THI rose above 75 (Abeni et al. 1993). Nasr and El Tarabany (2017) found that milk fat percentage decreased from 3.91 to 3.74% from a group of high THI (THI 80-85) to a group of low THI (THI < 70). Such high numbers of THI were not found during the current research period. Not all research shows a difference in milk fat yield. Cowley et al. (2015) and Hammami et al. (2015) for example, found no difference in milk fat yield in association with THI. This current research showed an increase in fat yield in the highest THI group (THI > 72).

Heat stress in a cow leads to increased panting, causing respiratory alkalosis. To compensate, bicarbonate ions are excreted in the urine to maintain the acid-base balance in the blood. This results in reduced buffering capacity in the blood, affecting pH regulation in the rumen and potentially leading to rumen acidosis. Rumen acidosis disrupts fermentation, reducing the production of volatile fatty acids, which are crucial for milk fat synthesis. As a consequence, milk fat content decreases (milk fat depression). Additionally, rumen disruption can decrease microbial protein production and limit the availability of essential amino acids for milk protein synthesis, leading to reduced milk protein content. Overall, heat stress-induced physiological changes can have cascading effects on the rumen environment and nutrient utilization, resulting in lower milk fat and protein content in the cow's milk (Aggarwal and Upadhyay, 2013).

Inconsistencies in research results regarding milk yield, protein, fat, lactose, urea, and somatic cell count (SCC) in dairy cows exposed to heat stress may be attributed to various factors beyond just the Temperature-Humidity Index (THI). It is essential to consider other influential factors, such as housing facilities, grazing opportunities, diet, stage of lactation, thermoregulation capabilities, length of the research period, level of heat stress, milking shifts per day, and milking systems. While the THI is a valuable indicator of heat stress, it cannot fully account for all the complexities and variations in dairy production. Factors like different housing systems, ranging from open grazing to confined barns, can significantly impact cows' exposure to heat stress and thus their performance. Grazing opportunities and diet composition may also affect the nutrient intake and energy available for milk production. The stage of lactation plays a crucial role, as milk production naturally varies throughout lactation, and heat stress can exacerbate these fluctuations. Additionally, cows may exhibit different thermoregulation capabilities based on breed, adaptation, and individual resilience to heat stress. The duration and intensity of heat stress experienced during the research period can vary, and different levels of heat stress may have varying impacts on milk production and composition. The frequency of milking shifts per day and the milking system can also affect milk yield and composition.

It's important to acknowledge that the current research may have focused solely on THI without considering all these other influential factors. To draw more accurate and comprehensive conclusions about the effects of heat stress on dairy cow production, further research is necessary. Conducting specific studies that account for multiple factors and control for confounding variables will help isolate the true impact of heat stress on milk yield, protein, fat, lactose, urea, and SCC. This will aid in developing more targeted and effective management strategies to mitigate the adverse effects of heat stress on dairy cow performance.

6. Conclusion

The findings of this study revealed significant differences in temperature, dewpoint temperature, and THI between the barn locations and the official meteorological station. The climate data collected from on-farm loggers proved to be more accurate than the data from the nearby meteorological station. Regarding the relationship between THI and milk production variables, the results were inconclusive. No significant association was found between THI and average daily milk yield and lactose content. However, there was a significant negative correlation between THI and protein and fat yield, indicating that heat stress may have a detrimental effect on these specific milk components.

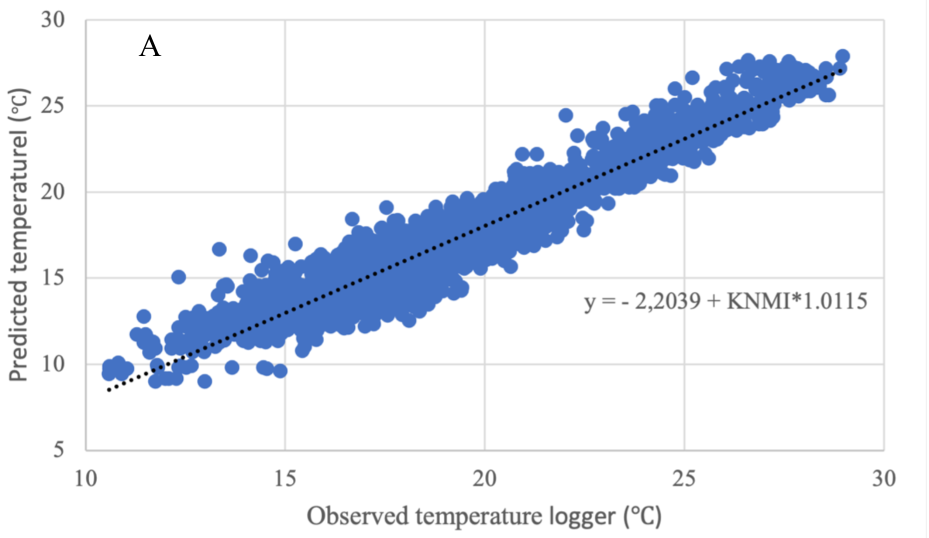
Despite these initial findings, further research is still required to gain a more comprehensive understanding of the relationship between THI and milk production variables. Future studies should be conducted under standard conditions that minimize potential influences on milk production variables, allowing for more definitive conclusions.

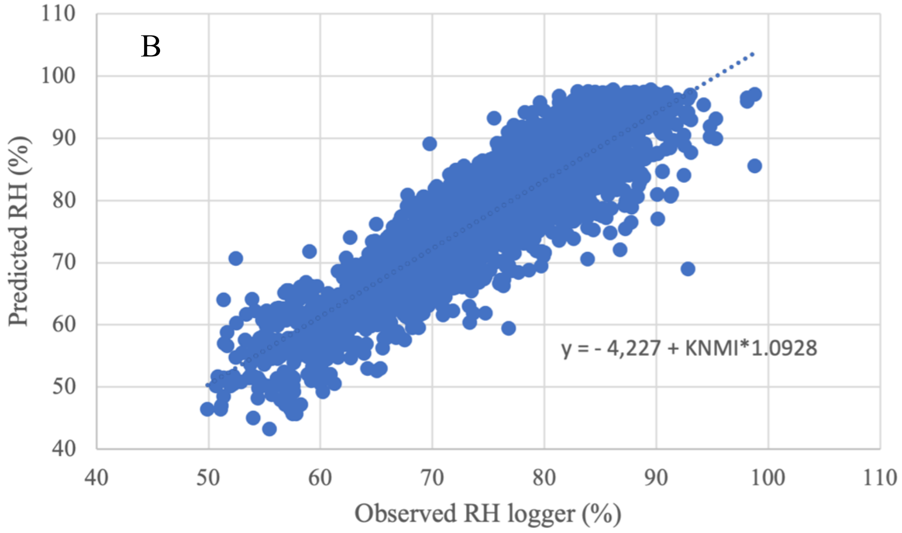
In conclusion, this study highlights the importance of on-farm climate data for accurate assessments of heat stress and indicates the need for additional research to explore the intricate interactions between THI and various milk production parameters. These insights will contribute to improved heat stress management strategies and better welfare and productivity outcomes for dairy cows.

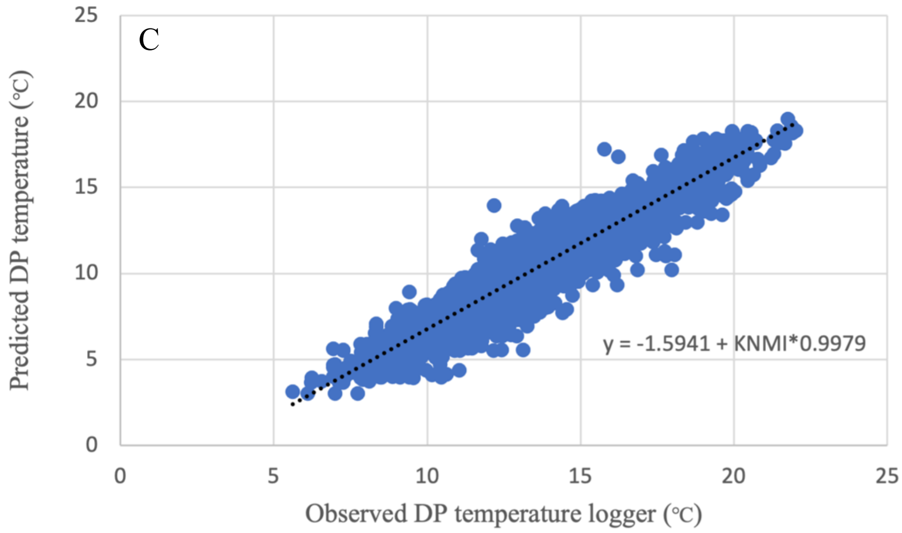
7. Acknowledgments

I would like to express my gratitude to all those who have supported and contributed to the completion of this thesis on heat stress in cows. Special thanks to my supervisors Kasper Dieho and Thomas Schonewille for their guidance and expertise, and to the farmers and stakeholders (Cargill Animal Nutrition) who participated in the study and who gave me this subject for my thesis. I am also thankful to my family and friends for their support throughout this journey, especially during the harder times in this process.

8. Appendix


A
Predicted temperaturel (°C)
30
25
20
15
10
5
10
15
20
25
30
Observed temperature logger (°C)
y = - 2,2039 + KNMI*1.0115


B
Predicted RH (%)
110
100
90
80
70
60
50
40
40
50
60
70
80
90
100
110
Observed RH logger (%)
y = - 4,227 + KNMI*1.0928


C
Predicted DP temperature (°C)
25
20
15
10
5
0
0
5
10
15
20
25
Observed DP temperature logger (°C)
y = -1.5941 + KNMI*0.9979

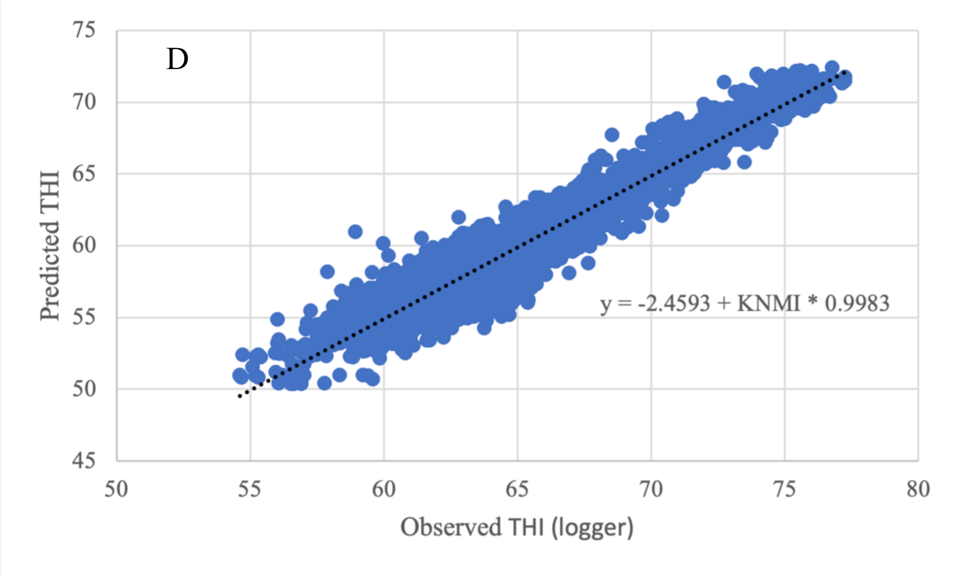


Figure 6. Observed and predicted temperature, relative humidity (RH), dewpoint (DP) temperature and THI (figure 6A, 6B, 6C, 6D) with their associated regression.

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