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Original Article

Changes in milk production and economic analysis in relation with the temperature-humidity index in Korean Holstein cows

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ABSTRACT

Background: Dairy cows exposed to heat stress have reduced milk production, milk quality, and conception rates, leading to lower profits. This study was conducted to analyze the effect of heat stress according to Temperature-Humidity Index (THI) on the milk production of Korean Holstein cows.

Methods: Monthly maximum temperature and average relative humidity data from January 2017 to August 2024 were obtained from 62 observation points used by the Korea Meteorological Administration to calculate the national average. Using this data, the THI, a key indicator for assessing heat stress in Korean Holstein cows, was calculated. Additionally, data from 240,088 Korean Holstein cows, collected through tests conducted by the Dairy Cattle Improvement Center of the NH-Agri Business Group, were analyzed.

Results: Comparative analysis of the relationship between THI and milk production revealed that milk yield remained relatively stable until THI reached the "very severe" heat stress threshold (THI ≥ 79). Beyond this level, milk production showed a tendency to decline. Conversely, when THI dropped below this threshold, milk yield tended to recover. Notably, the temperature in September, typically considered part of the autumn season, has been rising in recent years, with THI values now approaching the very severe stress level (THI ≥ 79).

Conclusions: These findings suggest that establishing an appropriate farm environment and implementing systematic THI management are essential for mitigating the decline in milk production, as well as the associated economic losses, caused by rising domestic temperatures due to global warming.

Keywords: climate challenge, heat stress, Korean Holstein cows, milk production, temperature humidity index

INTRODUCTION

Since industrialization, the accumulation of greenhouse gases in the Earth's atmosphere has led to a rise in global temperatures (Wadanambi et al., 2020). In 2023, the global average temperature increased by 1.45℃ compared to pre-industrial levels (1850-1900) (Pachauri and Meyer, 2015; Chanwoo, 2024). If the current rate of global temperature increase continues, the average global temperature is projected to rise by 3.7 to 4.8℃ by the end of the 21st century (Pachauri and Meyer, 2015; National Centers for Environmental Information, 2024). Korea has also been affected by global warming, with temperatures showing a continuous upward trend (Yun, 2002). In 2023, the average annual temperature in Korea reached 13.7℃, which was 1.2℃ higher than the historical average of 12.5℃ (KMA, 2025). This trend is particularly concerning, as the rate of temperature increase in Korea is faster than the global average (National Centers for Environmental Information, 2024).

The productivity of dairy cows is maximized when their physiological functions are maintained within appropriate stress levels (Baek et al., 2013; Jeon, 2020; Sumi et al., 2022; Jurkovich et al., 2024). In Korea, most dairy cows bred for milk production are Holsteins (Lim et al., 2020). This breed is particularly vulnerable to high temperatures and humidity, and experience heat stress when ambient conditions exceed critical thresholds (West, 2003; Hut et al., 2022; Lee et al., 2024). Prolonged exposure to heat-stressed environments reduces feed intake, lowers conception rates and milk yields, and degrades milk quality (Kim et al., 2017; Baek et al., 2019; Lim et al., 2020; Kim et al., 2021; Kirdeci et al., 2021; Chen et al., 2024; Lee et al., 2024). These factors increase production costs and reduce income, posing serious economic challenges to the dairy industry (Chanwoo, 2024; Chen et al., 2024).

Despite the significant temperature increase in Korea due to global warming, research on changes in dairy cow productivity remains limited. Most studies have relied on data collected only up to 2020, despite the ongoing and rapid climate changes in recent years (Jang et al., 2022). Therefore, this study sought to update our understanding of how the Temperature-Humidity Index (THI) affects milk production, and to analyze the associated economic impacts. Collectively, our findings provide essential data to support the prediction of Korea's agricultural outlook and to inform the development of policies in response to climate change.

MATERIALS AND METHODS

Milk production and economic data

Data from 240,088 dairy cows across Korea, collected between January 2017 and August 2024 by the Dairy Cattle Improvement Center of NH-Agri Business Group and the Dairy Science Division of the National Institute of Animal Science, were used for analysis. Trends in milk production were examined by year, region (province), and season. Economic profit was calculated based on the milk purchase price set by the Korea Dairy & Beef Farmers Association, which is KRW 1,084/kg. Data points with fewer than 10 samples were excluded from the analysis.

Temperature–humidity index

For weather data, monthly maximum temperature and average relative humidity values were obtained from 62 observation points used by the Korea Meteorological Administration to calculate the national average. Monthly THI values were then calculated using these data, based on the THI model developed by the National Research Council (National Research Council, 1971) as follows (Lee et al., 2018).

$$THI = (1.8 \times T + 32) - [(0.55 - 0.0055 \times H) \times (1.8 \times T - 26.8)]$$

where THI is the Temperature-Humidity Index, T is the maximum daily temperature (℃) in the region, and H is the average daily relative humidity (%) in the region.

The heat stress index was classified into four categories: comfort: THI $\leq$ 71; severe: THI 72-79; very severe: THI 80-89; deadly: THI $\geq$ 90 (Jang et al., 2022).

Statistical analysis

Differences in average monthly THI and milk production were expressed as mean ± standard error of the mean (SEM). Differences (mean ± SEM) of average monthly THI and milk production were analyzed using two-way analysis of variance (ANOVA) followed by Tukey's multiple comparisons test. Variations in THI (mean ± SEM) by year during the months of July to September from 2017 to 2024 were analyzed using one-way ANOVA. All statistical analyses were performed using GraphPad Prism (version 8.0.1; GraphPad Software Inc., USA).

RESULTS

The analysis revealed that the heat stress index reached the "very severe" level (THI 80-89) during the summer months (June to August) in most years, corresponding to periods of high temperature (Jang et al., 2022). In particular, August consistently recorded the highest THI, significantly exceeding the values observed in June and July of the same season. Conversely, during the winter months (December to February), classified as the cold season, the heat stress index remained within the "comfort" zone (THI ≤ 71). January, the coldest month, exhibited a significantly lower THI than December and February (Fig. 1, p < 0.001).

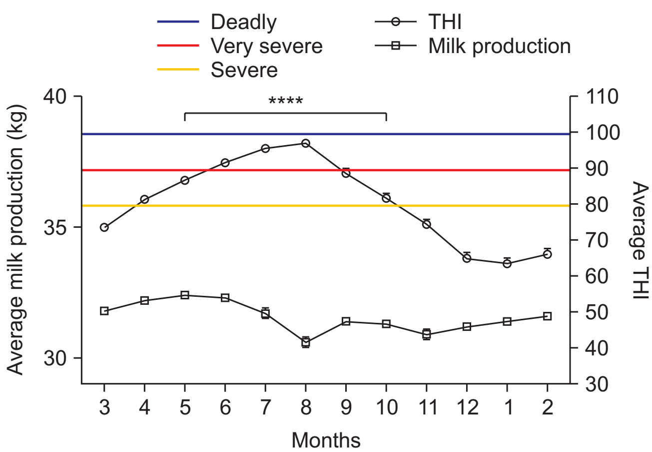

Fig. 1. Average monthly THI and milk production from January 2017 to August 2024 in Korean Holstein cows (n = 240,088). The orange line indicates the THI range associated with severe heat stress (THI 72-79), the red line represents very severe heat stress (THI 80-89), and the blue line denotes deadly heat stress (THI ≥ 90). Data are presented as means ± SEM. Differences in average monthly THI and milk production were analyzed using two-way analysis of variance (ANOVA) followed by Tukey's multiple comparisons test. ****p < 0.001.

Regarding milk production, Fig. 1 shows that output was lowest in August at 30.88 kg/day, coinciding with the peak in THI. In contrast, milk production peaked in May at 32.41 kg/day, when the THI was moderate. Production began to decline in June as THI rose, indicating that heat stress begins to affect milk yield once a certain threshold is exceeded. The cumulative effect of this stress resulted in the lowest production in August, followed by a recovery in September as conditions improved.

From an economic perspective, milk revenue in August was 33,222 KRW/day (24.16 USD/day), representing a 1,932 KRW/day (1.40 USD/day) decrease or a 5.5% decline compared to the 35,154 KRW/day (25.56 USD/day) recorded in May (exchange rate standard is 1 USD = 1,375.70 KRW). If such reductions persist over time, they could lead to significant financial losses for dairy farmers (Table 1).

In recent years, milk production has shown increased irregularity, and THI levels in September, typically considered part of autumn, have also risen. This suggests that climate change, driven by rapid global warming, may be extending the duration of high-temperature periods and disrupting the normal physiological activities of Korean

Table 1. Seasonal averages of the temperature-humidity index (THI), milk production, and milk price from January 2017 to August 2024 in Korean Holstein cows (n = 240,088)

Seasons/months		THI (index)		Milk production (kg)		Milk price (KRW/day)	
		Mean	SEM	Mean	SEM	Mean	SEM
Spring	3	73.6	0.9	31.8	0.1	34,509	131
	4	81.4	0.9	32.2	0.1	34,898	116
	5	86.7	0.7	32.4	0.1	35,154	139
Summer	6	91.6	0.6	32.3	0.1	35,040	119
	7	95.6	0.8	31.7	0.2	34,356	167
	8	97.0	0.5	30.6	0.2	33,222	249
Fall	9	88.7	1.2	31.4	0.1	34,067	85
	10	81.7	1.4	31.3	0.1	33,906	77
	11	74.5	1.3	30.9	0.2	33,539	255
Winter	12	65.0	1.6	31.2	0.1	33,770	144
	1	63.6	1.5	31.4	0.1	34,024	110
	2	66.2	1.5	31.6	0.1	34,244	145

Values for average THI, milk production, and milk price are expressed as means ± SEM.

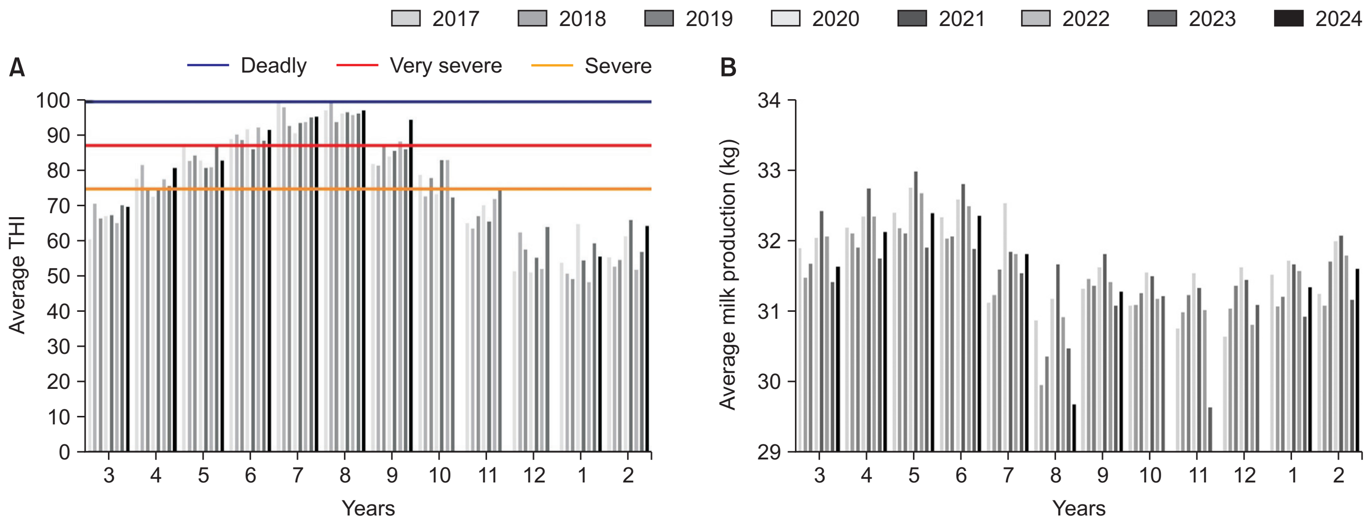

Fig. 2. Average monthly THI and milk production for each year from January 2017 to August 2024 in Korean Holstein cows (n = 240,088). (A) shows the average monthly THI, and (B) presents the average monthly milk production. Data from 2017 to 2024 are displayed as bar graphs with different colors for each year. The orange line indicates the THI range associated with severe heat stress (THI 72-79), the red line represents very severe heat stress (THI 80-89), and the blue line denotes deadly heat stress (THI ≥ 90).

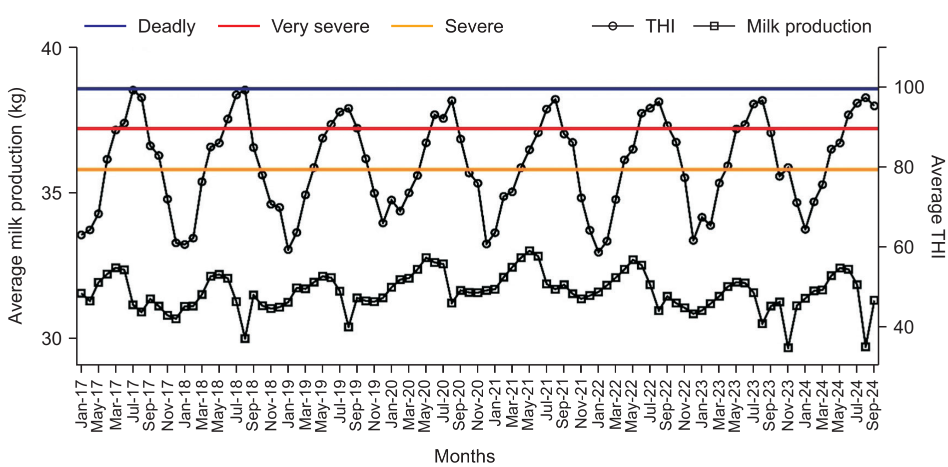

Fig. 3. Changes in the monthly average THI and milk production from January 2017 to August 2024 in Korean Holstein cows (n = 240,088). The orange line indicates the THI range associated with severe heat stress (THI 72-79), the red line represents very severe heat stress (THI 80-89), and the blue line denotes deadly heat stress (THI ≥ 90). Monthly averages of THI and milk production are presented as mean values.

Holstein cows by subjecting them to prolonged heat stress (Fig. 2-4).

An analysis of regional trends in milk production and THI across the country revealed that the heat stress index increased during the summer months in all regions, accompanied by a corresponding decline in milk production. Seasonal comparisons showed that milk production peaked in spring across all regions and then declined during the summer, aligning with previous research indicating that high-temperature and high-humidity conditions negatively impact dairy performance (Fig. 5).

During the summer, all regions recorded THI levels within the "very severe" category (THI 80-89). Among them, Gyeongsangnam-do had the highest average THI at 84.03, while Gangwon-do had the lowest at 81.34 (Fig. 6B). Interestingly, despite the large differences in THI between the two regions Gangwon-do also recorded the highest average summer milk production at 31.97 kg/day, closely followed by Gyeongsangnam-do at 31.96 kg/day, a marginal difference of only 0.01 kg/day. The lowest summer milk production was observed on Jeju Island, at 26.61 kg/day (Fig. 6A). The largest seasonal decline in milk yield (from spring to summer) was also seen on Jeju Island, with a drop of 1.61 kg/day, whereas Gangwon-do experienced the smallest decline at just 0.1 kg/day. Gyeongsangnam-do, despite having the highest summer THI, showed a moderate decline of 0.7 kg/day.

In the case of Gyeongsangnam-do, Korean Holstein

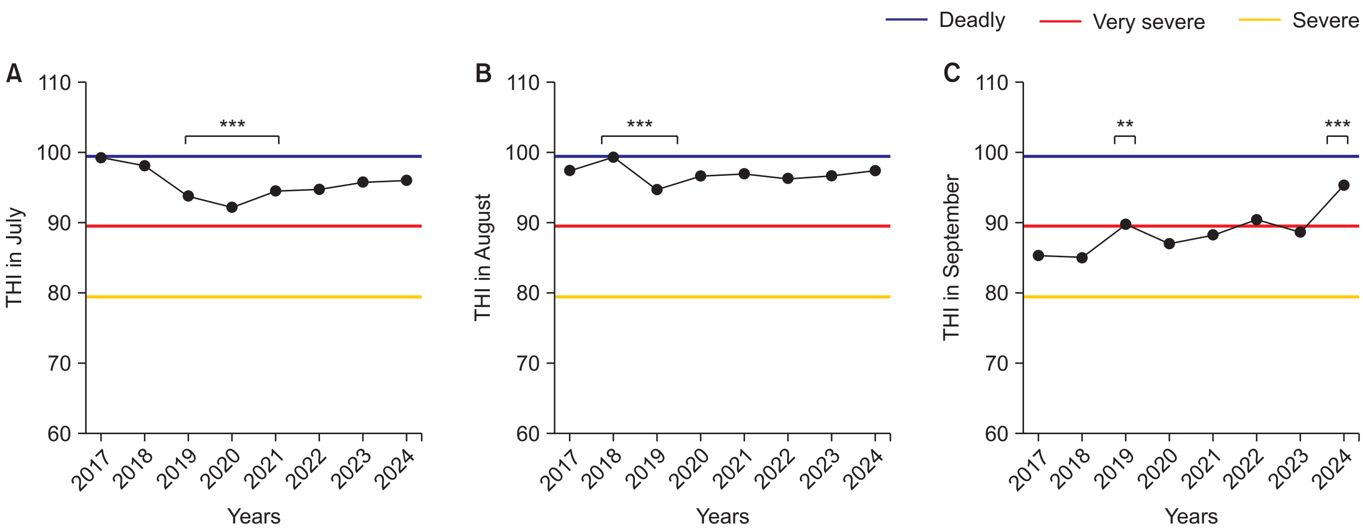

Fig. 4. National average THI from July to September for the years 2017 to 2024. (A) shows the trend in average THI for July, (B) for August, and (C) for September. The orange line indicates the THI range associated with severe heat stress (THI 72-79), the red line represents very severe heat stress (THI 80-89), and the blue line denotes deadly heat stress (THI ≥ 90). Differences in THI (mean ± SEM) by year during the July-September period were analyzed using one-way analysis of variance (ANOVA). **$p < 0.01$, ***$p < 0.005$.

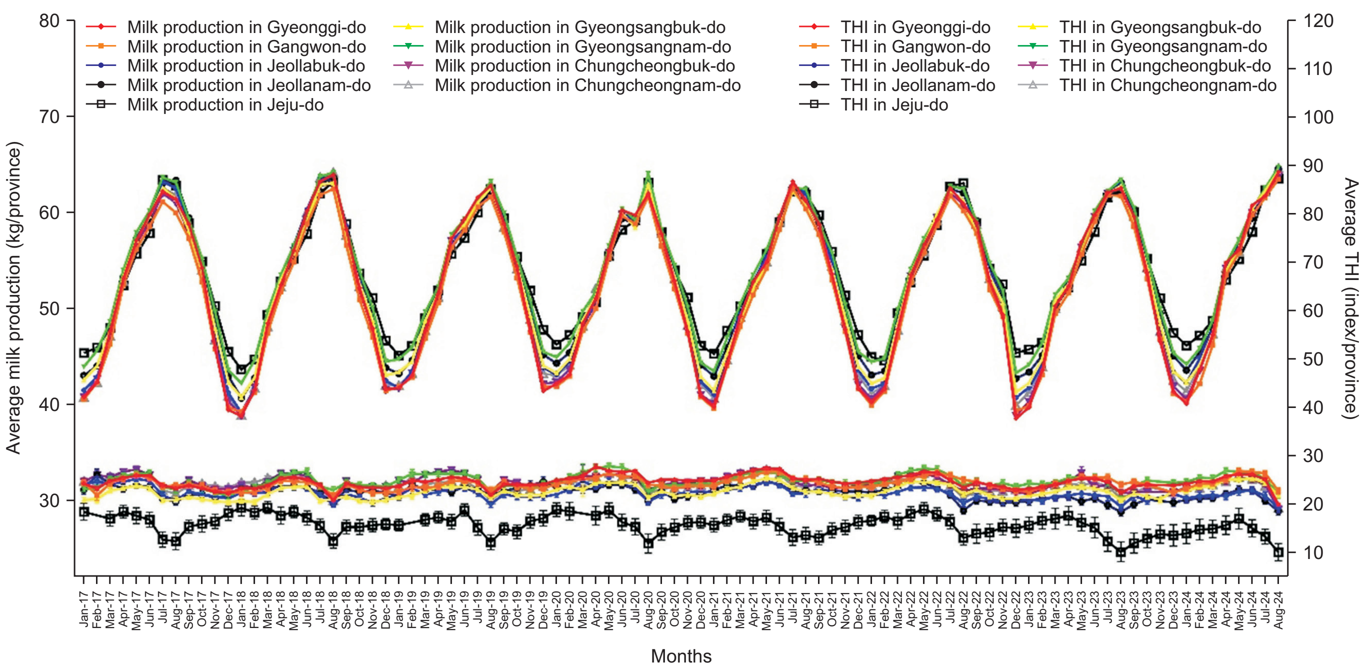

Fig. 5. Average monthly THI and milk production from January 2017 to August 2024 in Korean Holstein cows (n = 240,088). The graph shows the average monthly THI and milk production by province, with each province represented by differently colored lines. Data are expressed as means ± SEM.

cows farms are concentrated because they are geographically located near Busan, a large-scale source of sales. It is similar to Gyeonggi Province, near Seoul, raising the largest number of Korean Holstein cows in the Korea. Therefore, it seems that because Korean Holstein cows were raised for a long period of time, the specification management technology of the Korean Holstein cow farm was relatively good compared to other regions and the preparation for heat stress was good. However, this part is only speculation, and various additional studies and analysis are needed, including the genetic capabilities of Korean Holstein cows in Gyeongnam and Korean Holstein

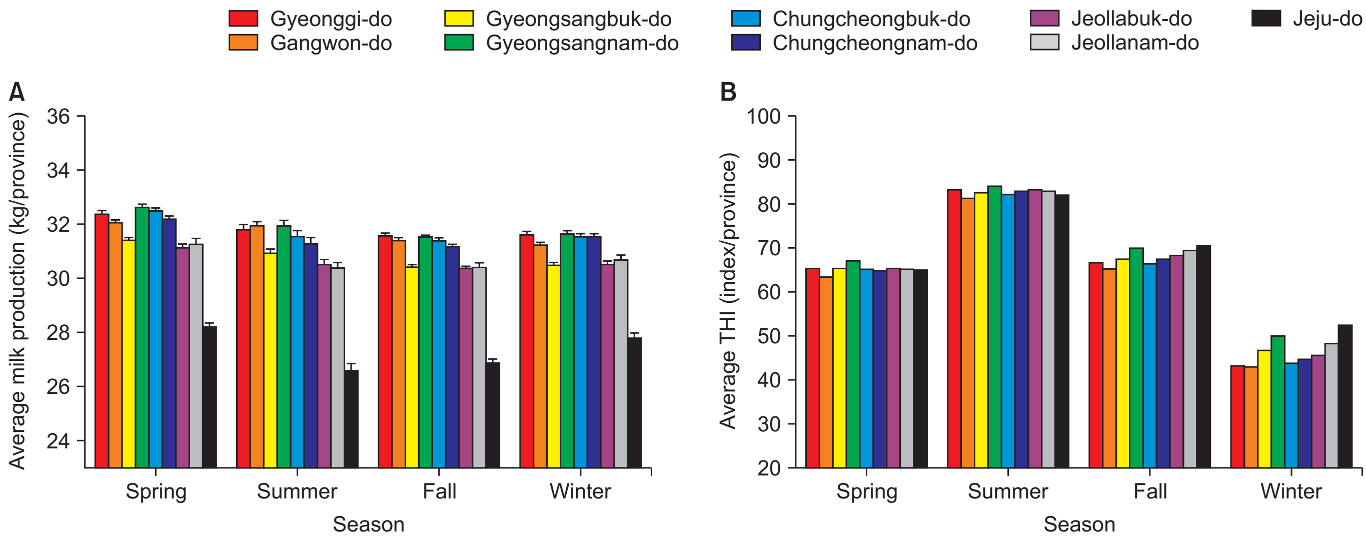

Fig. 6. Seasonal average milk production and THI from July to September between 2017 and 2024 in Korean Holstein cows (n = 240,088). Seasonal averages for THI and milk production are represented by bars of different colors. Values are presented as means ± SEM.

cows in other regions.

These findings suggest that regional differences in THI levels may not directly translate into proportional changes in milk production, as all areas exceeded the threshold for very severe heat stress. Thus, it is likely that other factors, such as the level of genetic improvement, the proportion of high-performing cows, and specific herd management practices, played a more substantial role in regional variations in milk production under heat stress conditions.

DISCUSSION

This study analyzed the impact of the THI, calculated using temperature and relative humidity data in Korea, on milk production and milk purchase prices for Korean Holstein cows. The results showed that when THI exceeded a critical threshold (THI ≥ 79), milk production declined due to heat stress, leading to a reduction in milk purchase prices during the warm summer months (June to August).

Notably, in recent years, temperatures in September, traditionally considered part of autumn, have continued to rise, effectively extending the high-temperature period beyond summer. This shift, driven by global warming, suggests a growing risk of prolonged heat stress in dairy cows, which could further reduce milk production and milk prices over time (St-Pierre et al., 2003; Chen et al., 2024; Jurkovich et al., 2024).

Indeed, climate data confirm that temperature and humidity levels in Korea have been steadily increasing due to global warming, resulting in a consistent rise in THI (Lee et al., 2018; Pinto et al., 2020). Elevated THI levels are known to induce heat stress in dairy cows (Dunn et al., 2014; Hut et al., 2022), which in turn negatively affects milk yield (St-Pierre et al., 2003; Tao et al., 2020). Since milk production accounts for over 90% of total income on dairy farms (Do et al., 2013), any decline in yield due to heat stress could significantly reduce farm profitability.

CONCLUSION

To safeguard long-term farm income and support the sustainable growth of the dairy industry, adaptive strategies must be implemented. These include improving barn environments, enhancing ventilation and cooling systems, developing targeted management strategies for high-temperature periods, advancing genetic improvement programs, and consistently selecting high-performing animals. Furthermore, the findings of this study provide valuable baseline data for developing sustainable dairy production systems by guiding the application of heat stress mitigation technologies, promoting heat-tolerant genetic lines, and enhancing genetic selection frameworks.

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