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Comparison of environment quality measurements between 3 types of calf housing in the United Kingdom

Sophie A. Mahendran,* Nicola Blackie, D. Claire Wathes, and Richard E. Booth
Pathobiology and Population Sciences, Royal Veterinary College, Hawkshead Lane, Hatfield, Hertfordshire, AL9 7TA United Kingdom

ABSTRACT

Preweaning calves are kept in a range of housing types that offer variable protection against the weather and provide differing internal environments. This cross-sectional observational study assessed the effect of housing type (shed, polytunnel, or hutches) on internal environmental parameters, using 2 blocks of 8-wk measurements from 10 commercial dairy farms in the south of England, covering both summer and winter periods. Continuous measurements for internal and external temperature and humidity were recorded by data logger placed within the calf housing and used to calculate the temperature-humidity index (THI). Weekly point readings were also taken for temperature, humidity, light, air speed, ammonia level, and airborne particulate matter. Airborne bacterial levels were determined at wk 2, 5, and 8 by incubating air samples at 35°C for 24 h in aerobic conditions. Data were analyzed using linear mixed models. Housing type influenced THI significantly in both seasons. In summer, calves were exposed to heat stress conditions (THI $\geq$72) for 39, 31, and 14 of 46 d in polytunnel housing, hutches, and sheds, respectively. The maximum summer temperature (37.0°C) was recorded in both hutch and polytunnel housing, with sheds remaining consistently cooler (maximum 31.0°C). In winter, the lowest minimum internal temperature recorded was in hutches at −4.5°C, with both the sheds and polytunnel, but not hutches, providing a significant increase in temperature compared with the external environment. Hutches remained $\leq$ 10°C for 86% of the winter study period. Light levels were reduced in all housing types compared with the external environment. The particulate matter in air that is capable of reaching the lungs (particulate matter <10 μm) was highest in sheds, intermediate in hutches, and lowest in polytunnel housing (0.97 ± 3.75, 0.37 ± 0.44, and 0.20 ± 0.24 mg/m^3, respectively). This was mirrored by airborne bacterial numbers, which were also highest in sheds (8,017 ± 2,141 cfu/m^3), intermediate in hutches (6,870 ± 2,084 cfu/m^3), and lowest in the polytunnel (3,357 ± 2,572 cfu/m^3). Round, white, catalase-positive, and oxidase-negative colonies were most prevalent, likely indicating *Staphylococcus* species. This study demonstrated that UK calves are routinely exposed to either heat or cold stress, especially when housed in hutches or polytunnels. Sheds had the highest levels of particulate matter and airborne bacteria, both known contributory factors for respiratory disease. These findings demonstrate that all calf housing systems result in environmental compromises that could have long-term impacts on calf health and growth; therefore, further studies should identify husbandry and housing modifications to mitigate these factors.

Key words: calf, housing, environment, temperature, humidity

INTRODUCTION

Preweaning dairy calves in the United Kingdom (UK) are typically housed using 3 main building designs: sheds, hutches, and polytunnels, all of which provide variable protection from the weather and potentially expose the animals to very different environmental conditions. The UK has a temperate climate that typically features cool, wet winters and warm, wet summers, with mean winter and summer temperatures in 2021 of 3.5°C and 15.3°C, respectively, and specific ranges for the southern UK being 0.5 to 9.0°C and 13.8 to 22.9°C, respectively (https://www.metoffice.gov.uk/research/climate/maps-and-data/summaries/index). In addition to temperature, air quality encompasses many other parameters, including humidity, air speed, particulate matter, and presence of other compounds such as ammonia and microorganisms. Many of these parameters are interlinked, and although geographical location will have a large effect on these values, the type of housing that a calf resides in will create its own microclimate. This can substantially alter the living conditions of the calf, potentially negatively affecting health and growth rates, resulting in increased heifer age at first calving (Heinrichs et al., 2005; Tyson, 2011).

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*Corresponding author: smahendran@rvc.ac.uk

Housing temperature is affected by stocking density, insulation, and ventilation of a shed, as well as the outside temperature. The thermoneutral zone of a calf is considered to be 10 to 20°C, with both high and low temperatures and large diurnal variations having negative effects on calf health and performance (Seedorf et al., 1998). Cold air reduces mucociliary clearance (Caswell, 2014), and prolonged exposure of young calves to low temperatures increases their risk of developing bovine respiratory disease (**BRD**; Johnson et al., 2021) and reduces growth rates in terms of weight (Bell et al., 2021) and height (Johnson et al., 2017). Provision of high planes of nutrition and clean, dry bedding with a high nesting score can alleviate the effects of low environmental temperatures if there are no drafts at calf level (Lago et al., 2006).

Humidity is linked to environmental moisture levels, but the effect of fluid management within a shed is also important. Good drainage is needed to remove urine and feces as well as spilled water and milk on the floor. Avoidance of the unnecessary introduction of more liquid through washing of equipment and pens within the same building is also important. General recommendations are for humidity levels <80%, although peer-reviewed evidence for this value is not available. Higher humidity values have been associated with increased lung fluid basophil counts, indicative of lung inflammation (van Leenen et al., 2020), and an overall increased risk of BRD, especially in conjunction with low wind speeds (Alban et al., 1999). High humidity is also linked to aerosol formation, which is thought to propagate transfer of pathogens between animals (Colenutt et al., 2016) and increase the survival time of bacteria transported within the aerosol (Wathes et al., 1986).

Assessment of thermal stress is usually undertaken by calculating the temperature-humidity index (**THI**). A THI >72 causes heat stress in adult cattle (Armstrong, 1994; Bohmanova et al., 2007; Gantner et al., 2011), reducing feed intakes and milk yields and increasing physiological parameters such as heart and respiratory rate and systemic cortisol levels (Bouraoui et al., 2002). A range of THI thresholds have been proposed in calves from as low as 69 (Dado-Senn et al., 2020b) up to 78 (Kovács et al., 2020). Similar systemic effects from high THI are reported in calves, including immunosuppression, increased morbidity and mortality, and reduced growth rates and long-term survival (Roland et al., 2016). There is also a positive association between THI and BRD (Louie et al., 2018), with more lung lesions found in heat-stressed calves (van Leenen et al., 2020).

Air speed at calf level is important for the determination of whether there is exposure to detrimental drafts. Air speeds >0.3 m/s lead to increased heat loss (Buczinski et al., 2018), meaning this will negatively affect thermoregulation in the winter but may be useful during summer periods to help combat periods of heat stress. However, air speeds >0.5 m/s are associated with an increased risk of moderate to severe lung sounds on auscultation (Lundborg et al., 2005), and speeds >0.8 m/s are associated with increased odds of lung consolidation (van Leenen et al., 2020). The risk of BRD is further increased through the use of group housing in conjunction with poor ventilation and drainage (Cobb et al., 2014), with higher environmental moisture likely contributing to increased humidity levels and increased pathogen aerosolization, survivability, and therefore spread within the inhabitants of the housing (Wathes et al., 1986). This demonstrates the relationship between multiple environmental parameters and their combined effects on the animals housed within it.

Particulate matter (**PM**; dust) in the air originates from the calves themselves, their bedding, and dry feeds. Small particles <10 μm in diameter (**PM_{10}**) are able to travel deep into the lungs, causing respiratory tract irritation and an increased risk of BRD due to pathogen transfer (Urso et al., 2021). There is also a potential effect on the health of farm workers in this environment, with prolonged exposure contributing to human diseases such as bronchitis and occupational asthma (Alberta Agriculture and Food, 2008). Air may also contain bacteria, either in aerosol form or attached to PM. Concentrations of fine dust, but not air bacterial load, have been positively linked with BRD (van Leenen et al., 2020, 2021). The same authors demonstrated that PM levels in the air varied throughout the day, with peaks linked to bedding of pens and increased activity within sheds. They concluded that calves should be exposed to <50 μg/m^3 of $PM_{1.0}$ (fine particles) in the air over a 24-h period to reduce their odds of suffering from severe lung consolidation and increased lung fluid neutrophil levels. The PM may also contain noxious gases and endotoxins, and higher temperatures in calf housing can lead to bedding fermentation and production of ammonia (Maeda and Matsuda, 1998). Ammonia levels in the air also vary throughout the day, with chronic exposure thought to lead to ciliary dysfunction, degeneration of nasal epithelium, and rhinitis, and levels >10 ppm linked to increased antimicrobial usage in veal calves (Schnyder et al., 2019).

Understanding the effects of different types of calf housing on the environmental parameters described above will lead to a better understanding of the most suitable types of housing facilities, helping to further our understanding of how calf housing needs to adapt at the farm level to improve parameters that are outside the ideal ranges. The aim of this study was to establish and compare the levels of multiple environmental parameters within different types of calf housing commonly used on commercial farms in the UK.

MATERIALS AND METHODS

Farm Characteristics

Ethical approval was provided by the Royal Veterinary College (Hatfield, UK) Clinical Research Ethical Review Board (URN 2020 2006–2). A cross-sectional study was performed with calf pen as the experimental unit. A convenience sample of 10 dairy farms from the south of England were enrolled between June and July 2021 to provide summer readings, with revisits to 9 premises between January and March 2022 to provide the winter readings. The block calving nature of the 10th herd prevented their further participation. All farms kept their calves within the same pen from birth until after weaning, with 3 pens used for observations from each farm. All calves were fed milk manually twice per day at a rate of between 3 and 4 L per feed in both seasons, with additional fiber consisting of straw from bedding (7 farms), straw in racks (2 farms), or silage (1 farm), and access to ad libitum concentrates and water from buckets. All farms used unchopped straw bedding for the calf pens. Only one farm cleaned out the calf pens while the calves were still being reared in them; all other farms cleaned out the pens once the calves had been weaned and moved into another housing area. Fresh bedding was added on top of soiled bedding daily in 30% (3/10) of farms, and 2 or 3 times a week on the remaining farms. Hutches placed outside were used on 4 farms, with a single farm using a polytunnel with group pens created using gates within it. The remaining 5 farms housed calves in a shed with either gates (2/5 farms) or solid walls between calf pens (3/5 farms).

At the initial visit, multiple measurements to describe the physical properties were taken from the calf housing (Table 1), including housing dimensions, pen sizes, and the number of calves housed. No formal measurements of calf health were made during the visits.

Environmental Measurements

On each farm, a single pen or hutch located approximately within the center of the housing area had one temperature and relative humidity (**RH**) data logger (Omega OM-EL-USB-2-LCD; range: −35 to 80°C and 0 to 100% RH; accuracy: ±0.1°C and 0.1% RH) placed within it at approximately 0.25 m from the top of the bedding. An additional single data logger was placed outside under shade in a central geographical location to collect data representative of the environmental temperature and humidity. The data loggers took readings

Table 1. Description of the calf housing used in the 10 farms on the study (all housing met the minimum UK recommendations of 1.5 m^2/calf)

Farm	Overall housing type	Overall house dimensions (length × width, m)	Pen dimensions (length × width, m)	Calves per pen	Pen area per calf[1] (m^2)	Floor material[2]	Mechanical ventilation	Artificial lighting
1	Shed	31.9 × 11.0	2.2 × 2.0	2	2.2	Concrete	No	Yes
2	Shed	32 × 13.9	1.9 × 1.8	2	1.7	Concrete	No	Yes
3	Hutch	1.8 × 2.2	1.8 × 2.2	2	2.0	Hardcore	No	No
4	Hutch	3.6 × 0.9	3.6 × 0.9	2	1.6	Hardcore	No	No
5	Shed	7.7 × 6	6 × 6	11	3.3	Concrete	Yes	Yes
6	Shed	19.3 × 16	1.9 × 1.9	2	1.9	Concrete	Yes	Yes
7	Shed	40.1 × 18	7 × 4.5	10	3.2	Hardcore	Yes	Yes
8	Hutch	3.6 × 0.9	3.6 × 0.9	2	1.6	Hardcore	No	Yes
9	Hutch	3.6 × 9	3.6 × 2.5	4	2.2	Hardcore	No	Yes
10	Polytunnel	14.5 × 8.8	2.9 × 2.3	3	2.2	Concrete	No	Yes

[1] The pen area for the hutches included the outside run.

[2] Hardcore refers to aggregate material composed of a mixture of sands, gravel, crushed limestone, and granite that has been compressed and compacted to form a surface.

every 10 min over the 2 study periods. The collected data were used to calculate the THI using the following formula (NRC, 1971), where T = temperature (°C) and RH = relative humidity (%):

$$\mathrm{THI} = (1.8 \times \mathrm{T} + 32) - [(0.55 - 0.0055 \times \mathrm{RH}) \times (1.8 \times \mathrm{T} - 26.8)].$$

Point readings were taken from each farm on one day per week for 8 consecutive weeks within each season (summer and winter). Readings were taken from 3 pens selected to represent the area covered by the calf housing, with pens positioned at each end and within the middle area of the housing to account for different locations within the housing area, and the same 3 pens or hutches were used for data collection each week. In addition, an external point reading was taken on each farm approximately 5 m away from the calf housing to enable differences to be calculated between pen and external environmental measurements. The internal point measurements were all taken at approximately 0.5 m above bedding level, representing calf height (van Leenen et al., 2020; Hyde et al., 2021). The temperature and humidity levels were measured using a handheld meter (M86, Mengshen), with accuracy ±3% RH and ±0.5°C. The light level was measured using a luxmeter (LX-90, Amtast), with resolution of 1 lx. The ammonia level was measured using a handheld meter (BW Solo Ammonia Meter), which had a range of 0 to 400 ppm and an accuracy of 1%. The air speed was measured using a handheld digital anemometer (GM 816, Amgaze), with threshold 0.1 m/s and accuracy of ±5%.

The PM levels in the air were measured using an air sampler with a combined photometric measurement to cover the mass concentration range and a single particle detection measurement (DustTrak DRX 8533, TSI Ltd.). This was placed in approximately the center of each of the 3 pens on the bedded surface (Lago et al., 2006) and actively sampled 30 L of air over a 10-min period (flow rate 3.0 L/min). The sampler measured the PM_{10} and $\mathrm{PM}_{\mathrm{Total}}$, defined as PM that passes through a size-selective inlet with a 50% efficiency cut-off at a 10-µm aerodynamic diameter (van Leenen et al., 2021). The device was calibrated by the manufacturer before use.

On visits at wk 2, 5, and 8 in each season, the air within each of the 3 pens on each farm was sampled to determine the concentration of airborne bacteria. A gravimetric sample was collected using the same air sampler, with the air passed across a filter paper (GLA-500 5-µm, 37-mm low-ash polyvinyl chloride membrane, Pall Corp.) in a 37-mm cassette with a flow rate of 2.0 L/min. The filter paper was transported from the farm to the laboratory in a cool box, and kept at 4°C for a maximum of 24 h before being rinsed in 2 mL of PBS. Plate count nutrient agar (Thermo Scientific Nutrient agar powder CM0003B; Oxoid) was then used to culture 1 mL of the PBS fluid, with 2 plates cultured per pen. The plates were incubated at 35°C for 24 h in aerobic conditions, and colony-forming units were counted manually. Within each batch of samples, negative controls of filter paper and PBS solution were processed. Following enumeration, colony morphology was noted and Gram staining was carried out on a sample of each colony. This was followed by a catalase test to differentiate bacteria that produce catalase, such as *Staphylococcus* and *Micrococcus* spp., from those that do not, such as *Enterococcus* and *Streptococcus* spp., and an oxidase test (Sigma-Aldrich) to differentiate bacteria that produce cytochrome oxidase, such as *Pseudomonas*, from enteric bacteria such as *Escherichia coli* that do not (Quinn et al., 2015).

Statistical Analysis

All data were stored in Excel (Microsoft Corp.). All analyses were performed using SPSS (version 27.0, IBM SPSS Statistics for Windows; IBM Corp.). Significance was declared at $P \leq 0.05$, and trends were reported if $P \leq 0.10$. For all analyses, the assumption of normality was assessed through visual inspection of residual plots. Linear regression was carried out to assess the effect of mechanical ventilation on the outcomes of temperature, THI, and PM_{10} levels to ascertain whether the shed category of housing could be amalgamated into one housing group. A linear mixed model structure was used to investigate the effect of housing type and season on the THI, with interaction between the housing and season. A first-degree autoregressive (AR1) covariance structure was used to account for the repeated measure from the same farm, period, and day over the study periods. A linear mixed model structure was used to investigate the effect of housing type and season on point measurement differences between the internal and external measurements of the light level and air speed; compound symmetry covariance structure was used to account for the repeated measure from the same farm and pen over the 8 weekly visits in both seasons.

Log_{10} transformations were used for measurements of PM_{10} and concentrations of bacteria in the air (cfu/m^3) to ensure an approximate normal distribution. A linear mixed model structure was used to investigate the effect of housing type, season, number of calves per pen and point humidity on the point measurement of pen PM_{10}; compound symmetry covariance structure was used to account for the repeated measure from the same farm and pen over the 8 weekly visits in both seasons. A linear mixed model structure was used to investigate the effect of housing type, season, bedding hygiene score, and the number of calves within the pen, on the bacteria number; compound symmetry covariance structure was used to account for the repeated measure from the same farm and pen over the 3 visits in both seasons. Results are reported as F-values in the format $F_{(\text{treatment df, error df})}$.

RESULTS AND DISCUSSION

Commercial dairy farms within the UK were assessed to monitor the environmental parameters within their calf housing using a cross-sectional study design. Ten farms were followed over the summer season and 9 farms of them were monitored again during the winter. One farm (farm 1) had missing values for the continuous monitoring of temperature and humidity in the winter period due to technical failure of the equipment used. A summary of the mean values of the internal environmental parameters in each of the 3 housing types used (shed, hutch, and polytunnel) and the external environment is given in Table 2.

Comparison in the use of mechanical ventilation within shed housing indicated that there was no significant difference in the temperature ($F = 31.0$, $P = 0.26$), THI ($F = 28.2$, $P = 0.51$), or PM_{10} ($F = 76.3$, $P = 0.42$) between sheds that did and did not use mechanical ventilation; therefore, the data for shed housing were analyzed together. The sample size in each group was relatively small (3 sheds with mechanical ventilation and 2 sheds without), but this finding does indicate that the mechanical ventilation used on the study farms may not have been working optimally. Assessment of the specific air flow patterns within the sheds was beyond the scope of this study, but possible reasons for the lack of difference made by the mechanical ventilation may be a bias toward placement of mechanical ventilation within sheds that already have poor natural ventilation. All 3 farms used positive pressure ventilation tubes, which are designed to push fresh air into a shed, which then exits passively through ridges and eave openings (Nordlund and Halbach, 2019). This might suggest that the air outlets in these sheds prevented old air from effectively exiting the sheds, compromising the effectiveness of these mechanical systems.

It should be noted that the management of calf housing (regardless of type) will invariably affect environmental parameters. This was an observational study carried out on commercial dairy farms; therefore, control of management (eg, water management such as drainage affecting parameters such as humidity) was

Table 2. Summary values of the environmental parameters [mean (range)] measured during the 2 study periods (summer and winter) between different housing types[1]

Environmental parameter	Season	External environment	Shed (5 farms)	Hutch (4 farms)	Polytunnel (1 farm)
Temperature (°C)	Winter	6.7 (−4.0 to 13.5)	8.1 (−4.0 to 23.5)*	7.1 (−4.5 to 14.5)	8.5 (−2.5 to 18.5)*
	Summer	17.2 (5.5–38.0)	17.4 (7.0–31.0)	17.7 (4.5–37.0)	19.0 (8.5–37.0)*
Humidity (%)	Winter	83.6 (52–97)	81.2 (43.0–97.0)*	86.5 (56.0–99.5)*	73.6 (46.5–86.5)*
	Summer	77.4 (26.0–96.5)	76.7 (44.0–94.5)*	79.2 (33.0–99.9)	73.2 (35.0–91.5)*
Temperature-humidity index	Winter	45.1 (26.8–56.8)	47.8 (26.8–70.2)*	45.6 (26–58.2)	48.8 (30.9–64.2)*
	Summer	61.7 (42.6–84.5)	62.3 (45.7–78.1)	62.4 (40.7–82.5)	64.3 (48.1–84.6)*
Light (lx)	Winter	20,654 (1,863–62,800)	440 (5–18,700)*	1,148 (86–4,810)*	4,647 (1,861–13,400)*
	Summer	66,669 (4,670–405,000)	1,162 (47–7,420)*	4,603 (352–73,300)*	16,900 (288–50,000)*
Airspeed (m/s)	Winter	1.1 (0.0–7.0)	0.004 (0.0–0.3)*	0.03 (0.0–0.3)*	0.08 (0.0–1.0)*
	Summer	0.89 (0.0–7.0)	0.1 (0.0–1.6)*	0.03 (0.0–0.7)*	0.08 (0.0–0.9)*
Bacterial numbers (cfu/m^3)	Winter	NA[2]	8,183 (600–30,750)	10,031 (450–40,550)	3,217 (350–12,050)
	Summer	NA	19,175 (200–72,800)	18,335 (400–64,450)	5,572 (1,400–19,400)
PM_{Total}[3] (mg/m^3)	Winter	NA	1.53 (0.07–14.4)	0.55 (0.2–1.8)	0.28 (0.08–1.1)
	Summer	NA	0.64 (0.02–38.6)	0.41 (0.03–4.6)	0.20 (0.06–1.3)
PM_{10}[3] (mg/m^3)	Winter	NA	1.48 (0.05–14.3)	0.47 (0.20–1.7)	0.24 (0.07–1.1)
	Summer	NA	0.58 (0.03–38.4)	0.27 (0.03–4.5)	0.16 (0.04–1.2)

[1] Values were averaged between across the 3 pens followed on each farm, and across the 8 visits in each season.

[2] Not applicable.

[3] PM_{Total} = total particulate matter; PM_{10} = particulate matter <10 μm.

*Significant difference from the external environmental measurements, $P < 0.05$.

not possible. However, the data provide evidence of environmental parameters currently encountered in calf housing within the UK, and should help shape practitioners' areas of focus for improving the calf environment through consideration of both housing design and management factors.

Temperature and Humidity

The maximum summer temperature in this study was 37.0°C, recorded within both the hutch and polytunnel housing. Sheds remained consistently cooler, with a maximum temperature of 31.0°C (Table 2). Heat stress is defined as the sum of internal and external forces that cause an increase in body temperature and evoke a physiological response (Yousef, 1985). Animals require body temperature to be stable within a narrow range to optimize biochemical processes essential for normal metabolism (Shearer and Beede, 1990). Heat stress can occur in temperate climates such as the UK, whereby the summer weather produces episodic periods of thermal stress rather than the extended periods found in tropical climates. These episodic conditions are problematic for cattle because less acclimation is possible (Ominski et al., 2002). The high temperatures recorded in this study are uncomfortable for calves, far exceeding the recommended 10 to 20°C thermoneutral zone, and potentially compromising their welfare. Other individual calf characteristics such as coat color may also alter the effects of high temperatures, with calves that have dark hair color absorbing more solar radiation than those with lighter coats (Da Silva et al., 2003).

Although temperature itself has a large effect on calf comfort, the combined effect of temperature and humidity levels within the THI calculation allows for a more robust interpretation of the degree of thermal stress experienced. The THI threshold for calves has variable reports within the literature but, in this study, a THI threshold of 72 was used to indicate the point of heat stress, and this was reached or exceeded in the housing environment during the summer for 14 of 46 d in the sheds, 31 of 46 d in the hutches, and 39 of 46 d in the polytunnel. The mean THI within all types of calf housing was greater than the environmental measurements in both seasons ($F_{1,1169}$ = 2,461.4; $P < 0.01$), with mean summer and winter THI of 60.1 and 45.7, respectively (Figures 1A, B). The THI was also significantly affected by the overall type of housing ($F_{4,2030}$ = 11.6; $P < 0.01$). The polytunnel had the greatest mean THI of all housing in the summer of 64.3 (range: 48.1–84.6), closely followed by hutches, with a mean summer THI of 62.4 (40.7–82.5). These wide variations over a relatively short period are concerning, with the maximum values experienced by calves likely to have negative effects on welfare (Polsky and von Keyserlingk, 2017). When considering the parameters measured within hutch housing, consideration should be given to the access that calves have to the integrated outside area that accompanies a hutch. Under some weather conditions, this may help to reduce the negative effect of environmental parameters within the hutch itself. Our findings agree with those from Young et al. (2020), who demonstrated that the average THI was higher in hutches (mean ± SE; 64 ± 0.21) than in sheds (63 ± 0.19; $P < 0.0001$). However, the difference found in this study between internal housing and external environmental THI differs from the findings of Seedorf et al. (1998) and Hyde et al. (2021), who demonstrated minimal differences between internal housing and external environmental temperatures when using multiple data loggers simultaneously across farms. This difference may be due to the current study using only a single external data logger placed at a central geographical site for comparison with all the farm measurements, rather than a data logger placed outside on site at each of the recruited farms. It should also be noted that only a single polytunnel was followed in our study compared with the multiple farms with sheds and hutches in use. This reflects the low use of polytunnels across the UK, but we acknowledge that extrapolation of data from this housing type to other farms should consider the effects that different siting (e.g., orientation and location relative to other buildings) or use of mechanical ventilation might have on the environmental parameters measured within the polytunnel.

Overall, these findings demonstrate that both the hutch (Young et al., 2020) and polytunnel housing systems present a high risk of heat stress compared with shed housing, and they suggest that extra management strategies are required to mitigate the high THI levels to reduce exposure to heat stress. Provision of shade is effective (Kawabata et al., 2005; Kovács et al., 2018), along with use of fans for continuous cooling to reduce respiratory rate and rectal temperatures in heat-stressed calves (Dado-Senn et al., 2020), although for practical reasons they can only be used in sheds or polytunnels. Further work on the effect of these mechanical ventilation systems in polytunnel housing should be considered.

Calves may tolerate a higher THI than adult cattle due to their larger surface area relative to BW and because calves do not any additional metabolic heat outputs from milk production (Tyson, 2011) or heat generation by the rumen. Physiological changes that occur due to heat stress in calves include increased rectal temperatures and respiratory and heart rates

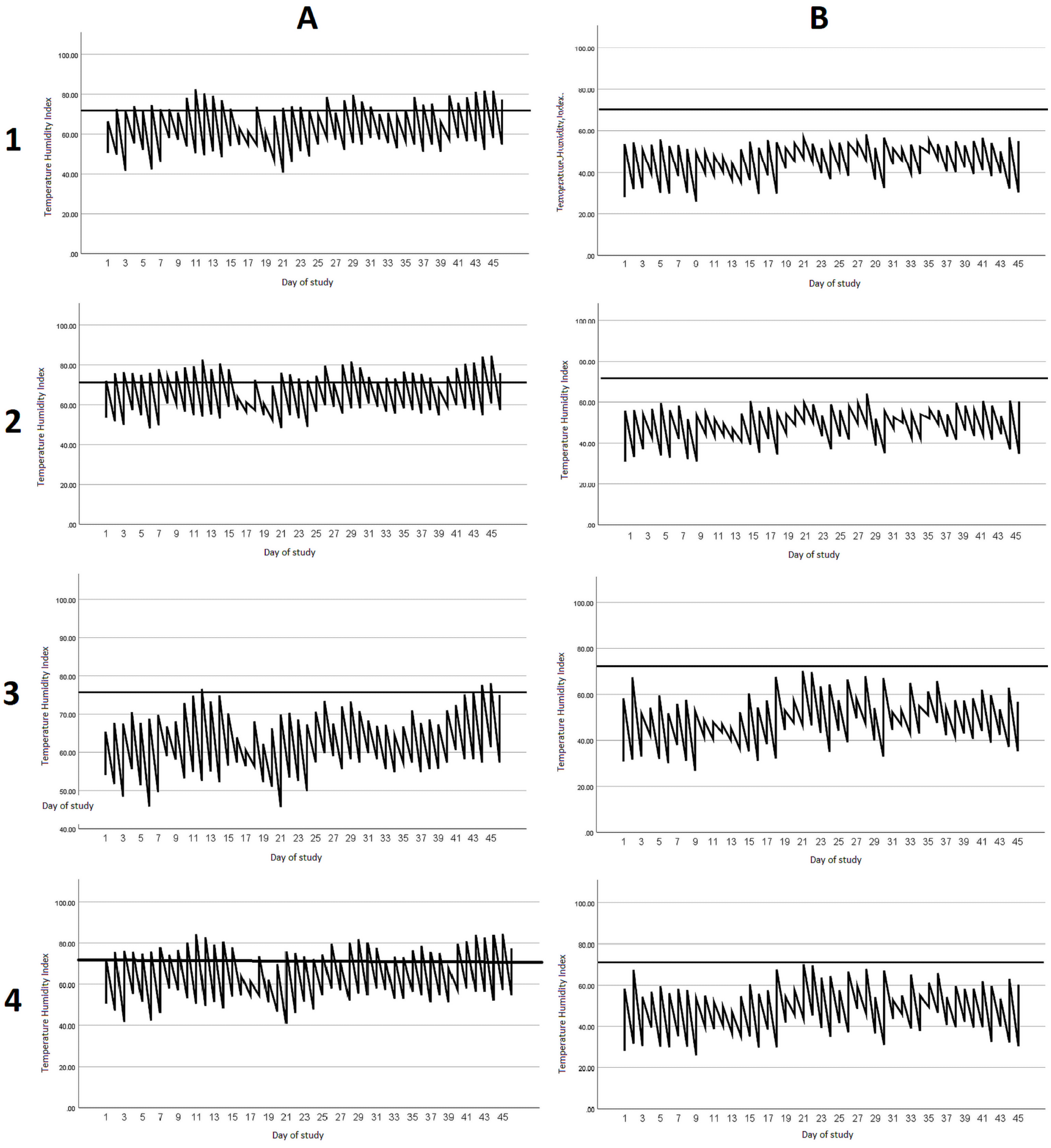

Figure 1. Mean temperature-humidity index (THI) across farms in southern England (A) over the summer trial period from June to July 2021, and (B) over the winter trial period from January to March 2022. Panels 1 to 4 represent hutch housing, polytunnel housing, shed housing, and mean THI across all housing types, respectively. The horizontal line represents a THI of 72, the level at which heat stress was experienced by the calves. During the summer, a THI ≥72 was present for 4.4% of the time in sheds, 10.9% of the time in hutches, and 17.9% of the time in polytunnel housing.

(Kovács et al., 2018), with forced respiration reported to be the first response to a hot environment (Kovács et al., 2020). Higher temperatures are also linked to thoracic ultrasonographic lung consolidation (van Leenen et al., 2020) and increased respiratory disease risk (Louie et al., 2018), along with reduced starter feed intakes and reduced growth rates (Broucek et al., 2009). Further work to elucidate the threshold at which calves experience heat stress would be beneficial (Bell et al., 2021).

Calves are also prone to cold stress during winter periods due to their high surface-to-mass ratio and poor insulation (Roland et al., 2016). Their ability to keep warm is further compromised by drafts and damp hair coats and bedding (Rawson et al., 1989). The thermoneutral zone of a calf is influenced by management factors such as the plane of nutrition and use of calf jackets, but taking 10°C as the lower critical temperature, animals in our study spent 62.3% of the winter period in cold stress within the polytunnel compared with 74.7% in sheds and 85.7% in hutches. Sub-zero temperatures were experienced in all 3 housing types, with a minimum temperature of −4.5°C reached in the hutches. The shed and polytunnel housing both provided a slight but significant increase in temperature (mean 8.1 and 8.5°C, respectively) compared with the environment (mean 6.7°C), but the hutches did not (mean 7.1°C). This agrees with other studies (Jorgenson et al., 1970; McKnight, 1978) and demonstrates that hutch housing will not alleviate the effect of cold climatic conditions. Cold stress is known to be detrimental to calf growth and therefore reduces rearing efficiency (Johnson et al., 2017; Bell et al., 2021). Calves born during colder months are also at higher risk of BRD (Johnson et al., 2021). Provision of deep, dry bedding may help reduce the effects of cold weather (Nordlund, 2008), with the use of 1-kW heat lamps shown to improve growth rates, whereas use of calf jackets within the UK has not (Scoley et al., 2019; Hyde et al., 2022). Calf jackets may, however, have a more beneficial effect in countries with more severe winter weather than that experienced in the UK. The effect on thermoregulation that pair housing within hutches or group housing within sheds might have is unclear, but the ability of calves to remain in close contact may aid in heat retention and could be investigated further. Hutches also have relatively low space provision, compromising the calf's ability to be active and move around, which is a behavioral adaptation to mitigate cold stress (Roland et al., 2016). In addition to low minimum temperatures, there was great diurnal variation in temperature throughout the day, with such variation previously linked to higher mortality rates in calves (Roland et al., 2016; Schnyder et al., 2019).

Within the winter period, the highest humidity levels across housing types was 99.5% in hutches, with high humidity causing condensation and resulting in wet walls, bedding, and hair coat (Abshoff and Steimle, 1983). High humidity levels in housing are associated with increased Wisconsin calf scores and bronchoalveolar fluid basophil levels, potentially due to increased spore or fungal levels in aerosols (van Leenen et al., 2020). This means it is imperative to check the siting of hutches to ensure the groundwork allows drainage of fluids away from the hutch (Roland et al., 2016), or addition of roofing to protect from direct rain entry and drafts onto the beds. Slope and drainage were not measured in this study, but we acknowledge that this would have affected moisture accumulation within housing. Other siting considerations include orientation, with traditional recommendations being to place housing perpendicular to the prevailing wind to avoid high air speeds within.

Light

The mean overall light level across all the housing was 2,889 lx, which is higher than that found by Brown et al. (2021) between January and May in Northern Ireland. The light difference between the internal calf housing and the external environmental measurement was not affected by housing type ($F_{2,47} = 0.81$; $P = 0.45$), with the mean light difference being 42,074 ± 46,289 lx. However, sheds had the lowest recorded point measurements of 5 lx, and the winter was significantly darker than the summer ($F_{1,47} = 188.0$; $P < 0.01$). There is relatively little literature surrounding the effect of light provision on calves, but levels <100 lx have been associated with reduced feeding and social behavior and increased lying behavior (Dannenmann et al., 1985). Direct sunlight has also been shown to reduce microorganism levels (Mascher et al., 2003), which may affect bacterial levels in bedding. This aspect warrants further investigation. In pigs, the recommendation is to have at least 40 lx for a minimum of 8 h/d [Welfare of Farmed Animals (England) Regulations; National Archives, 2007], but bovine guidelines stipulate only that calves kept in artificially lit buildings must be provided with light for a period at least equivalent to that naturally available, with no specific level stated.

Air Speed

The maximum recorded internal housing air speed in this study was 1.6 m/s in a shed, much lower than the maximum external recording of 7.0 m/s (Table 2). Air speed was thus reduced within all housing types compared with the external environment, with hutches providing the most protection ($F_{2,47} = 9.7$; $P < 0.01$). This has been established in other studies, especially if the orientation of the hutch is correct in relation to the prevailing wind (Hoshiba, 1986). Air speed was not affected by season ($F_{1,47} = 0.59$; $P = 0.45$), and there was no interaction between housing type and season ($F_{2,47} = 1.6$; $P = 0.22$). Reduction of high air speed at calf level is important, especially in the winter when it is linked to cold stress. However, limiting air movement will inevitably compromise ventilation within housing and could reduce air quality through build-up of pathogens, dust, and noxious gases (Lago et al., 2006). Air speeds of >0.8 m/s have been linked with more severe ultrasonographic lesions in calf lungs (van Leenen et al., 2020). This value was rarely reached in any of the calf housing types, although in this study we used only point measurements rather than continuous monitoring. The latter would have provided more detail on daily fluctuations of air speeds given changing weather conditions over time.

Ammonia

The current maximum occupational exposure standard to ammonia in humans is 8 h of exposure to 25 ppm in any 24-h period (Health and Safety Executive, 2011). This is often taken as a guideline for ammonia exposure of housed livestock in the absence of limited evidence to the contrary, with recommended safe ammonia thresholds of 15 to 20 ppm suggested (CIGR, 1984; Urbain et al., 1994). All ammonia readings throughout this study were <10 ppm, with more accurate readings not possible with the equipment used. These low levels are in agreement with multiple other studies (Lago et al., 2006; Kaufman et al., 2015; Buczinski et al., 2018; van Leenen et al., 2020) and are well below the suggested safe threshold. In contrast, van Leenen et al. (2020) demonstrated a significant association of ammonia levels >4 ppm with lung consolidation in calves, and Hamilton et al. (1996) found that ammonia levels of 5 ppm were linked with rhinitis in pigs, due to a synergism with *Pasteurella multocida.* Others, however, have failed to show changes in lung tissue or growth when pigs were co-exposed to both ammonia and an infectious agent (Drummond et al., 1981; Diekman et al., 1993). Exposure of pigs to atmospheric ammonia up to ~40 ppm for 5.5 wk postweaning also had no effect on either respiratory disease (Done et al., 2005) or productivity (Wathes et al., 2004). This makes it unlikely that the ammonia levels present in the calf housing used in our study would have affected calf health. Given the link between provision of good ventilation and low ammonia levels in the air (Hillman et al., 1992), it might be concluded that the low ammonia levels found throughout this study indicate that the ventilation within the housing types monitored was appropriate, but future studies could evaluate this link in more detail via specific quantification of housing ventilation.

Particulate Matter and Airborne Bacteria

The current maximum occupational exposure standard to dust in humans is 8 h of exposure to 10 mg/m^3 in any 24-h period (Health and Safety Executive, 2011). In this study, the mean PM_{10} concentration was 0.6 mg/m^3 (SD: 2.5 mg/m^3), with a range between 0.03 and 38.4 mg/m^3 (Table 2, Figure 2). The PM_{10} showed a trend with the calf housing type ($F_{2,50} = 3.1$; $P = 0.052$), with sheds having the highest levels at 0.97 ± 3.75 mg/m^3, followed by hutches (0.37 ± 0.44 mg/m^3) and then the polytunnel (0.20 ± 0.24 mg/m^3). This was mirrored by the bacterial numbers found in the air, which were significantly affected by calf housing type ($F_{2,50} = 3.6$; $P = 0.034$), with sheds having the highest mean levels of 8,017 ± 2,141 cfu/m^3, hutches having an overall mean of 6,870 ± 2,084 cfu/m^3, and the polytunnel with 3,357 ± 2,572 cfu/m^3. Our findings are in contrast to those of Hill et al. (2011), who demonstrated that hutches had higher airborne bacterial concentrations than sheds; however, that study was conducted on a single research farm whose shed design and ventilation may have been better than those found on many commercial dairy farms. The reason for the very high PM levels recorded in sheds (Figure 2) is unclear, with the high weekly average readings attributed to single, high pen readings across different farms on different weeks. This lack of consistency in the occurrence of high readings make them harder to explain. All farms used straw to bed but the type and quality of the straw was not quantified in this study. Recent calf or management activity within the pen could produce more PM in the air.

Previous studies have demonstrated a link between the occurrence of respiratory disease and PM and bacterial levels in the air within housing (Pritchard et al., 1981; Hillman et al., 1992; Lago et al., 2006). Although it is recognized that much of the bacteria contained in the air is nonpathogenic (Wathes et al., 1984), exposure can still elicit respiratory tract defenses and compromise respiratory function.

There was a significant association of PM_{10} with season ($F_{1,68} = 44.3$; $P < 0.01$), with PM_{10} being lower in summer at 0.40 ± 0.14 mg/m^3 and higher in winter at 0.85 ± 0.31 mg/m^3. This is in contrast to findings by Islam et al. (2020), who found higher PM_{10} in the summer, but this could be due to the high winter humidity found in the current study, with higher air moisture reducing the disintegration of airborne particles (Jones and Harrison, 2004). The bacteria numbers in the air samples were also significantly associated with the season ($F_{1,100} = 6.9$; $P = 0.01$), but with the reverse trend of summer having a higher mean bacterial air counts than winter (7,962 cfu/m^3 vs. 4,074 cfu/m^3). This goes against the general theory that airborne bacteria are usually associated with aerosol particles and PM. However, higher bacterial numbers in warmer air temperatures were also found by Lago et al. (2006), who hypothesized that this was due to warmer conditions favoring increased bacterial production within the bedding. In contrast, colder temperatures are not conducive to survival, reproduction, and spread of microorganisms (Zhong et al., 2016). Further studies could include temperature readings from within the bedding pack to assess how this links to airborne bacteria levels.

Increasing calf numbers within the pen were significantly associated with higher PM_{10} levels ($F_{1,56} = 4.2$, $P = 0.046$), along with a trend for increasing bacteria counts ($F_{1,65} = 2.8$; $P = 0.10$). This may be due to the calf itself being the main source of airborne particles (Wathes et al., 1984), with grouped calves likely to be more active and therefore producing more bedding disturbance and dust formation. However, there was no association with the point humidity in the pen (PM_{10} $F_{1,381} = 0.001$; $P = 0.98$; bacteria number $F_{1,137} = 0.05$; $P = 0.83$).

The most prevalent bacterial colony type identified in the air samples following bacterial culture was a round, white colony (Table 3) that was catalase positive and oxidase negative, likely indicating *Staphylococcus* spp. (Table 4). Specific bacterial speciation during this study would have allowed better direct comparison with results from other studies, but a general trend can be inferred. *Staphylococcus* spp. are reported to be typical components of the natural microflora of skin, hair, and mucous membranes (Szulc et al., 2020), and are therefore likely to be present in higher numbers due to the multiple routes of shedding. The presumptive species of bacteria identified were similar to those cultured by Wilson et al. (2002), who found *Staphylococcus*, *Bacillus*, and *Micrococcus* spp., and by Islam et

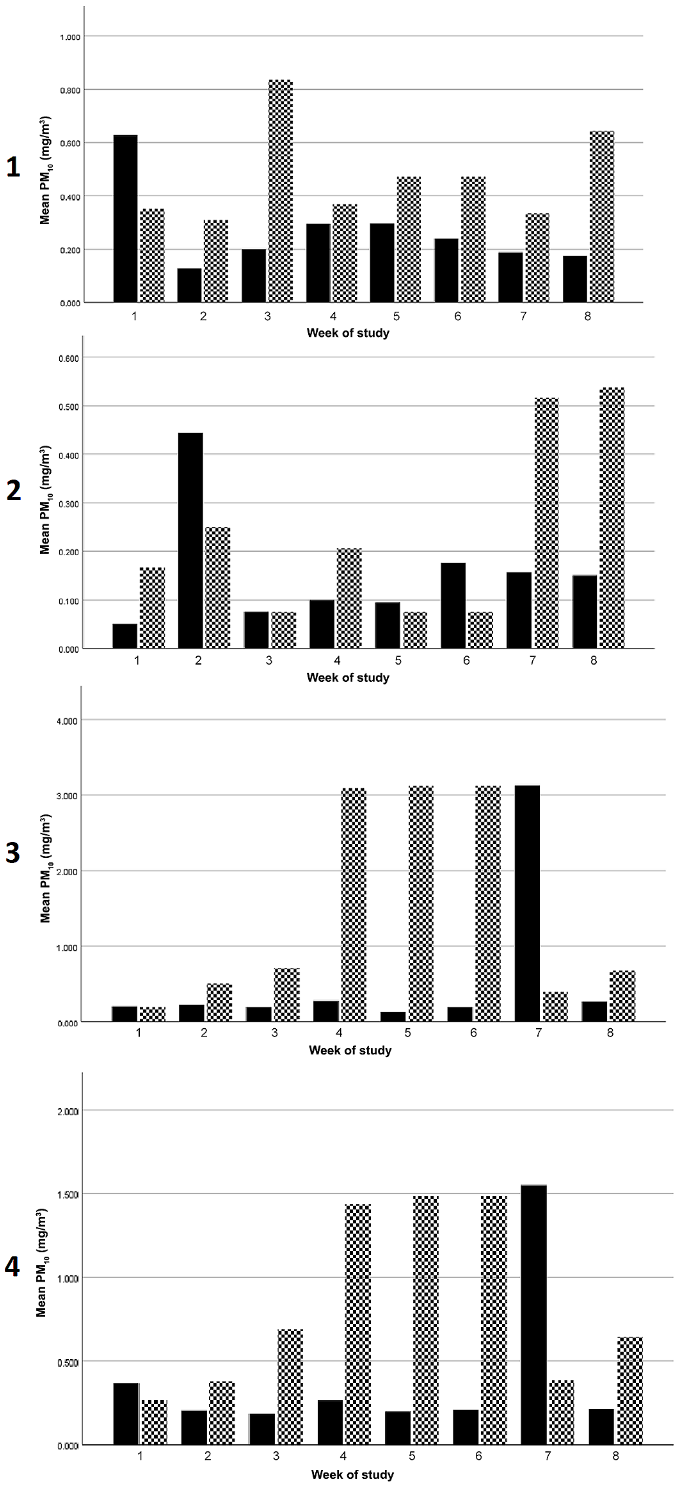

Figure 2. Mean PM_{10} (particulate matter <10 μm) concentration over the 8-wk study periods in the summer (solid black bar) and winter (checkered bar) periods, with panels 1 to 4 representing hutch housing, polytunnel housing, shed housing, and mean temperature-humidity index (THI) across all housing types, respectively. The values in the winter were generally higher than in the summer, with a large variability between housing types and between weeks of the study.

Table 3. Mean number of colonies (cfu/m^3) collected from air samples across the 10 farms, averaged across the 6 samples taken over the study period (data are subdivided by gross colony morphology)

	Gross colony morphology					
Farm	Round, white	Round, yellow	Round, cream	Round, orange	Irregular, white	Total
Farm 1	9,706	422	114	28	1,117	11,644
Farm 2	10,169	506	236	50	597	12,253
Farm 3	7,639	322	336	147	553	10,603
Farm 4	4,481	308	197	28	686	5,678
Farm 5	10,883	642	258	58	925	13,900
Farm 6	11,358	1,256	319	392	331	15,622
Farm 7	8,942	286	500	39	431	11,106
Farm 8	11,536	686	181	6	619	15,375
Farm 9	17,028	922	217	28	542	20,919
Farm 10	4,772	208	217	25	614	8,294

al. (2019, 2020), who found *Staphylococcus aureus* in air samples from dairy housing. The proportion of different species of bacterial colonies cultured across the farms was similar, suggesting that farms tend to have similar patterns of bacterial populations regardless of the housing type used or the differing environmental conditions produced.

The present study only recovered gram-positive bacteria, which also agrees with Wilson et al. (2002). Gram-negative bacteria are more susceptible to high temperatures, desiccation, UV light, and the stressors caused by the sampling methods used, meaning they may have been present in the air but not in a state that allowed culture. However, other studies have successfully sampled and cultured gram-negative bacteria from air samples (Stewart et al., 1995; Chang et al., 2001). In terms of airborne bacterial numbers, these were similar to those found by Hill et al. (2011) and van Leenen et al. (2020) in their shed samples. Our numbers were lower than those reported by Lago et al. (2006) but they only used sheds with a minimum of 12 calves within them, which is more than those housed within the hutches in this study. Our bacterial numbers were higher than those found by Wilson et al. (2002), although that study only sampled the air for 5 min and used blood agar to culture their samples as opposed to the nutrient agar used in this study.

CONCLUSIONS

Results from this study demonstrate the extent to which calves in the UK are exposed to both heat and cold stress, especially when housed in hutches and polytunnels. The highest humidity levels were also recorded in hutches, and this combination resulted in hutch-housed calves being in heat stress 67.4% of the summer and in cold stress 85.7% of the winter. Sheds had the highest PM_{10} and airborne bacterial levels, possibly indicating an issue with suitable ventilation as well as having more calves present in the pen. *Staphylococcus* spp. were the most prevalent bacteria species identified in air cultures, possibly due to their multiple routes of shedding.

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Table 4. Description of gross and microscopic results from the analysis of colonies produced from air samples from each type of calf housing, cultured on nutrient agar at 35°C for 24 h in aerobic conditions

Morphology	Gram stain	Catalase test	Oxidase test	Possible organism
Small, round white colony; cocci shape in clusters	+	+	−	*Staphylococcus* spp.
Small, round white colony; cocci shape in chains	+	−	−	*Streptococcus*/*Enterococcus* spp.
Small, round yellow colony; cocci shape, individuals and clusters	+	+	−	*Staphylococcus* spp.
Small, round cream colony; cocci shape in pairs and clusters	+	+	+	*Micrococcus* spp.
Large, irregular white colony; bacilli shape with endospores	+	+	+	*Bacillus* spp.

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ORCIDS

Sophie A. Mahendran https://orcid.org/0000-0003-2170-7112
Nicola Blackie https://orcid.org/0000-0002-4247-4015
D. Claire Wathes https://orcid.org/0000-0002-8206-6091
Richard E. Booth https://orcid.org/0000-0001-8695-4697