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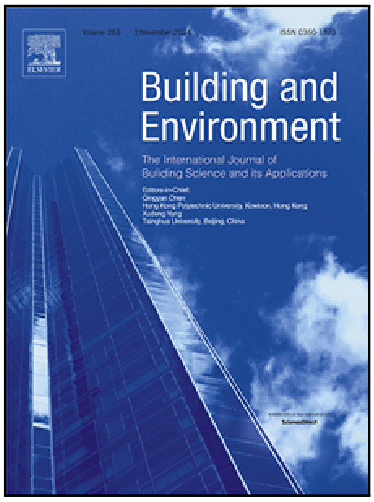

Heat Stress Monitoring, Modelling, and Mitigation in a Dairy Cattle Building in Reading, UK: Impacts of Current and Projected Heatwaves

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1. Highlights

- Integrated realistic dairy cows' heat dissipation into building thermal modelling.
- 2021 UK Heatwave: severe heat stress in milking parlour while moderate in housing
- 2080s Heatwave: indoor heat stress severity predicted to Level 4 (Emergency)
- Building adaptation strategies need to be tailored to housing and milking parlours
- Advanced building adaptation strategies are critical for combating future heatwaves

Heat Stress Monitoring, Modelling, and Mitigation in a Dairy Cattle Building in Reading, UK: Impacts of Current and Projected Heatwaves

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Abstract

Heat stress in dairy cattle buildings is a pressing challenge under global warming. While building climate resilience is as critical as improving animal thermal resilience, limited research has evaluated the effectiveness of building adaptations in specific spaces, such as cattle housing and milking parlours, particularly under extreme climate conditions. This study addresses this gap by assessing the impacts of observed and projected heatwaves on dairy housing and a milking parlour and possible mitigation solutions, through indoor heat stress measurements and dynamic livestock building thermal modelling. We advance the modelling capability by incorporating realistic sensible and latent heat dissipation from dairy cattle, accounting for body mass, daily milk production, and ambient temperatures. Measurements during the 2021 UK Heatwave revealed consistently higher indoor Temperature-Humidity Index (THI) levels compared to outdoors. The milking parlour experienced more severe heat stress (Level 3: Severe) than the housing (Level 2: Moderate) due to higher internal heat gains and poor ventilation, with notable differences between morning and afternoon milking times. Projections for the 2080s heatwave indicated that both spaces would experience heat stress day and night, with severity reaching Level 4 (Emergency) for most of the time. Under current heatwave conditions, solar reflective roof paint proved effective for the housing, while hybrid ventilation was effective for the milking parlour. However, these strategies were insufficient for future extreme heatwaves, emphasizing the need for advanced, tailored building adaptations. This study highlights the critical importance of designing climate-resilient dairy buildings to safeguard animal welfare and productivity in a warming world.

Keywords: Indoor Heat Stress; Animal Welfare; Milking Parlour; Cubicle Housing Barns; Temperature and Humidity Index; Building Simulation.

2. Introduction

Mitigating the risk of heat stress in dairy cattle has become a critical concern, particularly in the context of more extreme heat events driven by climate change (Becker et al., 2020, IPCC, 2023). Dairy cattle are more susceptible to warm conditions than cold conditions (Ohnstad, 2016). This susceptibility arises from an imbalance between the metabolic heat attributable to feed digestion, nutrient assimilation and milk synthesis and the animal's ability to dissipate heat (Das et al., 2016). This challenge is compounded by their typical housing in non-air-conditioned buildings, which exacerbates heat stress risks during hot summers. Furthermore, dairy cows tend to bunch together when ambient temperatures exceed 20°C, raising localized temperature, and further exacerbating heat stress (Chopra et al., 2024). Such maladaptive behaviours can create a negative feedback cycle, intensifying the overall risk. Even in temperate climate zones, like Central Europe, the northern United States, and Canada, dairy farming is not immune to the impacts of climate change in terms of heat stress events (Silanikove and Koluman, 2015, Polsky and von Keyserlingk, 2017, Hempel et al., 2019, Gauly and Ammer, 2020). As a result, the assessment of heat stress and the implementation of effective mitigation strategies are critical to ensuring welfare of dairy cattle, as well as the profitability and sustainability of dairy farming. This is particularly important given that dairy farming supports the livelihoods of approximately 150 million households worldwide (FAO, 2025).

To assess heat stress in dairy cows, the Temperature-Humidity Index (THI) (Thom, 1958, NRC, 1971) has been widely calculated using outdoor meteorological data (Ouellet et al., 2019, Campos et al., 2022). This practice is largely due to the better accessibility of meteorological data from public weather stations. However, environmental conditions on farms can differ significantly from those at meteorological stations, and more importantly, these differences can be unpredictable (Shock et al., 2016). It has been well established that using temperature and humidity data from meteorological stations can significantly underestimate both the intensity and duration of heat stress in barns used for dairy cattle housing (Schüller et al., 2013, Ouellet et al., 2019). Multiple temperature and humidity sensors were installed near cubicles or feeding troughs at various heights (e.g., 1.0 m to 3.5 m) (Hempel et al., 2018, Lovarelli et al., 2021, VanderZaag et al., 2023, Herbut and and Angrecka, 2018) to capture environment condition within barns. Additionally, mobile sensors such as temperature and humidity sensors attached to cows' neck collars and eat tags have been used to observe area-specific differences (Moretti et al., 2017). Monitoring durations varied, ranging from a few days to full-year assessments. The indoor heat stress evaluations depend in large part on sensor placement and barn design (Hempel et al., 2018). However, there is limited research focused on measuring environmental conditions in milking parlours. While on-site measurements could improve accuracy, they are impractical for systematically evaluating how building design influences heat stress or for testing mitigation strategies.

Current mitigation efforts fall into two categories: enhancing cattle resilience and modifying the physical environment. The first approach—encompassing nutrition, breeding, and health management—aims to improve long-term heat tolerance (Abeni and Galli, 2017, Negrón-Pérez et al., 2019, Reddy et al., 2023, Lovarelli et al., 2024, Heinicke et al., 2018). Yet these measures often fail to provide immediate relief during extreme heat events. In contrast, building adaptations can rapidly reduce stress by altering the thermal environment in livestock buildings

(Becker et al., 2020). For instance, Georg and Ashour (2012) indicated that using a marsh plant green roof reduced indoor temperatures by 5°C, maintaining approximately 25°C during summer of 2003. Vox et al. (2016) showed that high solar reflective roofing materials, such as red aluminium (22.1% solar reflectivity) compared to green steel (8.7% solar reflectivity), lowered surface temperatures by 8°C. Liberati (2008) also emphasized the importance of roof shape and insulation which could reduce building heat load, especially for closed barns. In the review by Fournel et al. (2017), roof insulation for barns was identified as a broadly applicable solution across various climate zones. Additionally, the use of sprinklers can also be effective though caution is needed in humid continental climates (average summer humidity ~75%) as high humidity may counteract the cooling benefits and exacerbate heat stress (Fournel et al., 2017). Ventilation design has also been extensively studied, due to its critical role in maintaining a healthy indoor environment. Tomasello et al. (2021) conducted Computational Fluid Dynamics (CFD) simulations to optimize building layouts, wall openings, and their positioning to enhance natural ventilation in dairy housing barns. Similarly, Sugiono et al. (2016) demonstrated through CFD models that exhaust fans effectively reduce temperature and humidity, lowering heat stress levels (e.g., from moderate to mild) in tropical climates. However, Pakari and Ghani (2021) found that exhaust fans alone may not meet the ventilation demands of dairy housing barns. Jiang et al. (2024) further showed that tube cooling, when combined with exhaust fans, serves as an effective supplemental cooling strategy. Critically, most studies focus on dairy housing barns, and less attention has been given to milking parlours, which are more enclosed, and experience significantly greater internal heat gains due to higher animal density and milking equipment operation. VanderZaag et al. (2023) noted that milking parlours consistently showed higher heat stress compared to housing during milking times, driven by the accumulation of high internal heat gains from grouped dairy cattle. This notable difference between the housing and milking parlours has significant implications for developing effective heat stress mitigation strategies tailored to each specific environment.

Dynamic building energy simulation (BES) has been recognized as a valuable tool for evaluating the effectiveness of building adaptations in reducing heat stress risks in dairy cattle facilities (Hempel et al., 2019, Costantino, 2023). For instance, De Masi et al. (2021) demonstrated the effectiveness of passive building envelope solutions using BES tools such as EnergyPlus (U.S. DOE, 2019) and DesignBuilder CFD module (DesignBuilder, 2021). Yet a key limitation persists in current building energy simulation (BES) approaches: most models continue to assume static sensible and latent heat loads from cattle, typically fixed at 25°C ambient temperature (Jackson et al., 2017, Shin et al., 2024). However, empirical evidence has shown that total metabolic heat generation and sensible heat dissipation decrease substantially under higher ambient temperatures, while latent heat dissipation increases sharply (CIGR, 2002). Specifically, as ambient temperatures approach skin temperature, the temperature gradient between them decreases to zero, meaning sensible heat dissipation becomes negligibly small. As a result, cows rely almost entirely on evaporative cooling, i.e., latent heat dissipation (Shephard and Maloney, 2023). Unfortunately, previous BES models fail to account for this dynamic variation in cows' heat dissipation. This can lead to substantial discrepancies between simulated and actual indoor heat stress. Therefore, it is crucial to incorporate this dynamic variation into BES models to reliably predict indoor heat stress risks under different building adaptation strategies and climate scenarios.

While various passive design and management solutions have been proposed, their combined effects on heat stress mitigation - especially in milking parlours - remain critically understudied. Different adaptation measures may produce synergistic, neutral, or even counterproductive interactions when implemented. A critical assessment of these adaptations allows for the identification of the most efficient and cost-effective solutions or combinations. Furthermore, the differential effectiveness of adaptations between primary housing barns and milking parlours has not been examined in the context of current or projected heatwave conditions. Addressing these knowledge gaps will enable stakeholders to make well-informed and impactful investments in building adaptations, thereby ensuring the long-term sustainability of dairy farming.

This paper aims to fill the research gap by thoroughly investigating heat stress levels and mitigation solutions in a cubicle dairy housing barn and a milking parlour, based on onsite measurements, and dynamic building thermal modelling in the context of current and future climates. The research objectives are: 1) to measure the indoor microclimate and assess heat stress in dairy housing barns as well as in a milking parlour, an area that has received less attention in previous research, during a heatwave; 2) to predict the risk and severity levels of heat stress in these spaces, taking into account dairy cattle sensible and latent heat dissipation, under both current and future heatwave conditions; and 3) to evaluate effectiveness of building adaptation strategies for heat stress mitigation.

3. Methodology

Subsection 3.1 presents indoor microclimate measurements, which are essential for investigating the current indoor thermal environment and validating the thermal model of the dairy cattle building. Thermal modelling of the dairy cattle building is described in subsection 3.3. Heat stress assessment metrics and future heatwave data are presented in subsection 0 and 3.5, respectively. Building adaptation strategies to mitigate the risk of heat stress in dairy cattle are presented in subsection 3.6.

3.1. Building information

Indoor temperature and relative humidity were measured at the dairy cattle facility of the University of Reading's Hall Farm (51.41° N, 0.91° W) in Shinfield, UK. Hall Farm is home to the Centre for Dairy Research (CEDAR) at the University of Reading, UK. Lactating dairy cattle are housed in covered cubicle yards with passages that are aligned from northeast to southwest (Figure 1), with sidewall openings above solid walls. There is a solid wall along the southwest side, where offices and other facilities, and a collecting yard for the milking parlour are located. The sidewall openings are fully open and aligned with the prevailing summer wind from the southwest. This design optimizes natural ventilation to remove heat, moisture, and odours. The solid walls are over 1.3 m high—above the height of dairy cattle—to prevent draughts at animal level. As shown in Figure 1, the facility consists of three main sections: Building A (82.2 m × 27 m × 8.7 m ridge height), which houses the milking parlour in the southeast corner of the building and the dairy cattle collecting yard; and Buildings B (82.2 m × 27 m × 9.6 m) and C (82.2 m × 27 m × 8.5 m), which contain cubicle yards with feed passages accessible by tractors. The eave height for all buildings is 5.4 m. Buildings B to C are referred to as cubicle yards, while octagon area (see Figure 1) in Building A is referred to as the milking parlour.

3.2. Indoor microclimate measurement during 2021 heatwave

Indoor microclimate measurements for the cubicle yards and milking parlour were conducted from 26th May to 28th July 2021, capturing 2021 UK heatwave period (16th–23rd July), which marked the fifth warmest July on record (Met Office, 2021). Hourly outdoor meteorological datasets were obtained from the University of Reading's Atmospheric Observatory (URAO), located 3.8 km from Hall Farm. The datasets included all the key thermally-related weather variables, such as dry bulb temperature, atmospheric pressure, relative humidity, global solar irradiation, wind speed, and wind direction, necessary for dynamic building simulations.

Indoor air temperature and relative humidity in the cubicle yards and milking parlour were recorded every 10 minutes using Tinytag sensors (model TGU-4500, Gemini Data Loggers (n.d.)), with accuracies of less than ±0.5°C (for temperatures between 0°C and 50°C) and ±3% (for relative humidity in the 0%–95% non-condensing). The sensors were installed at heights of 2 m in the cubicle yard and 2.5 m in the milking parlour, ensuring they were out of reach of standing cattle.

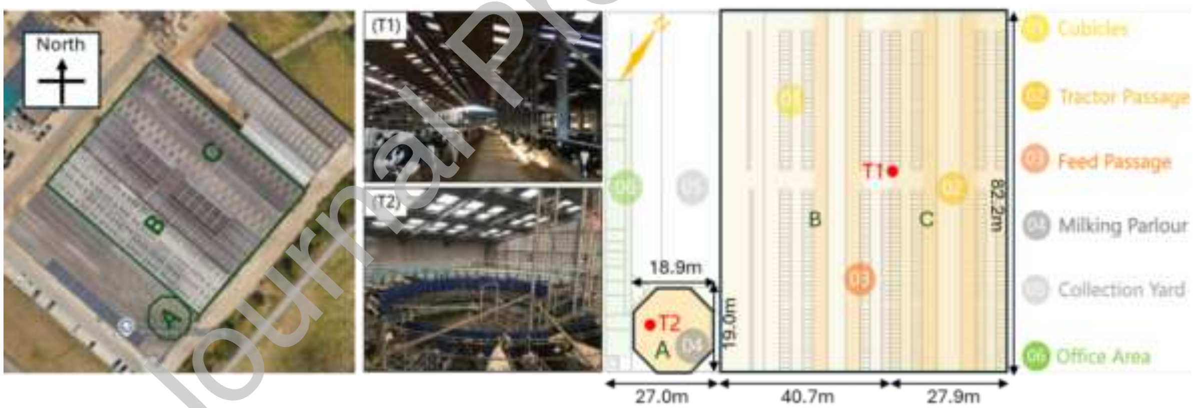

Figure 1. Orientation of the dairy cattle buildings at CEDAR, Hall Farm, Shinfield, UK along with interior pictures of the barn and milking parlour. Building A (octagon area) is referred to as the milking parlour, and B to C are referred to as the cubicle yards. The temperature and relative humidity sensors (Tinytag) were installed at position T1 in the cubicle yards and T2 in the milking room.

3.3. Thermal modelling for the dairy cattle buildings

3.3.1. Basic dairy cattle building model

DesignBuilder (version 7.02.006) was primarily used to create the 3D geometry and construction for the basic cow building model, based on field measurements. After that, we transitioned to

EnergyPlus (version 22.1), as it offers more flexibility, powerful objects and granular control over simulations, making it well-suited for handling customized thermal modelling scenarios. Consequently, the basic model created in DesignBuilder was exported as an IDF (Input Data File) to be further edited using EnergyPlus Editor.

Figure 2 displays images of both the actual and the modelled building, including the offices, milking parlour (A) and cubicle yards (B and C). The construction details and thermal properties of materials are provided in Appendices. The cubicle yards, equipped with five exhaust fans, and the milking parlour, fitted with two exhaust fans, were modelled with their sidewall and ridge openings fully open. However, during indoor microclimate measurements, the exhaust fans were turned off, thus only natural ventilation was active in the basic model. Each exhaust fan has a power of 250 W and an airflow rate of 23,200 m^3/hr (6.4 m^3/s @ 0" Static Pressure), which were utilized in mechanical ventilation simulations for heat stress mitigation. Additionally, the cubicle yards sheeted gates and the milking parlour door remained closed in the basic model configuration. The Reference Crack Conditions was used in EnergyPlus AirFlowNetwrok:MultiZone:Surface:Crack for simulating air infiltration of the dairy cow building. The uncertainty related to airtightness is minimal, as the impact of air infiltration on the indoor thermal environment is negligible compared to the large, fully open sidewall openings in the cubicle yards. Similarly, the milking parlour has a side that is connected to the cubicle yards via a sheet gate, further reducing the influence of airtightness. Regarding the internal gains from equipment, the rotary milking system at Hall Farm requires 100 kW of power, while the lighting intensity is 10 W/m^2 in the cubicle yards and 15 W/m^2 in the milking parlour. The power requirements for the fans, lighting, and rotary milking system are sourced from the product suppliers, as contacted by the staff at Hall Farm. Internal gains from people are minimal and, therefore, were not considered in the model.

Figure 2. Images of both the actual dairy cattle building and its basic thermal model created using DesignBuilder. The barn with the grey colour was newly built and unoccupied during that period.

The floor areas of the barns and milking parlour are 7048.2 m^2 (0.06 cows per m^2) and 305.6 m^2 (0.15 cows per m^2), respectively. The barns (hereafter referred to as cubicle yards) were occupied continuously, while the milking parlour was used only during scheduled milking times. Consequently, the total occupancy hours differ significantly between the two spaces. Additionally, the cubicle yards and milking parlour are not fully occupied at all times. On average, there were 420 cows in the cubicle yards throughout the day (24 hours). The milking parlour has a capacity of 50 dairy cattle, corresponding to the number of milking units. On average, 47 cattle were in the milking parlour during the morning (04:00–06:50) and afternoon (14:00–16:30) milking sessions.

3.3.2. Internal gains from dairy cattle

The internal heat gain from dairy cows differs significantly from that of humans due to distinct physiological characteristics such as body size and metabolic rate. However, current building simulation software, such as DesignBuilder and EnergyPlus, calculates internal heat gains based on human parameters rather than those specific to animals. This discrepancy highlights the need for careful consideration when applying these tools to livestock environments. Key factors influencing the total heat generation of dairy cattle include body mass, daily milk production, and physical activity levels (CIGR, 2002). Notably, high-yielding dairy cows produce substantially more heat than low-yielding or dry cows due to differences in feed intake and digestion and milk synthesis (Kadzere et al., 2002, Ohnstad, 2016, Das et al., 2016). To address this, we have calculated the total heat generation of a dairy cow based on the average body mass (650.0 kg) and daily milk production (35.5 L/day) of the lactating cattle during the measurements at Hall Farm. The total heat dissipation ϕ_{total} (W) from a dairy cow can be determined using Eq(1) from the 4th report of CIGR (Commission Internationale du Génie Rural) working group (CIGR, 2002). This formula provides a scientifically validated basis for more accurately modelling the total heat gains from dairy cattle in building simulations, ensuring that the unique physiological and production characteristics of livestock are adequately represented.

The total heat dissipation $\phi_{total}^{20°C}$ under thermoneutral conditions (20°C) can be calculated using the following equation:

$$\phi_{total}^{20°C} = 5.6 \times m^{0.75} + 22 \times Y + 1.6 \times 10^{-5} \times P^3, \qquad \text{Eq(1)}$$

where

- $\phi_{total}^{20°C}$ is the total heat dissipation at 20°C,
- $5.6 \times m^{0.75}$ (W) represents the basal metabolic rate, i.e., the heat production due to life maintenance requirement,
- m is the body mass of a cow,
- Y is the yield of milk per day (kg/day),
- P is the number of days of pregnancy, which is approximately 100 days based on measurements.

The influence of P on $\phi_{total}^{20°C}$ is negligible in this study as changing P from zero to 100 days results in only a 1% increase in $\phi_{total}^{20°C}$. Given the average body mass (650.0 kg) and daily milk production (36.7 kg/day or 35.5 L/day) of a dairy cow at Hall Farm, $\phi_{total}^{20°C}$ is calculated to be 1545.2 W. At thermoneutral conditions (20°C), one heat producing unit (1hpu) corresponds to 1000 W (Strøm, 1978). Therefore, the total heat generation of a dairy cow at Hall Farm (1545.2 W) is equivalent to approximately 1.55 hpu under thermoneutral condition (20°C).

However, ϕ_{total} typically decreases with increasing ambient temperature because animals tend to reduce their feed intake, resulting in lower body heat production (Kadzere et al., 2002, Shephard and Maloney, 2023). To account for varying ambient temperatures, the total heat generation (ϕ_{total}), sensible heat dissipation ($\phi_{sensible}$) and latent heat dissipation (ϕ_{latent}) at different ambient temperatures (T) can be calculated using the following equations adapted from the CIGR 2002 report (CIGR, 2002):

$$\phi_{total}(T) = [1000 + 4 \times (20 - T)] \times 1.55, \quad \text{Eq(2)}$$

$$\phi_{sensible}(T) = \{0.71 \times [1000 + 4 \times (20 - T)] - 0.408 \times T^2\} \times 1.55 \times cf, \quad \text{Eq(3)}$$

and

$$\phi_{latent}(T) = \phi_{total}(T) - \phi_{sensible}(T), \quad \text{Eq(4)}$$

where cf is the correction factor for $\phi_{sensible}$. As part of $\phi_{sensible}$ is used for evaporating water from feed, manure and drinking water, cf of 0.85 was recommended by the CIGR report working group (CIGR, 2002). Figure 3 shows the changes of ϕ_{total} , $\phi_{sensible}$ and ϕ_{latent} with increasing ambient temperature. As T is close to the constant body core temperature (~39°C) of cattle, $\phi_{sensible}$ becomes negligibly small while ϕ_{latent} increases significantly, which is in good agreement with the diagram presented in the CIGR 2002 report (CIGR, 2002). In fact, $\phi_{sensible}$ depends on the temperature gradient between ambient temperature and the skin temperature rather than the body core temperature. Shephard and Maloney (2023), in their recent review of thermal stress in cattle, concluded that cattle rely entirely on evaporative cooling when T exceeds their skin temperature which is approximately 36°C. Thus, it is more realistic to assume that ϕ_{latent} equals ϕ_{total} when $T \geq 36°C$. EnergyPlus users are not permitted to modify the source code related to the equations used for calculating internal heat gains from dairy cows. Therefore, as shown in Table 1, we have considered four partitions of sensible and latent heat gains (W) for the creation of the basic and reliable EnergyPlus model. The Energy Management System (EMS) object in the EnergyPlus Editor enables programming, which was used to implement the internal gains from the dairy cows, as presented in Table 1. This approach ensures a more accurate representation of the thermal load in the cubicle yards and milking parlour. Therefore, it marks a novel advancement compared to previous studies, such as De Masi et al. (2021)'s work,which assumed constant sensible and latent heat loads in thermal modelling.

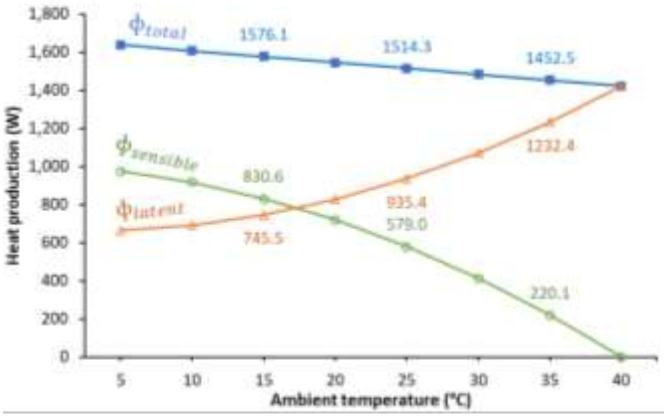

Figure 3. Changes in a dairy cow's total heat production, sensible and latent heat dissipation with increasing ambient temperature (T).

Table 1. Internal gains from the dairy cattle. The percentages in parentheses denote the partition of sensible and latent heat dissipation, i.e., the proportion of total heat production attributed to each.

Ambient temperature range	Total heat (ϕ_{total}), W	Sensible heat ($\phi_{sensbile}$), W	Latent heat (ϕ_{latent}), W
1) $10°C < T \leq 20°C,$	$\phi_{total} = \phi_{total}^{15°C} = 1576.1$	830.6 (53%)	745.5 (47%)
2) $20°C < T \leq 30°C,$	$\phi_{total} = \phi_{total}^{25°C} = 1514.3$	579.0 (38%)	935.4 (62%)
3) $30°C < T \leq 35°C,$	$\phi_{total} = \phi_{total}^{35°C} = 1452.5$	220.1 (15%)	1232.4 (85%)
4) $T > 35°C,$	$\phi_{total} = \phi_{total}^{36°C} = 1446.3$	0.0 (0%)	1446.3 (100%)

3.4. Heat stress assessment metrics

This study used THI to assess heat stress. Originally introduced by Thom (1958) to predict human thermal comfort, THI laid the foundation for the work of Berry et al. (1964) who developed the early version of the THI formula for assessing heat stress in dairy cattle. We used Eq(5) referenced in the (NRC, 1971) which was adapted from the Berry et al. (1964)'s THI formula. Eq(5) has been adopted by the United States National Weather Service and utilized in studies investigating heat stress in dairy cattle across diverse climate conditions, including tropical (Boonkum et al., 2011), sub-Sahra African (Ekine-Dzivenu et al., 2020), temperate (Hempel et al., 2019), maritime and temperate climates (Hut et al., 2022).

$$THI = (1.8 \times T + 32) - (0.55 - 0.0055 \times RH) \times (1.8 \times T - 26) \quad \text{Eq(5)}$$

where T is dry-bulb temperature (℃) and RH is relative humidity (%).

As shown in Table 2, the heat stress classification proposed by Collier et al. (2012) was adopted to assess the heat stress level in dairy cattle.

Two static heat stress assessment metric were used: one defined as hours above the heat stress thresholds ($THI_{threshold}^{level}$), referred to as *Heat Stress Hours* (hours), and the other defined as the percentage of *Heat Stress Hours* relative to the total occupied hours, referred to as *Heat Stress Risk* (%). Both *Heat Stress Hours* and *Heat Stress Risk* were calculated for the specified THI range to analyze the distribution of heat stress levels during heatwave periods.

Table 2. Heat stress classification cited from (Hempel et al., 2009).

THI Classification	**THI Range**	$\boldsymbol{THI_{threshold}^{level}}$
Level 1: Mild Stress	**68** ≤ THI < 72	68
Level 2: Moderate Stress	**72** ≤ THI < 80	72
Level 3: Severe Stress	**80** ≤ THI < 90	80
Level 4: Emergency	**90** ≤ THI	90

3.5. Future heatwave data

Example Extreme Weeks (EEWs) in the format of EnergyPlus Weather file, as developed by Coley et al. (2023), were utilized to predict the future risk of heat stress in dairy cattle. The EEWs are available from a repository of future weather (colbe.bath.ac.uk) at a spatial resolution of 5 km by 5 km across the UK. These datasets cover two time periods: the 1970s (1961–1990) and the 2080s (2070–2099), with three return periods: 10, 20, and 50 years. The EEW consists of a seven-day, hourly weather dataset generated from synthetic hourly outputs of the Spatial Urban Weather Generator (SUWG), a tool designed for future climate impact assessments (Kilsby et al., 2011). The SUWG is an updated version of the UKCP09 Weather Generator (Kilsby et al., 2007, Jones et al., 2010) and provides daily and hourly future climate datasets projected under a medium emission scenario (SRES A1B) specifically for the UK. The SUWG's capability in reproducing persistent heatwaves and extreme temperatures has been significantly enhanced. Utilizing future climate data projected from the latest climate models, based on Representative Concentration Pathways (RCPs) or Shared Socioeconomic Pathways (SSPs) emission scenarios, can improve the reliability of climate change impact assessments. However, implementation challenges persist as GCMs/RCMs lack complete thermally-relevant variables for building simulations. The common practice of only replacing EPW file temperatures with climate model projections often creates unrealistic variable relationships, reducing reliability. Moreover, selecting the most suitable GCM, or an ensemble of GCMs, along with performing downscaling and bias correction to generate localized future heatwave data, is essential. However, this process falls outside the scope of the current study. For this work, we believe that using localized EEWs (.epw) created by Coley et al. (2023) is the best option for this work.

Coley et al. (2023) employed the SUWG, which provides all thermally-related variables, while maintaining realistic inter-variable relationships, at a 5km by 5km spatial resolution across the UK landscape. Each run of the weather generator generates 30-year of daily and hourly weather data including all thermally-related weather variables. Each run incorporates one randomly selected projection from a pool of 10,000 probabilistic climate change projections. These projections were generated through multiple runs of the UK Met Office Hadley Centre Regional Climate Model (RCM), combined with outputs from other IPCC models. To minimize bias, Coley et al. (2023) conducted 100 independent runs of the weather generator for the target location, each incorporating a randomly selected climate projection. This approach yielded 3,000 sample years (30 years × 100 runs) of data for the 1970s and 2080s periods. Then, the 1970s EEW with different return periods were extracted from the large samples. The 2080s EEWs were created by morphing the 1970s EEW (Coley et al., 2023) based on the differences in probabilistic projections between the two periods. For the purposes of this study, the EEWs are referred to as the 1970s Heatwave and the 2080s Heatwave. The effects of heat stress mitigation scenarios were evaluated across three time slices: the 1970s, 2021, and the 2080s.

Figure 4 and

Table 3 provide detailed comparisons of the EEWs for the 1970s and 2080s, alongside the observed heatwave in 2021 at the building site. The 2021 Heatwave was slightly warmer than the 1970s Heatwave, which has a return period of 20 years (i.e., expected to occur once every 20 years). However, the 2080 Heatwave is projected to be significantly warmer than current observations. A heatwave of this magnitude is anticipated in the future, particularly given that England experienced an unprecedented heatwave in 2022, with daily maximum temperatures exceeding 40°C and daily minimum temperatures surpassing 25°C (Kendon, 2022). Predicting the risk of heat stress under future climate scenarios, such as the 2080s, is essential for developing effective mitigation strategies to safeguard dairy cattle and ensure the sustainability of dairy farming.

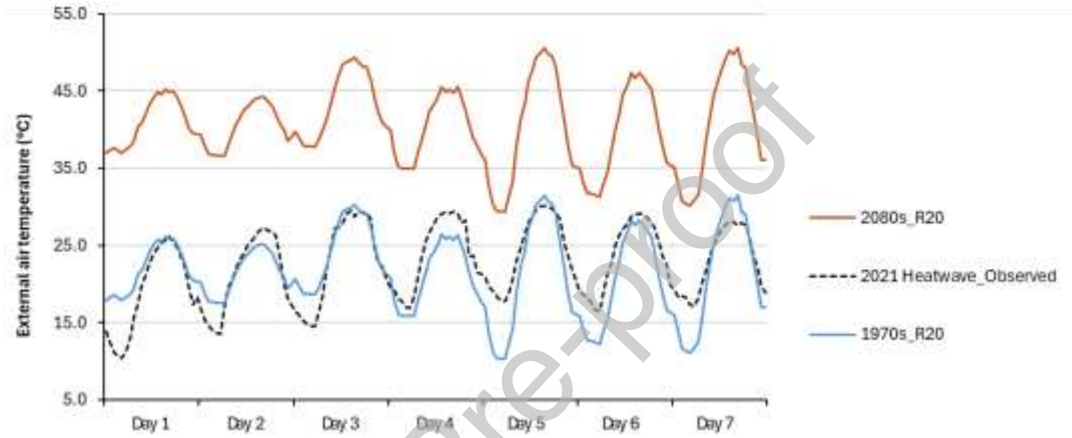

Figure 4. Comparison between the observed 2021 heatwave and the synthetic heatwaves (Extreme Example Weeks) for the 1970s and 2080s with a return period of R =20 years.

Table 3. The comparison between the three heatwaves.

	The 1970s Heatwave	The 2021 Heatwave	The 2080s Heatwave
$T^{highest}$(°C)	31.5	30.1	50.6
$\overline{T_{daily}^{max}}$(°C)	28.5	28.5	47.6
T_{daily}^{mean}(°C)	21.6	22.5	40.7
$\overline{T_{daily}^{min}}$(°C)	14.8	15.2	33.9
T^{lowest}(°C)	10.3	10.4	29.4

3.6. Heat stress mitigation strategies

Table 4 presents various heat stress mitigation strategies from the perspective of building adaptations. Scenario 1 involves reducing solar gain from the large roof areas of the cubicle yards and milking parlour by painting them a light colour. This helps reflect more sunlight and reduces the absorption of solar heat. Natural ventilation is another effective method for lowering indoor temperatures and removing moisture during hot summer months, thereby reducing the THI without incurring additional costs. Scenario 2 (building management through opening doors and gates) represents an improvement in natural ventilation. Both Scenario 1 and Scenario 2 are passive solutions. Scenario 3 considers mechanical ventilation, specifically the use of exhaust fans, while Scenario 3+2 combines mechanical and passive ventilation in a hybrid approach to enhance the building's ventilation rate. For hybrid ventilation, the gates and doors are fully open, and the exhaust fans are turned on during occupied hours for the cubicle yards and milking parlour. Finally, Scenario 4 integrates all strategies to assess their combined effectiveness in mitigating heat stress.

Table 4. The heat stress mitigation strategies for the dairy cattle building.

Scenarios	Description of the heat stress mitigation strategies
Scenario 1: *Solar reflecting paint over the roofs*	Apply light-coloured paint to the roofs to reflect more sunlight and absorb less solar heat (i.e., reducing solar absorptivity α from 0.7 to 0.3)
Scenario 2: *Building management by opening doors and gate*	Enhance natural ventilation* by opening the external sheeted gates and doors.
Scenario 3: *Use of exhaust fans*	Activate the exhaust fans installed on the external walls to improve airflow.
Scenario 3+2: *Hybrid ventilation*	Combine mechanical and natural ventilation to optimize air circulation.
Scenario 4: *All of the above*	Integrate all the above strategies to assess their combined effectiveness in mitigating heat stress.

Note: *The EnergyPlus AirFlow Network model has been used to simulate natural ventilation

4. Results and discussion

4.1. Model validation with observed heatwave data

Dynamic building simulation was conducted for 2021 UK Heatwave period (16th to 23rd July) with localized weather observed from the URAO as weather inputs. The simulated indoor climate data were then compared against actual measurements taken during the same period.

Figure 5 compares the model accuracy between the traditional and new approaches. The traditional approach (De Masi et al., 2021, Jackson et al., 2017, Shin et al., 2024) assumes fixed values for total metabolic heat generation, with constant proportions for latent (60%) and sensible (40%) heat dissipation, regardless of ambient temperature variations. Due to this unrealistic assumption, the traditional approach consistently overestimates both indoor temperature and relative humidity, as illustrated in Figure 5.

In contrast, the new approach demonstrates significantly improved accuracy by incorporating a more realistic representation of latent and sensible heat dissipation from dairy cows (see subsection 3.3.2). This improvement is evident in the temperature predictions for the milking parlour, where the R^2 value increased from 0.58 to 0.96, as shown in Table 5**Error! Reference source not found.**.

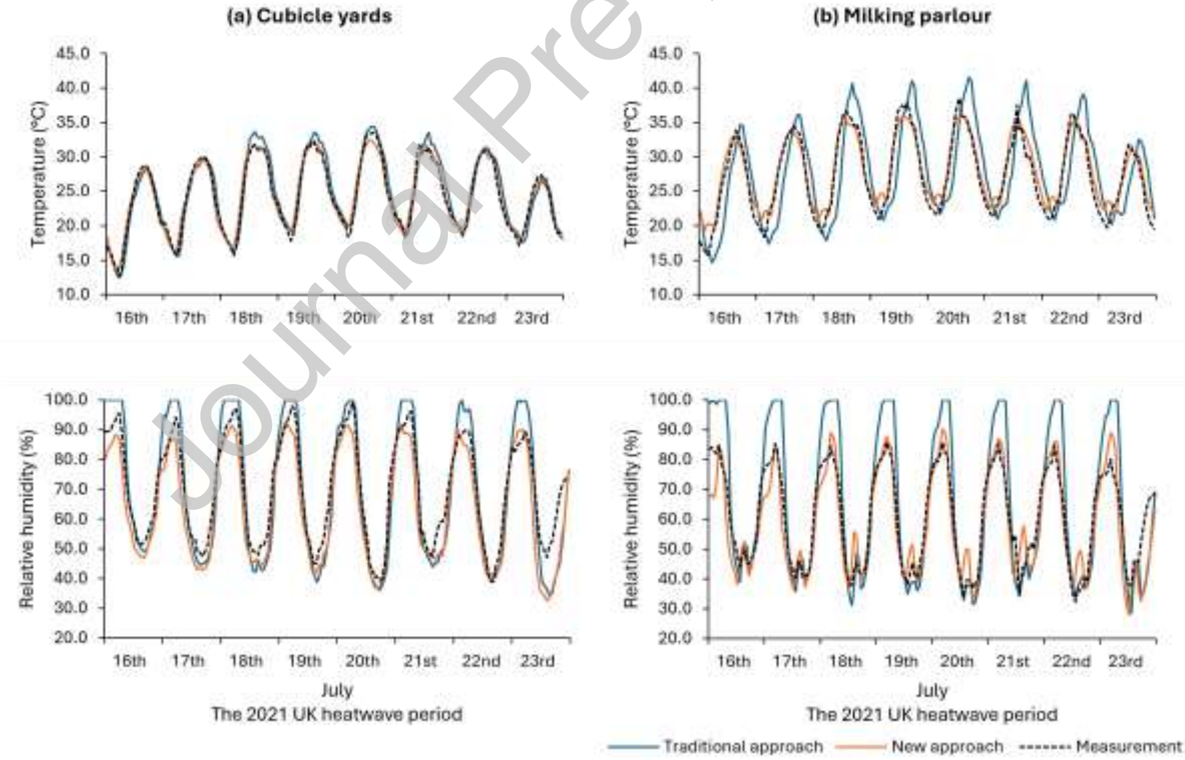

Figure 5. Comparison of model accuracy between the traditional and new approaches. The new approach integrates a more realistic representation of latent and sensible heat dissipation from dairy cows.

The accuracy of the new model was evaluated using the calibration criteria specified in the ASHRAE Guideline 14 (ASHRAE, 2002) and Federal Energy Management Program (FEMP)'s Guideline (Webster et al., 2008). The key performance metrics, including Normalized Mean Bias Error (NMBE), Coefficient of Variation of the Root Mean Square Error (CV(RMSE)), and R^2, were used to assess how well the model replicated the measured indoor temperatures. As shown in Table 5**Error! Reference source not found.**, both the NMBE and CV(RMSE) fall within the required ranges, while the R^2 value exceeds the recommended benchmark. These results, along with the earlier comparisons, confirm that the new model demonstrates satisfactory accuracy and is deemed reliable for use in subsequent heat stress mitigation scenarios.

Table 5. Model evaluation criteria and simulation performance

ASHRAE Guideline 14 and FEMP's criteria		Cubicle yards (barns)		Milking parlour	
		New model	Traditional model	New model	Traditional model
NMBE	**± 10%**	**-0.02%**	-1.37	**-2.09%**	-1.50
CV(RMSE)	**≤ 30%**	**3.39%**	5.12	**5.70%**	16.2
R^2	**> 0.75**	**0.97**	0.95	**0.96**	0.58

Furthermore, Figure 6 compares the hourly time series of the measured and simulated temperature and relative humidity (RH) from the new model for the 19th and 20th of July. The diurnal patterns of both the measured and simulated data align closely, indicating strong consistency between the two datasets. During the milking hours, i.e., from 04:00 to 06:50 and 14:00 to 16:30, the measured data for the milking parlour show higher internal temperatures and RH compared to non-milking periods. These fluctuations are effectively captured in the building simulation.

More detailed validation results during the whole 2021 UK Heatwave period are provided in Figure A1 and Table A1 (Appendices). The results include a summary of key statistics, including daily maximum, mean and minimum temperature and RH for both the simulations and measurements in the cubicle yards and milking parlour. For example, relative differences for the mean daily temperature (T_{daily}^{mean}) are 0.0% and +2.0%, while for the mean relative humidity (RH_{daily}^{mean}) are -7.9% and -2.8%. The differences in averaged daily minimum and maximum values for both indoor temperature and RH are all within 10%.

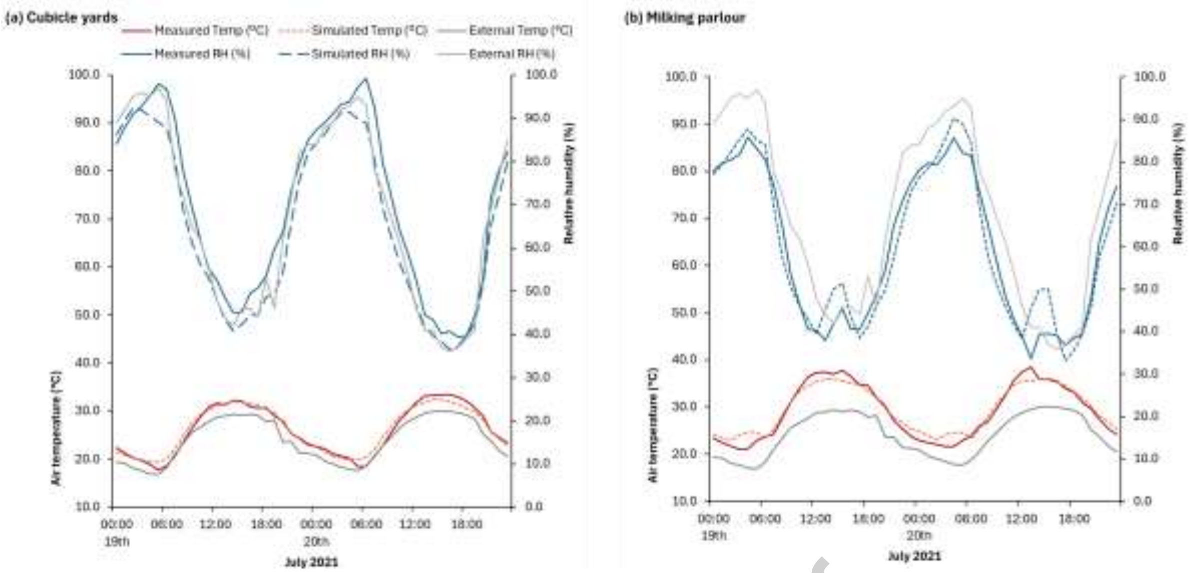

Figure 6. Comparison of the measured and simulated temperature (°C) and relative humidity (%) data for the (a) cubicle yards and (b) milking parlour during the UK heatwave period between the 19th and 20th July, 2021.

Additionally, as illustrated in Figure 7, the simulated and measured THI values align closely for both the cubicle yards and milking parlour, with R^2 values of 0.96 and 0.90 respectively. This further validates the model's accuracy in predicting heat stress conditions.

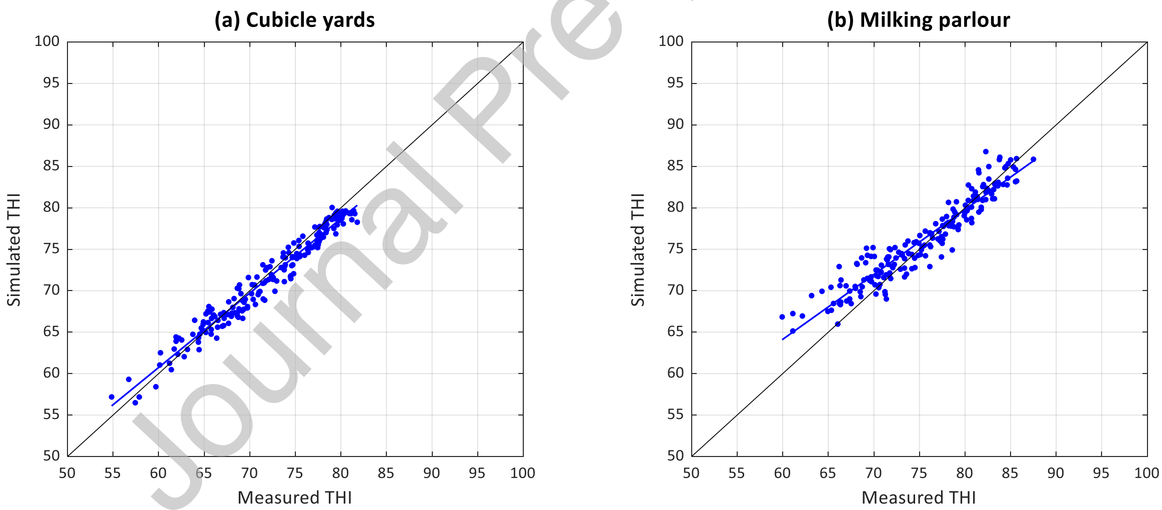

Figure 7. Comparison between the measured and simulated THI in the (a) cubicle yards and (b) milking parlour.

4.2. Indoor heat stress measurements during the 2021 UK heatwave

The hottest day of the 2021 UK heatwave occurred on the 20th July, with a daily mean temperature of 24.3°C. The outdoor daytime temperature exceeded 29°C for six hours, peaking at 30.1°C between 15:00 and 16:00, as shown in Figure 8. Peak indoor temperatures reached 33.2°C in the cubicle yards and 38.5°C in the milking parlour, both recorded when dairy cattle were present. The largest temperature differences between indoor and outdoor environments, observed during occupancy, were up to 2.3°C and 3.7°C in the morning, and up to 3.6°C and 8.9°C in the afternoon, for the cubicle yards and milking parlour, respectively. In the cubicle yards, the internal heat gains primarily originated from the dairy cattle, indicating that these heat sources significantly contributed to the indoor thermal conditions being notably warmer than outdoors. This finding aligns with previous research (Shock et al., 2016, Ouellet et al., 2019, VanderZaag et al., 2023), which has shown that dairy cattle buildings can often become substantially warmer than the surrounding outdoor environment, particularly when occupied by animals.

In the milking parlour, the THI exceeded 68 (Level 1: Mild stress) throughout the day and surpassed 80 (Level 3: Severe stress) during the afternoon milking period from 14:00 and 16:30. The maximum THI in the cubicle yards and milking parlour, recorded between 14:00 and 15:00, reached 81.5 and 85.5 (Level 3: Severe stress), respectively, while outdoor THI was 76.4 (Level 2: Moderate stress). As shown in Figure 8, the severity of heat stress in the milking parlour decreased by one level after 19:00. Consequently, delaying the afternoon milking by five hours during a hot period could be considered a viable strategy for mitigating heat stress, as recommended by (Atrian and Shahryar, 2012). This adjustment could help alleviate the adverse effects of severe heat stress during peak temperatures.

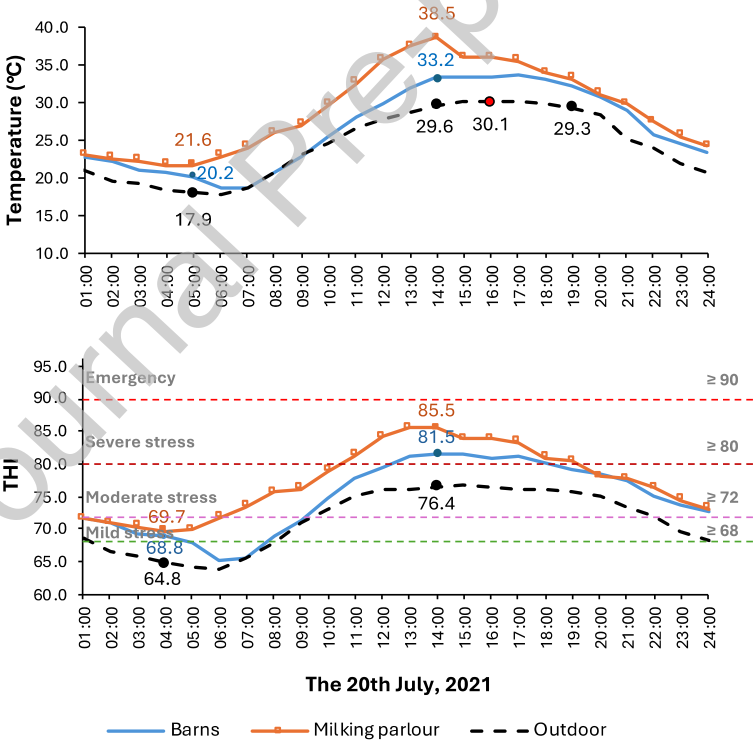

Figure 8. Indoor temperature and Temperature-Humidity Index (THI) measurements for the cubicle yards and milking parlour on the hottest day of the 2021 UK heatwave.

Figure 9 shows *Heat Stress Hours* and *Heat Stress Risk* (%) from the 16th to 23rd July, 2021, corresponding to the 2021 UK heatwave period. The hours of THI exceeding 68 were significantly longer in the cubicle yards than in the milking parlour, as the cubicle yards were occupied throughout the day, while the milking parlour was only in use during milking hours (approximately six hours per day). Nonetheless, the severe *Heat Stress Hours* were notably longer in the milking parlour (27 hours) compared to the cubicle yards (15 hours). The *Heat Stress Risk* (THI≥68) in the milking parlour shows that the dairy cattle experienced heat stress, regardless of severity, for 86% of the milking time, which was higher than the 72% risk observed in the housing yards. Additionally, the moderate and severe *Heat Stress Risks* are 45% and 8% in the cubicle yards, compared to 14% and 42% in the milking parlour. This indicates that the dairy cattle experienced moderate heat stress (Level 2) most of time in the cubicle yard housing, while severe heat stress (Level 3) was more prevalent in the milking parlour. The higher internal heat gains in the milking parlour, resulting from the rotary milking system and increased animal density, contributed to the greater risk of heat stress in the milking parlour compared to the housing yards.

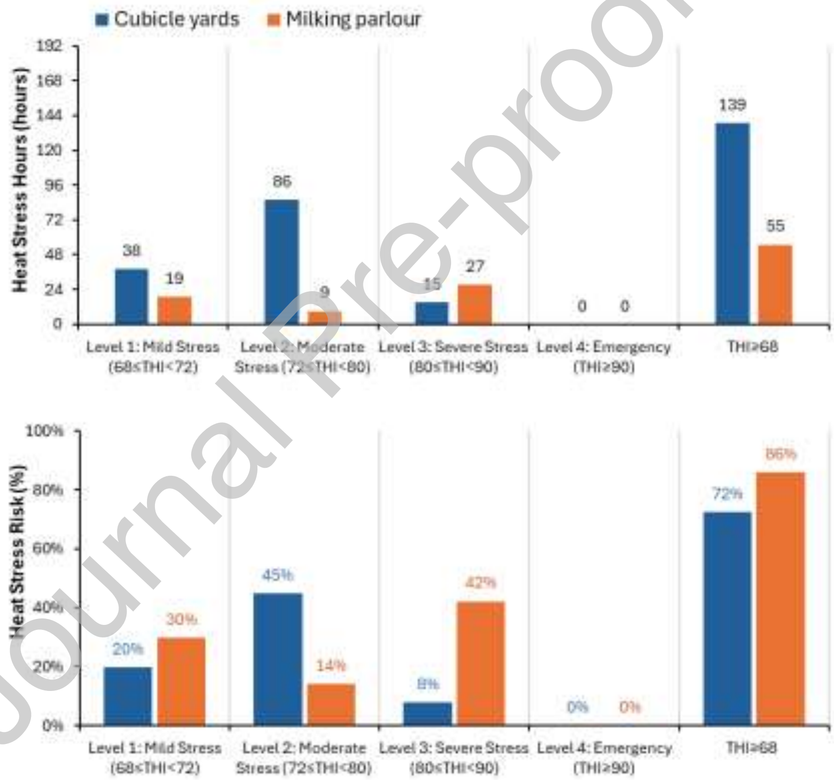

Figure 9. Heat Stress Hours and Heat Stress Risk (%) during the 2021 UK heat wave (from the 16th to 23rd July) for the cubicle yards (occupied throughout the day) and milking parlour (occupied during the milking times: 04:00-06:50 and 14:00-16:30).

4.3. Indoor heat stress mitigations

Figure 10 illustrates the impacts of the heat stress mitigations on the cubicle yards and milking parlour during the hottest day of the 2021 UK heatwave, 20th July. The base case presents the simulated temperature and THI results under the observed conditions of the 2021 heatwave, without any building adaptations. The effects of heat stress mitigation were significantly greater in the milking parlour compared to the cubicle yards. Under mitigation Scenario 4, the peak temperature was reduced by 2.0°C in the cubicle yards, while it was reduced by 5.6°C in the milking parlour. In the cubicle yards, the mitigations strategies did not reduce the severity levels compared to the base case throughout the day. However, in the milking parlour, the Scenario 4 reduced the heat stress level from Level 2 (Moderate stress) to no stress in the morning milking session, and from Level 3 (Severe stress) to Level 2 in the afternoon milking session.

In addition, each mitigation scenario, when applied individually, effectively reduced the mean temperature and THI. The passive mitigation Scenarios 1 and 2 had a similar cooling effect in the afternoon, while Scenario 2 (Building management by opening doors and gate) was more effective in the morning compared to Scenario 1 (Solar reflecting paint over the roof). Scenario 3 (Use of exhaust fans) and Scenario 3+2 (Hybrid ventilation), achieved the most significant reductions in temperature and heat stress levels in the milking parlour compared to the passive mitigation Scenarios 1 and 2. In contrast, Scenario 1 appeared to be the most effective mitigation strategy in the cubicle yards as solar reflective painting on a large portion of the building roof significantly reduced solar heat gain. The use of exhaust fans in the cubicle yards did not result in much of a difference as in the milking parlour. This was likely due to the small indoor-outdoor temperature differences caused by ridge openings and large openings on the building sidewalls. Thus, the effectiveness of ventilation (including Scenarios 2, 3, and 3+2) in lowering temperature and THI in the cubicle yards is diminished. The ventilation rates for the cubicle yards and milking parlour under different mitigation scenarios are presented in Figure A2 in Appendices.

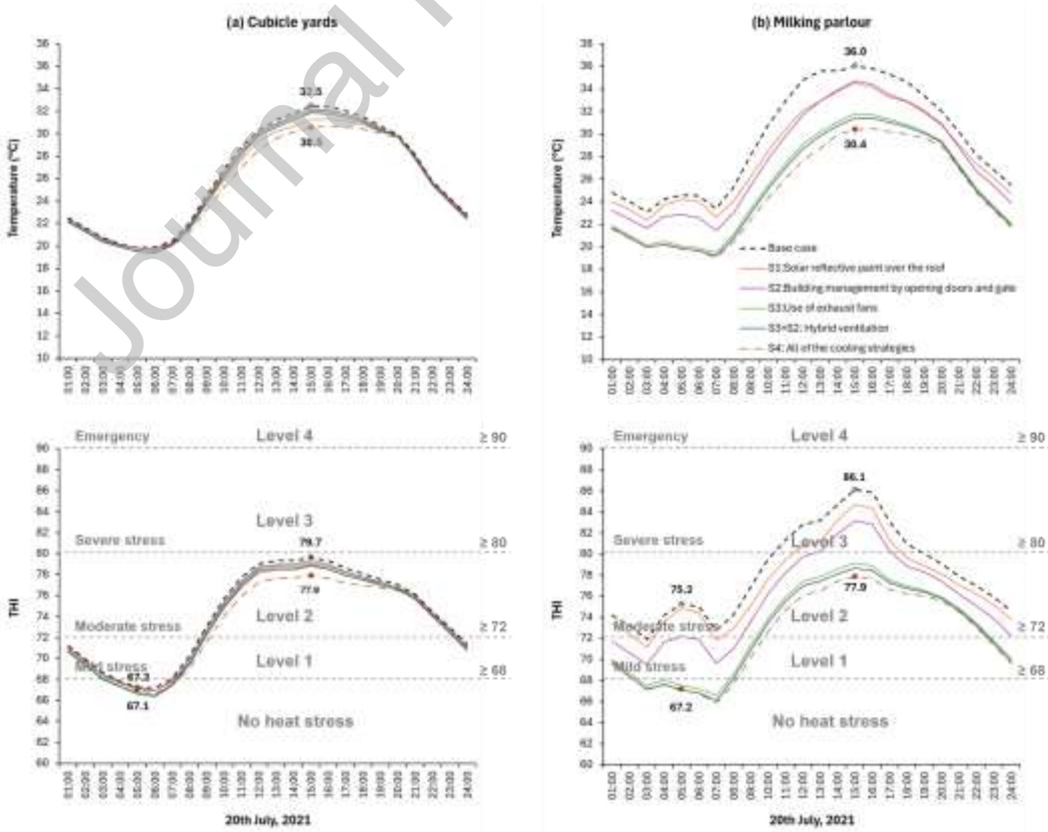

Figure 10. The effects of heat stress mitigation strategies on the cubicle yards and milking parlour during the hottest day of the 2021 UK heatwave.

4.4. Impacts of the future heatwave

Figure 11 presents *Heat Stress Hours* and *Heat Stress Risk* (%) in the cubicle yard housing and milking parlour, without any building adaptations, during the 1970s Heatwave, the 2021 Heatwave, and the 2080s Heatwave. Both *Heat Stress Hours* and *Heat Stress Risk (%)* for THI ≥68 in the cubicle yards and milking parlour are projected to increase significantly in the future. For instance, *Heat Stress Risks* were predicted to reach 100% for both spaces during the 2080s heatwave, up from 72% and 86% during the 2021 heatwave. Additionally, during the 1970s and 2021 heatwaves, the cubicle yards and milking parlour were primarily at risk of Level 2 and Level 3 heat stress respectively, for most of time, with no Level 4 Heat Stress Hours. However, under the 2080s heatwave, dairy cattle would face Level 4 (Emergency) heat stress for 92% and 100% of the time in the cubicle yards and milking parlour, respectively, representing a substantial shift in heat stress severity.

While these projections highlight a concerning future trend, the extent of the increased risk may vary depending on factors such as building design and operation, regional climate variations, and the physiological resilience of the animals. Nevertheless, the findings underscore the urgent need to critically evaluate the thermal resilience of current dairy cattle building designs under a warming climate.

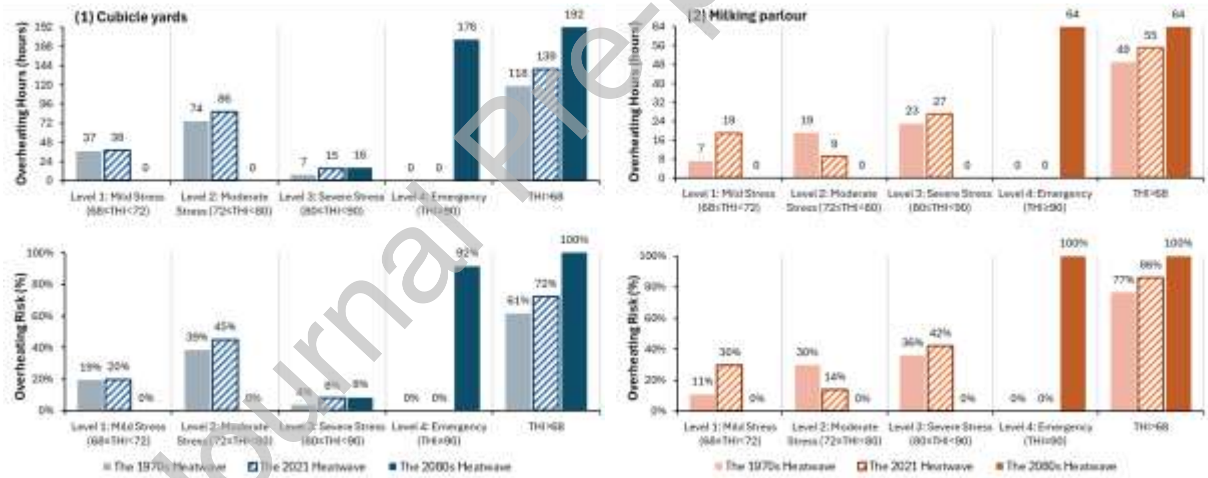

Figure 11. *Heat Stress Hours and Heat Stress Risk (%)* in response to changing heatwaves for the cubicle yards (occupied throughout the day) and milking parlour (occupied during the milking times: 04:00-06:50 and 14:00-16:30).

Figure 12 illustrates the impacts of heat stress mitigation strategies on *Heat Stress Hours* under the three heatwaves. *Heat Stress Hours* under Scenario 1 and Scenario 3 are similar in the cubicle yards, regardless of the heatwaves, though their mitigation effects are not significant. Given the extensive roof area of the cubicle yard housing, there is a great potential to reduce solar heat gain through more advanced passive roof design.

In the milking parlour, however, *Heat Stress Hours* and heat stress levels under Scenario 3 (Use of exhaust fans) and Scenario 3+2 (hybrid ventilation) were notably reduced compared to the base case during the 1970s and 2021 heatwaves. During the 2080s heatwave, Scenario 4 (integration of all the mitigation strategies) altered heat stress levels in both the cubicle yards and milking parlour but did not reduce *Heat Stress Hours* in either space. This indicates that more advanced passive and active cooling strategies will be essential to address the challenges posed by future heatwaves.

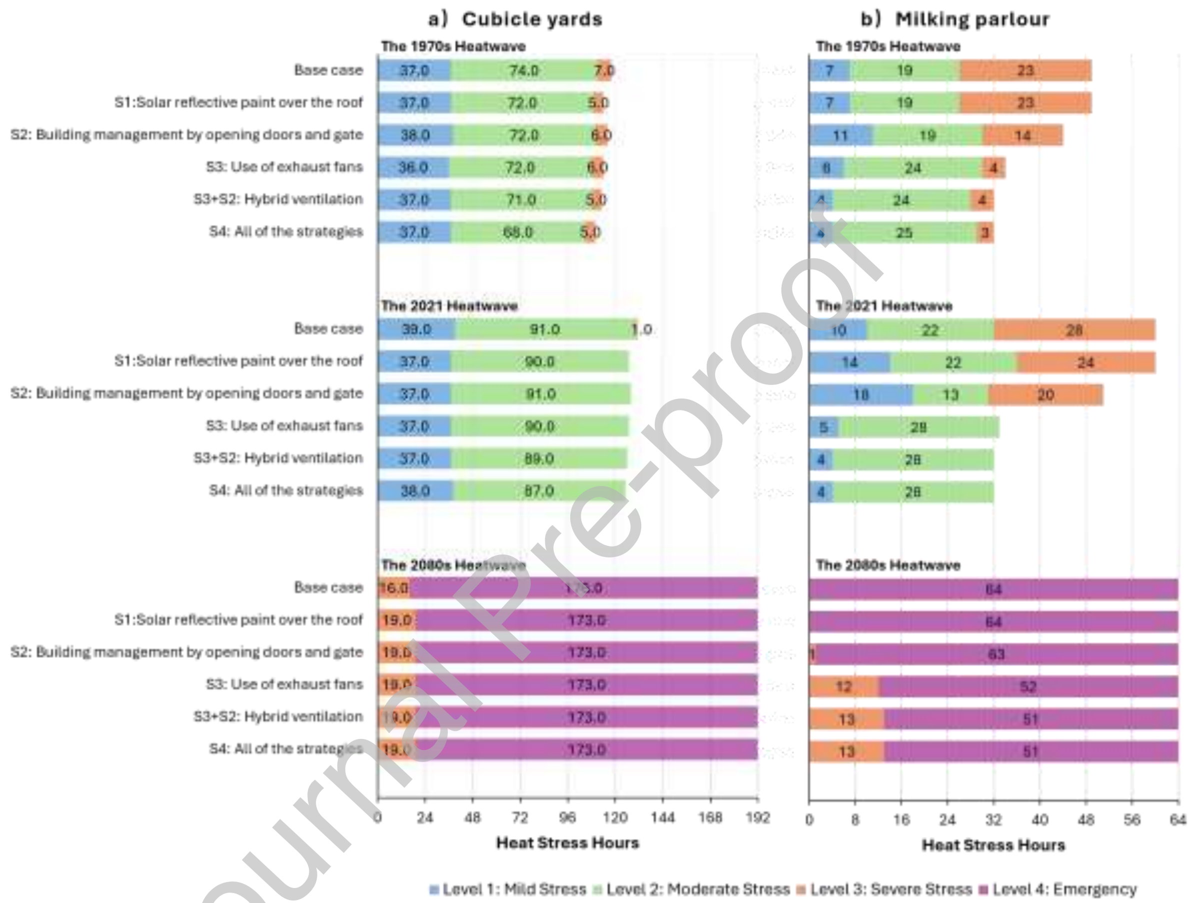

Figure 12. Comparison of mitigation strategies based on the distribution of *Heat Stress Risk (%)* across heat stress levels in the cubicle yards (occupied throughout the day) and milking parlour (occupied during the milking times: 04:00-06:50 and 14:00-16:30).

Figure 13 shows the impacts of heat stress mitigation strategies on the daily maximum temperature ($\bar{T}_{daily}^{max}$), averaged over the heatwave period. The results align with those shown in Figure 12. For example, compared to the base case, reductions in $\bar{T}_{daily}^{max}$ are minimal in the cubicle yard housing, while considerable in the milking parlour. During the 1970s Heatwave and the 2021 Heatwave, when the mitigation strategies were applied individually, Scenario 1 was the most effective in lowering $\bar{T}_{daily}^{max}$ in the cubicle yards, for the reasons explained previously, whereas Scenario 3 proved most effective in the milking parlour. Thus, it would be essential to tailor mitigation strategies to specific spaces within the dairy cattle buildings.

Under Scenario 4, $\bar{T}_{daily}^{max}$ in the milking parlour was reduced by up to -4.7°C and -5.9°C during the 1970s Heatwave and the 2021 Heatwave, respectively. However, they proved largely insufficient in addressing the more extreme conditions of the 2080s Heatwave.

Additionally, given the extremely high outdoor temperature during the 2080s heatwave, improving ventilation rates, whether natural or mechanical, is unlikely to lower indoor temperatures, and may even increase them. For instance, Scenario 4 reduced $\bar{T}_{daily}^{max}$ by 1.4 °C, while Scenario 1 achieved a reduction of 1.8 °C, suggesting that that hybrid ventilation unexpectedly raised $\bar{T}_{daily}^{max}$. Consequently, Scenario 1 outperformed the other mitigation scenarios during the 2080s heatwave.

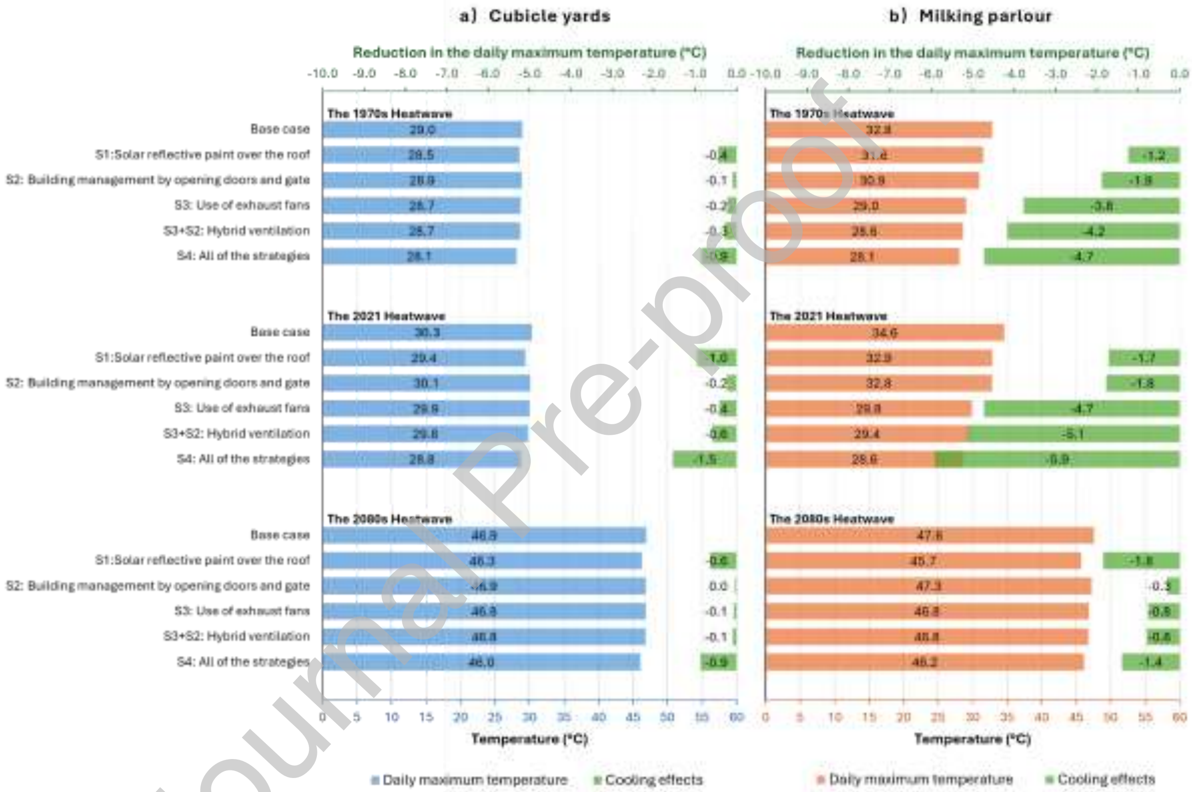

Figure 13. Comparison of mitigation strategies based on the daily maximum temperature ($\bar{T}_{daily}^{max}$) and their cooling effects, i.e., reduction in $\bar{T}_{daily}^{max}$ in the cubicle yards throughout the day and in the milking parlour during the milking periods: 04:00-06:50 and 14:00-16:30.

In the milking parlour, as shown in Figure 14, noticeable differences in *Heat Stress Hours* and *Heat Stress Risk* (%) were observed between the morning and afternoon milking sessions. During both the 1970s and 2021 heatwaves, *Heat Stress Hours* and *Heat Stress Risk* for THI≥ 68 were higher in the afternoon than in the morning. Specifically, the severity of heat stress remained at Level 1 and 2 during the morning, never reaching Level 3 (Severe stress), while in the afternoon, it reached Level 3 for 72% and 84% of milking time during the 1970s and 2021 heatwaves, respectively.

Under the 2080s heatwave condition, *Heat Stress Risk* was projected to be 100% for both milking sessions. More critically, the severity of heat stress was predicted to remain at Level 4 (Emergency) throughout both milking times.

Figure 15 further demonstrates that heat stress levels are higher during the afternoon milking session compared to the morning milking session, as evidenced by the distribution of *Heat Stress Risk* across different heat stress levels. Additionally, the heat stress mitigation strategies eliminated the *Heat Stress Risk* for THI≥ 68 during the morning milking time under Scenario 3+2 (Hybrid ventilation) under both the 1970s and 2021 heatwaves conditions. However, the risk remained at 100% during the afternoon milking session.

Under the 2080s heatwave conditions, these mitigation strategies notably reduced the severity levels from Level 4 (Emergency) to Level 3. However, the *Heat Stress Risk* for THI ≥ 68 remained at 100% for both morning and afternoon milking sessions, even with Scenario 4.

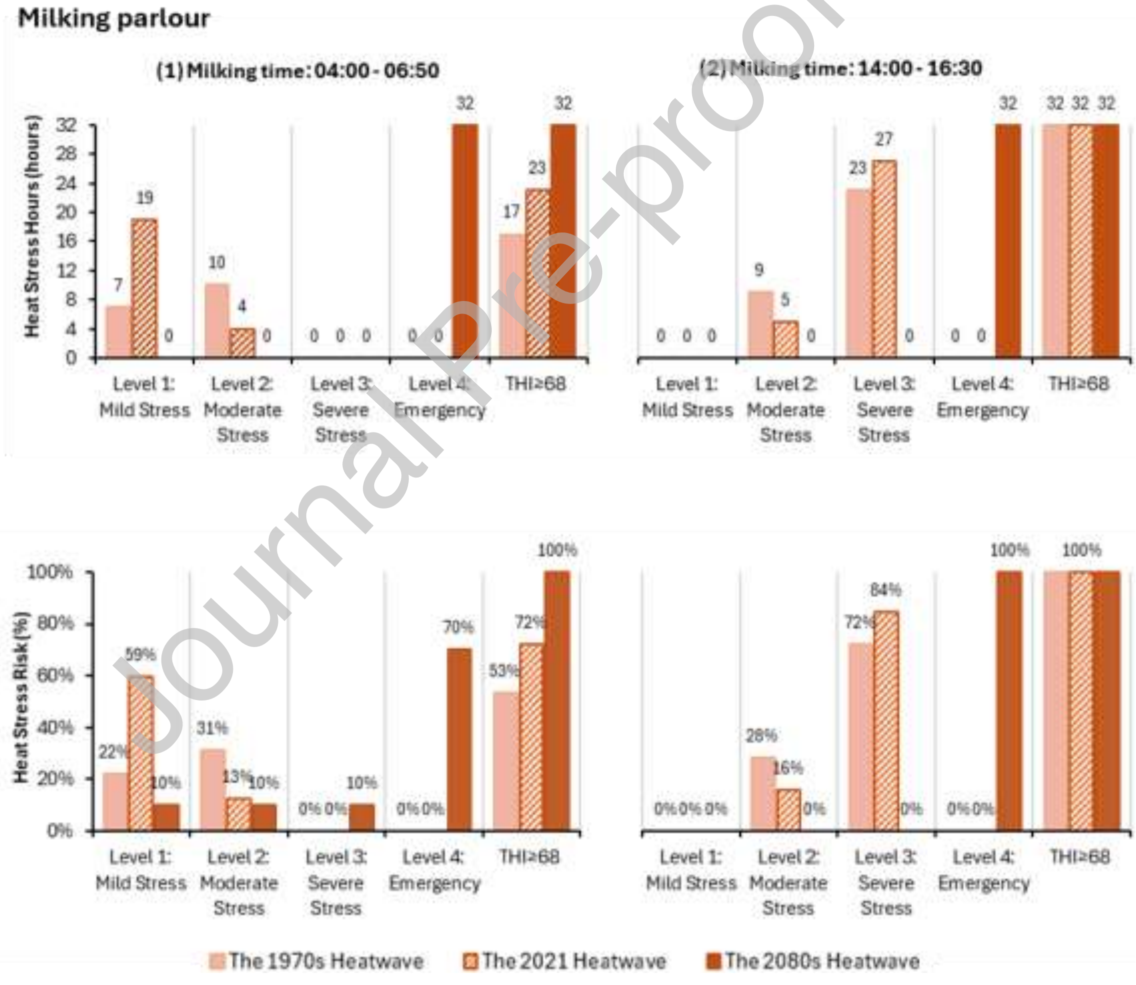

Figure 14. *Heat Stress Hours and Heat Stress Risk (%) during* the two milking periods: 04:00-06:50 and 14:00-16:30.

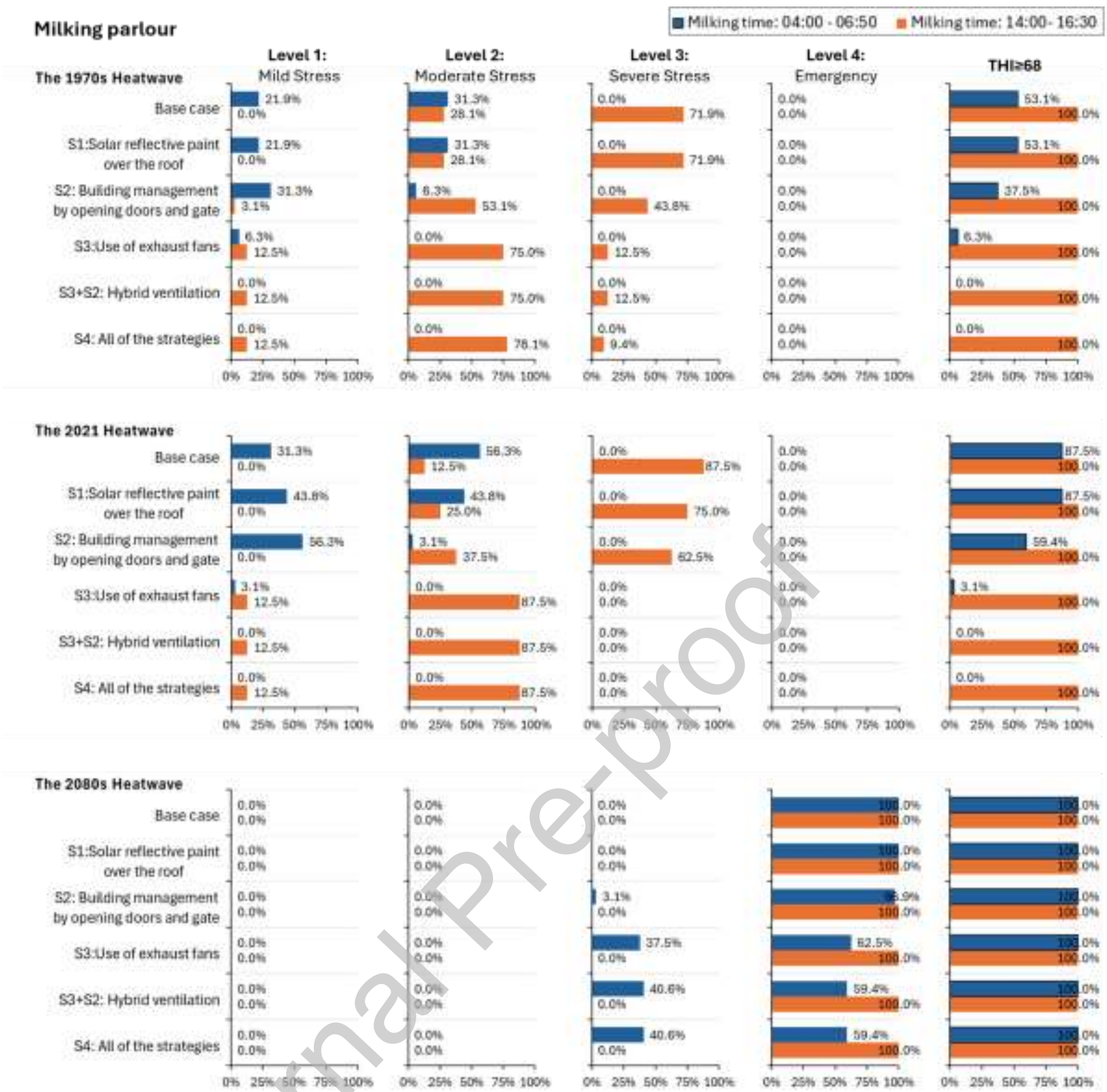

Figure 15. Effects of mitigation strategies on *Heat Stress Risk* (%) and its distribution across heat stress levels during two milking periods: 04:00-06:50 and 14:00-16:30.

5. Conclusions

Heat stress mitigation in dairy cattle buildings presents a significant challenge, particularly as heatwaves are projected to become more frequent, intense, and prolonged due to climate change. Building adaptation strategies are as critical as nutritional, breeding, and health management approaches, offering practical and immediate solutions to alleviate heat stress risks, and enhancing the long-term sustainability of dairy farming. However, there is a notable lack of studies that critically evaluate the impacts of building adaptations on dairy cattle buildings. Furthermore, such adaptations are rarely tailored to specific spaces within the buildings, especially under current and future extreme climate conditions.

This study addressed this research gap by assessing the impacts of heatwaves on cubicle yard housing and a milking parlour through measurements, by evaluating the effectiveness of potential building adaptations, and considering the differences between the two spaces, under both current and future heatwave scenarios. This was achieved via indoor heat stress measurements, and the use of a highly validated dynamic thermal model. For the first time, the model integrated the realistic heat dissipation of dairy cattle, accounting for key influencing factors such as body mass, daily milking production, and ambient temperature.

Indoor heat stress measurements during the 2021 UK Heatwave revealed that both the cubicle yard housing building and milking parlour were significantly warmer and experienced more severe conditions than the outdoor environment. The milking parlour was at a higher risk, with the THI exceeding 68 for 86% of milking time, often reaching Level 3 (Severe). In contrast, the cubicle yards had a lower risk (THI > 68 for 72% of the time) and were more likely to experience Level 2 (Moderate) stress. This disparity was primarily due to the milking parlour's higher internal heat gains from the rotary milking system, increased animal density, and limited natural ventilation in its more enclosed space. Additionally, the risk and severity were projected to rise to 100% and Level 4 (Emergency) stress under the 2080s Heatwave condition.

This study also offers critical insights into adapting dairy cattle buildings to extreme climate conditions. Scenario 1 (solar reflective roof paint) was preferred for the housing building, given the large roof area, while Scenario 3+2 (hybrid ventilation) was more effective for the milking parlour where the indoor-outdoor temperature difference was more significant. This suggests that building adaptation strategies should be tailored to the designs of specific spaces within dairy cattle buildings. Such targeted approaches could offer more cost-effective solutions under changing climate conditions. Nonetheless, the mitigations strategies examined in this study may not be adequate to cope with the extreme conditions projected for the 2080s heatwave.

These findings emphasize the necessity for continued research and innovation in building adaptation strategies to enhance dairy farming's resilience against growing heat stress risks. While constrained by earlier emission scenarios, the study provides compelling evidence to inform the development of climate-adaptive housing solutions for dairy cattle. As natural extension of this research, tailored building adaptations should consider vernacular livestock building designs, milking systems, regional climate variations, and the heat tolerance of dairy breeds (or other farm animals). Additionally, integrating building adaptation strategies with animal behavioural and physiological adaptations to heat stress may lead to synergistic effects, thereby improving the welfare of dairy cattle, particularly in response to the challenges posed by climate change.

Acknowledgement

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Appendices

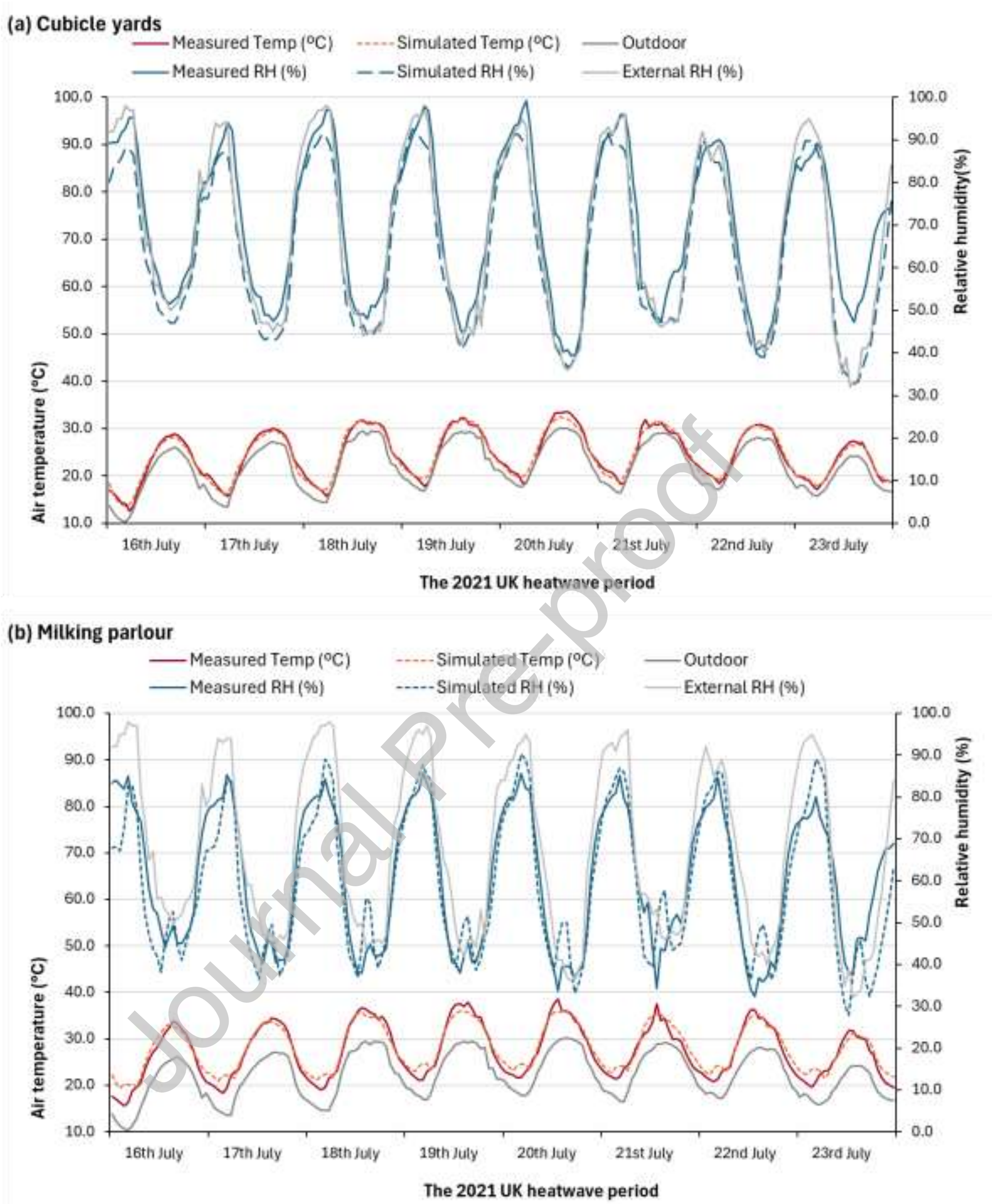

Figure A1. Comparison between the simulations and measurements during the whole 2021 UK Heatwave period between the 16th and 23rd July, 2021.

Table A1. Averaged daily temperatures (℃) and relative humidity (%), along with the absolute and relative differences between simulation and measurement for the cubicle yards and milking parlour during the whole 2021 UK Heatwave period between the 16th and 23rd July, 2021.

	Cubicle yards			Milking parlour		
	Simulated	Measured	Differences	Simulated	Measured	Differences
T_{daily}^{max} (℃)	30.3	30.8	-0.5 (-1.6%)	34.5	35.9	-1.4 (-7.2%)
T_{daily}^{mean} (℃)	24.4	24.4	+0.0 (+0.0%)	27.9	27.3	+0.6 (+2.0%)
T_{daily}^{min}(℃)	17.8	16.8	+1.0 (+6.0%)	21.6	19.7	+1.9 (+9.6%)
RH_{daily}^{max} (%)	90.3	94.9	-4.6 (-6.6%)	87.1	84.5	+2.6 (+3.1%)
RH_{daily}^{mean} (%)	64.4	69.9	-5.5 (-7.9%)	58.8	60.5	-1.7 (-2.8%)
RH_{daily}^{min}(%)	41.5	45.6	-4.1 (-9.0%)	36.0	37.3	-1.3 (-3.5%)

Table A2. Constructions and U-values. Construction materials are referenced from BS 5502-21:1990 (BSI, 1990).

Construction name	Layers (outside to inside)	Thickness (mm)	U-Value (W/m²·K)
External lower walls	Cast Concrete (dense)	200	3.2
External boarding	Timber board	200	3.0
External upper walls (Office & milking zone)	Metallic cladding	2	0.2
	Cast concrete	200	
	Wool	150	
	Plasterboard	12.5	
White walls (Office)	Plaster	20	0.3
	Cast concrete	200	
	Wool	100	
	Plasterboard	12.5	
Roof	Fibre cement corrugated sheets	6	6.3
Rooflights (SHGC=0.66)	Polycarbonate sheet	5.5	5.3
Ground floor	Cast concrete	150	0.4
Internal Partition	Cast Concrete	200	3.2
Metal door	Steel	50	5.8
Office window (Double glazing with UPVC window frame)	Generic clear glass	6	2.7
	Air gap	3	

Generic clear glass	6

Table A3. Thermal properties of livestock building materials (adapted from CIBSE Guide A (CIBSE, 2006))

Building materials	Thermal conductivity (W/m·K)	Specific heat capacity (J/kg)	Density (kg/m^3)
Cement plaster	0.35	840	950
Cast Concrete	1.4	840	2100
Timber board	0.12	1380	510
Fibre cement corrugated sheets	0.34	1000	1600
Metallic cladding	0.29	1000	1250
Wool	0.04	840	12
Plasterboard	0.16	840	950
Steel	50	450	7800
Polycarbonate sheet	0.2	-	-
Generic clear glass	0.9	-	-

Figure A2. The mean ventilation rate (ac/h) for the cubicle yards and milking parlour on 20th July, 2021 under the heat stress mitigation strategies.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used DeepSeek in order to assist in improving the English language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

ABENI, F. & GALLI, A. 2017. Monitoring cow activity and rumination time for an early detection of heat stress in dairy cow. *International Journal of Biometeorology,* 61**,** 417-425.

ASHRAE 2002. ASHRAE guideline 14: measurement of energy and demand savings. *American Society of Heating, Refrigerating and Air-Conditioning Engineers,* 35**,** 41-63.

ATRIAN, P. & SHAHRYAR, H. A. 2012. Heat stress in dairy cows (a review). *Research in Zoology,* 2**,** 31-37.

BECKER, C. A., COLLIER, R. J. & STONE, A. E. 2020. Invited review: Physiological and behavioral effects of heat stress in dairy cows. *Journal of Dairy Science,* 103**,** 6751-6770.

BERRY, I. L., SHANKLIN, M. D. & JOHNSON, H. D. 1964. Dairy Shelter Design Based on Milk Production Decline as Affected by Temperature and Humidity. *Transactions of the ASAE,* 7**,** 329-0331.

BOONKUM, W., MISZTAL, I., DUANGJINDA, M., PATTARAJINDA, V., TUMWASORN, S. & SANPOTE, J. 2011. Genetic effects of heat stress on milk yield of Thai Holstein crossbreds. *Journal of Dairy Science,* 94**,** 487-492.

BSI 1990. BS 5502-21:1990. Buildings and structures for agriculture - Code of practice for selection and use of construction materials. British Standards Institution.

CAMPOS, I. L., CHUD, T. C. S., OLIVEIRA, H. R., BAES, C. F., CÁNOVAS, A. & SCHENKEL, F. S. 2022. Using publicly available weather station data to investigate the effects of heat stress on milk production traits in Canadian Holstein cattle. *Canadian Journal of Animal Science,* 102**,** 368-381.

CHOPRA, K., HODGES, H. R., BARKER, Z. E., VÁZQUEZ DIOSDADO, J. A., AMORY, J. R., CAMERON, T. C., CROFT, D. P., BELL, N. J., THURMAN, A., BARTLETT, D. & CODLING, E. A. 2024. Bunching behavior in housed dairy cows at higher ambient temperatures. *Journal of Dairy Science,* 107**,** 2406-2425.

CIBSE 2006. CIBSE Guide A: Environmental Design. London: The Chartered Institution of Building Services Engineers.

CIGR 2002. The 4th report of CIGR working group on climatization of animal houses-heat and moisture production at animal and house levels. *In:* PEDERSEN, S. & SÄLLVIK, K. (eds.). Research Centre Bygholm, Danish Insitute of Agricultural Sciences, Horsens, Demark.

COLEY, D., LIU, C. & FOSAS, D. 2023. The week that will be: Communicating the impact of climate change via extreme weeks. *Building and Environment,* 227**,** 109809.

COLLIER, R. J., HALL, L. W., RUNGRUANG, S. & ZIMBLEMAN, R. B. 2012. Quantifying heat stress and its impact on metabolism and performance. *Department of Animal Sciences University of Arizona,* 68**,** 1-11.

COSTANTINO, A. 2023. Development, Validation, and Application of Building Energy Simulation Models for Livestock Houses: A Systematic Review. *Agriculture,* 13**,** 2280.

DAS, R., SAILO, L., VERMA, N., BHARTI, P., SAIKIA, J., IMTIWATI & KUMAR, R. 2016. Impact of heat stress on health and performance of dairy animals: A review. *Veterinary World,* 9**,** 260-8.

DE MASI, R. F., RUGGIERO, S., TARIELLO, F. & VANOLI, G. P. 2021. Passive envelope solutions to aid design of sustainable livestock buildings in Mediterranean climate. *Journal of Cleaner Production,* 311**,** 127444.

DESIGNBUILDER 2021. DesignBuilder [Computer software]. DesignBuilder Software Ltd.

EKINE-DZIVENU, C. C., MRODE, R., OYIENG, E., KOMWIHANGILO, D., LYATUU, E., MSUTA, G., OJANGO, J. M. K. & OKEYO, A. M. 2020. Evaluating the impact of heat stress as measured by temperature-humidity index (THI) on test-day milk yield of small holder dairy cattle in a sub-Sahara African climate. *Livestock Science,* 242**,** 104314.

FAO. 2025. *Gateway to dairy production and products: Milk production* [Online]. Food and Agriculture Organization of the United Nations. Available: https://www.fao.org/dairy-production-products/production/milk-production/en [Accessed 30th Janurary 2025].

FOURNEL, S., OUELLET, V. & CHARBONNEAU, É. 2017. Practices for Alleviating Heat Stress of Dairy Cows in Humid Continental Climates: A Literature Review. *Animals (Basel),* 7.

GAULY, M. & AMMER, S. 2020. Review: Challenges for dairy cow production systems arising from climate changes. *Animal,* 14**,** 196-203.

GEMINI DATA LOGGERS. n.d. *Tinytag TGU-4500 [Data logger].* [Online]. Available: https://assets.geminidataloggers.com/pdfs/original/3769-tgu-4500.pdf [Accessed 18th Feburary 2025].

GEORG, H. & ASHOUR, T. 2012. Sustainable livestock buildings – a challenge for the future of organic farming. *Agriculture and Forestry Research*.

HEINICKE, J., HOFFMANN, G., AMMON, C., AMON, B. & AMON, T. 2018. Effects of the daily heat load duration exceeding determined heat load thresholds on activity traits of lactating dairy cows. *Journal of Thermal Biology,* 77**,** 67-74.

HEMPEL, S., KÖNIG, M., MENZ, C., JANKE, D., AMON, B., BANHAZI, T. M., ESTELLÉS, F. & AMON, T. 2018. Uncertainty in the measurement of indoor temperature and humidity in naturally ventilated dairy buildings as influenced by measurement technique and data variability. *Biosystems Engineering,* 166**,** 58-75.

HEMPEL, S., MENZ, C., PINTO, S., GALÁN, E., JANKE, D., ESTELLÉS, F., MÜSCHNER-SIEMENS, T., WANG, X., HEINICKE, J., ZHANG, G., AMON, B., DEL PRADO, A. & AMON, T. 2019. Heat stress risk in European dairy cattle husbandry under different climate change scenarios – uncertainties and potential impacts. *Earth System Dynamics,* 10**,** 859-884.

HERBUT, P. & AND ANGRECKA, S. 2018. Relationship between THI level and dairy cows' behaviour during summer period. *Italian Journal of Animal Science,* 17**,** 226-233.

HUT, P. R., SCHEURWATER, J., NIELEN, M., VAN DEN BROEK, J. & HOSTENS, M. M. 2022. Heat stress in a temperate climate leads to adapted sensor-based behavioral patterns of dairy cows. *Journal of Dairy Science,* 105**,** 6909-6922.

IPCC 2023. Climate Change 2023: Synthesis Report. *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)].* IPCC, Geneva, Switzerland.

JACKSON, P., GUY, J., EDWARDS, S. A., STURM, B. & BULL, S. 2017. Application of dynamic thermal engineering principles to improve the efficiency of resource use in UK pork production chains. *Energy and Buildings,* 139**,** 53-62.

JIANG, L., YI, Y. & AKDENIZ, N. 2024. Energy-saving cooling strategies in tunnel-ventilated dairy buildings: Computational fluid dynamics (CFD) simulations and validation. *Smart Agricultural Technology,* 9**,** 100576.

JONES, P. D., KILSBY, C. G., HARPHAM, C., GLENIS, V. & BURTON, A. 2010. UK Climate Projections science report: Projections of future daily climate for the UK from the Weather Generator. University of Newcastle, UK: University of Newcastle, UK.

KADZERE, C. T., MURPHY, M. R., SILANIKOVE, N. & MALTZ, E. 2002. Heat stress in lactating dairy cows: a review. *Livestock Production Science,* 77**,** 59-91.

KENDON, M. 2022. *Unprecedented extreme heatwave, July 2022* [Online]. Met Office National Climate Information Centre. Available: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2022/2022_03_july_heatwave_v1.pdf [Accessed 10th Janurary 2025].

KILSBY, C., JONES, P., HARPHAM, C., GLENIS, V. & BURTON, A. 2011. Spatial Urban Weather Generator for Future Climates. The Adaptation and Resilience in the Context of Change network (ARCC).

KILSBY, C. G., JONES, P. D., BURTON, A., FORD, A. C., FOWLER, H. J., HARPHAM, C., JAMES, P., SMITH, A. & WILBY, R. L. 2007. A daily weather generator for use in climate change studies. *Environmental Modelling & Software,* 22**,** 1705-1719.

LIBERATI, P. 2008. ANALYSIS OF THE EFFECTS OF THE ROOFING DESIGN ON HEAT STRESS IN DAIRY COW HOUSING. *Journal of Agricultural Engineering,* 39**,** 1-7.

LOVARELLI, D., MINOZZI, G., ARAZI, A., GUARINO, M. & TIEZZI, F. 2024. Effect of extended heat stress in dairy cows on productive and behavioral traits. *animal,* 18**,** 101089.

LOVARELLI, D., RIVA, E., MATTACHINI, G., GUARINO, M. & PROVOLO, G. 2021. Assessing the effect of barns structures and environmental conditions in dairy cattle farms monitored in Northern Italy. *Journal of Agricultural Engineering,* 52.

MORETTI, R., BIFFANI, S., CHESSA, S. & BOZZI, R. 2017. Heat stress effects on Holstein dairy cows' rumination. *Animal,* 11**,** 2320-2325.

NEGRÓN-PÉREZ, V. M., FAUSNACHT, D. W. & RHOADS, M. L. 2019. Invited review: Management strategies capable of improving the reproductive performance of heat-stressed dairy cattle. *Journal of Dairy Science,* 102**,** 10695-10710.

NRC 1971. A Guide to Environmental Research on Animals. National Research Council, National Academy of Sciences.

OHNSTAD, I. 2016. Managing heat stress in dairy cows. National Animal Disease Information Service(NADIS) Animal Health Skills.

OUELLET, V., BELLAVANCE, A. L., FOURNEL, S. & CHARBONNEAU, É. 2019. Short communication: Summer on-farm environmental condition assessments in Québec tiestall farms and adaptation of temperature-humidity index calculated with local meteorological data. *J Dairy Sci,* 102**,** 7503-7508.

PAKARI, A. & GHANI, S. 2021. Comparison of different mechanical ventilation systems for dairy cow barns: CFD simulations and field measurements. *Computers and Electronics in Agriculture,* 186**,** 106207.

POLSKY, L. & VON KEYSERLINGK, M. A. G. 2017. Invited review: Effects of heat stress on dairy cattle welfare. *Journal of Dairy Science,* 100**,** 8645-8657.

REDDY, P. B., GOUD, P. M. K., KATAM, D., SUPRIYA, R., KUMAR, M. & SRAVATHI, V. 2023. Nutritional strategies for amelioration of heat stress in dairy cows: A Review. *International Journal of Veterinary Sciences and Animal Husbandry,* 8**,** 33-39.

SCHÜLLER, L. K., BURFEIND, O. & HEUWIESER, W. 2013. Short communication: Comparison of ambient temperature, relative humidity, and temperature-humidity index between on-farm measurements and official meteorological data. *Journal of Dairy Science,* 96**,** 7731-7738.

SHEPHARD, R. W. & MALONEY, S. K. 2023. A review of thermal stress in cattle. *Australian Veterinary Journal,* 101**,** 417-429.

SHIN, H., LEE, S.-Y., KIM, J.-G., PARK, D.-H., JO, S.-K. & KWAK, Y. 2024. Applicability evaluation of a temperature humidity index-controlled ventilation system in livestock using a building energy simulation model. *Case Studies in Thermal Engineering,* 57**,** 104335.

SHOCK, D. A., LEBLANC, S. J., LESLIE, K. E., HAND, K., GODKIN, M. A., COE, J. B. & KELTON, D. F. 2016. Studying the relationship between on-farm environmental conditions and local meteorological station data during the summer. *Journal of Dairy Science,* 99**,** 2169-2179.

SILANIKOVE, N. & KOLUMAN, N. 2015. Impact of climate change on the dairy industry in temperate zones: Predications on the overall negative impact and on the positive role of dairy goats in adaptation to earth warming. *Small Ruminant Research,* 123**,** 27-34.

STRØM, J. S. 1978. Heat loss from cattle, swine and poultry as basis for design of environmental control systems in livestock buildings.

SUGIONO, DEWI, H. & RUDY, S. Measuring Thermal Stress of Dairy Cattle Based on Temperature Humidity Index (THI) in Tropical Climate. MATEC Web of Conferences, 2016. 06004.

THOM, E. C. 1958. Cooling degree-days: air conditioning, heating, and ventilating.: Transactions of the American Society Heating, Re-frigerating and Air-Conditioning Engineers (ASHRAE).

TOMASELLO, N., VALENTI, F., CASCONE, G. & PORTO, S. M. C. 2021. Improving natural ventilation in renovated free-stall barns for dairy cows: Optimized building solutions by using a validated computational fluid dynamics model. *Journal of Agricultural Engineering,* 52.

U.S. DOE 2019. EnergyPlus (Version 22.1) [Computer software]. U.S. Department of Energy.

VANDERZAAG, A., LE RICHE, E., BALDÉ, H., KALLIL, S., OUELLET, V., CHARBONNEAU, É., COATES, T., WRIGHT, T., LUIMES, P. & GORDON, R. 2023. Comparing thermal conditions inside and outside lactating dairy cattle barns in Canada. *Journal of Dairy Science,* 106**,** 4738-4758.

VOX, G., MANETA, A. & SCHETTINI, E. 2016. Evaluation of the radiometric properties of roofing materials for livestock buildings and their effect on the surface temperature. *Biosystems Engineering,* 144**,** 26-37.

WEBSTER, L., BRADFORD, J., SARTOR, D., SHONDER, J., ATKIN, E. & DUNNIVANT, S. 2008. M&V Guidelines: Measurement and Verification for Federal Energy Projects (V3. 0). Nexant, Inc., Boulder, CO (United States).

Declaration of interests

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

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: