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Effect of cubicle hood system on methane concentrations around the lying area in cold climate dairy cattle buildings

Raphael Kubeba Tabase [a,*], Geir Næss [a], Yngve Larring [b]

[a] Animal science, Production and Welfare Division, Faculty of Biosciences and Aquaculture, Nord Universitet, Steinkjer, Norway
[b] SINTEF, Oslo, Norway

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ABSTRACT

There is scarcity of data on methane (CH_4) concentration levels and other gas compositions around animals in commercial cattle barns, especially for developing technology for gaseous CH_4 treatment. Consequently, use of biofiltration and catalytic combustion strategies as alternative enteric CH_4 mitigation techniques remain concepts yet to be validated in real cattle barns. One of the major barriers to implementing these techniques is that they require close buildings, which is not the case for most cattle barns. Open cattle barns are frequently associated with excessive ventilation, resulting in low CH_4 concentrations, which can reduce the cost effectiveness of CH_4 treatment techniques. With the development of low-cost, low-CH_4-concentration enrichment technologies still in their infancy, developing local ventilation systems at the animal level capable of collecting breath CH_4 from cows prior to air mixing could be an option. Therefore, the effect of a cubicle hood system (CHS) with different air extraction techniques on increasing CH_4 concentrations at the lying area were evaluated in natural and mechanically ventilated dairy cattle buildings during the winter in Norway. In both barns, the use of CHS increased CH_4 concentrations under the hood at the lying area by 14-25 % compared to without CHS. The results obtained depended on the height of the CHS from the floor and effect of outdoor temperature on air exchange rate in the barns. In the naturally ventilated barn, the hourly mean CH_4 concentrations under the cubicle hood ranged from 14-225 ppm, and 31-322 ppm in the mechanically ventilated building.

1. Introduction

Ruminant digestive processes (via enteric fermentation) account for 30 % of total global anthropogenic methane (CH_4) emissions; however, beef and dairy cattle are the most implicated, accounting for 77 % of these emissions (FAO 2016). The main concern is that CH_4, the second most important greenhouse gas (GHG), has 28 times the global warming potential of carbon dioxide (CO_2) over a 100-year time horizon (Anthropogenic and Natural Radiative Forcing — IPCC 2013). Consequently, pressure on the cattle industry to reduce enteric CH_4 emissions has intensified more than ever. Particularly following the Paris Agreement, which aims to achieve a peak in global GHG emissions by 2025 and a 43 % reduction by 2030 in order to limit global warming to at least 1.5°C by the end of the century (UNFCCC 2015). Although many potential enteric CH_4 mitigation techniques exist, research and progress on more direct measures such as feed modifications and additives, vaccines, and animal selection have received more attention and advanced than methods involving ventilated CH_4 treatment from cattle barns (Hristov et al., 2013, López-Paredes et al., 2020, van Breukelen et al., 2023, Norwegian Ministry of Climate Environment 2021, Knapp et al., 2014, Nisbet et al., 2020). As research in material science, microbial ecology, design, and engineering advances, biological (biofiltration) and chemical (catalytic combustion) enteric CH_4 treatments are prospective future mitigation measures that, if given enough attention, might help complement the more direct mitigation efforts (La et al., 2018, Pratt and Tate, 2018).

Catalytic CH_4 combustion techniques rely on abiotic factors, mainly minerals, to oxidise CH_4 into less harmful compounds (Feng et al., 2022, Samanta and Sani, 2023). In contrast to catalytic combustion, biofiltration relies on microorganisms (bacteria and fungi) to oxidise pollutants into less harmful byproducts (Sheoran et al., 2022). To achieve this, gaseous pollutants are adsorbed on the surface of a medium and metabolised by immobilised microbes into innocuous byproducts (Sheoran et al., 2022). Because of the success of biofiltration in eliminating hydrophilic pollutants, it has been regarded as a cost-effective Best Available Technique for removing ammonia (NH_3), odour, and particulate matter from livestock buildings (Giner Santonja et al.).

* Corresponding author.
E-mail address: raphael.k.tabase@nord.no (R.K. Tabase).

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Nomenclature

C_o	outdoor methane (CH_4) concentration (ppm)
C_e	CH_4 concentration in the cubicle hood's exhaust duct (ppm)
C_{ex}	pollutant concentration in the barn's exhaust duct (ppm)
C_p	pollutant concentration at point p (ppm)
C_r	barn CH_4 concentration (ppm)
T_p	air temperature at point p (°C)
T_{ex}	air temperature in the barn exhaust duct (°C)
ε_e	(dimensionless)
η_c	methane capture efficiency (dimensionless)
μ_e	heat removal effectiveness (dimensionless)
ACH	air exchange rate (h^{-1})
AOZ	animal occupied Zone
CHS	cubicle hood system
CON	control
CV	coefficient of variation (%)
RH	relative humidity (%)
T1 – T5	treatments 1 to 5
T_{CHS}	air temperature around the CHS (°C)
T_{in}	indoor Temperature (°C)
T_{out}	outdoor Temperature (°C)
ΔT	indoor and outdoor temperature difference (°C)

Likewise, pilot studies indicate biofiltration as a potential low-cost CH_4 abatement technique in the livestock sector (Fedrizzi et al., 2018, Oliver and Schilling, 2016, Melse and Van Der Werf, 2005). This is because, in contrast to catalytic CH_4 treatment, which require complex combustion units with higher operating temperatures (> 400 °C) and inlet CH_4 concentrations (> 5000 ppm) to effectively function (He et al., 2020), biofiltration systems are easier to design and can function at ambient temperature (< 30 °C), atmospheric pressure, and relatively low inlet CH_4 concentrations (Melse and Hol, 2017). However, one of the major barriers to implementing biofiltration in the cattle sector is that biofiltration require close buildings with mechanical ventilation, which is not the case for most cattle barns. This is because the sector prefers to house cows in open (naturally) ventilated buildings with easy access to graze outside. However, open cattle barns are often associated with overventilation, which results in low CH_4 concentrations. That is, whereas CH_4 concentrations between 250 and 10000 ppm are regarded optimal for biofiltration of ventilated CH_4 (Melse and Van Der Werf, 2005, Limbri et al., 2013), typical hourly average indoor CH_4 concentrations in naturally ventilated cattle barns range between 15 to 201 ppm (Tabase et al., 2023, Teye et al., 2008). Methane concentrations, especially at low levels, is a key factor influencing CH_4 oxidation performance in biofilters (Limbri et al., 2013). Feeding biofilters with low CH_4 concentrations has the disadvantage of requiring larger biofilter footprints (Melse and Van Der Werf, 2005) to archive long gas residence times (> 10 minutes) and overcome the mass transfer limitations of CH_4 within the biofilm in order to achieve higher CH_4 removal efficiencies (Melse and Hol, 2017, Ganendra et al., 2015, Du Plessis et al., 2003). With development of economical, low CH_4 concentration enrichment technologies still in their infancy (NORCE Norwegian Research Centre 2020, Wang et al., 2020, Yang et al., 2022), developing local ventilation techniques at the animal level capable of extracting breath CH_4 from cows before air mixing could be an option. In fact, a large body of literature already confirm that measured CH_4 concentrations close to cattle nostrils, as well as in enclosers such as feed bins and respiratory chambers ranged from 300 to 1500 ppm, compared to indoor CH_4 values of 15 to 201 ppm in naturally ventilated cattle barns (López-Paredes et al., 2020, van Breukelen et al., 2023, Teye et al., 2008, Blaise et al., 2018, Sorg et al., 2017, De Haas et al., 2019).

Norway, as party to the Paris Agreement, wants to reduce GHG emissions from the cattle industry, but depends heavily on rapid technological advances that are both climate friendly and environmentally sound to meet its climate ambitions (Norwegian Ministry of Climate Environment 2021). Norwegian cattle farms could be an ideal setting to experiment with local ventilation systems for collecting concentrated CH_4. Given that in Norway, mechanical is more widespread than natural ventilation, and cows stay indoors for a longer time of the year due to the cold temperature (Tabase et al., 2023). Furthermore, during cold seasons when outdoor air temperatures drop below 0 °C, typical air exchange rates inside cattle barns occur at less than 5 every hour in order to satisfy thermal requirements for animals (Tabase et al., 2023). By compromising with indoor air quality requirements, this leads to high indoor moisture and pollutant concentrations (Tabase et al., 2023, Bøe et al., 2017). Thus, such ventilation strategies have the potential to improve the microclimate around the animal occupied zone (AOZ).

Apart from Wu et al. (2016) who reported CH_4 concentrations around the lying cubicle, previous measurements of CH_4 concentrations in cattle buildings have been primarily concerned with calculating emissions. Therefore, gas sampling points are often positioned either beyond the AOZ at ventilation openings or in feed bins (López-Paredes et al., 2020, van Breukelen et al., 2023, Sorg et al., 2017, De Haas et al., 2019, Huang and Guo, 2018, Ngwabie et al., 2009). As a result, detailed information on CH_4 concentration levels and other gas compositions near animals are scarce for emerging technologies aimed at CH_4 capture and utilisation in commercial cattle barns (Nisbet et al., 2020, Pratt and Tate, 2018, NORCE Norwegian Research Centre 2020, Galama et al., 2020). Thus, the objectives are to:

1. Assess spatial and temporal variations in CH_4 concentrations in cold climate commercial cattle buildings during winter, particularly around the lying cubicle, feeding alley and at the feed bin.
2. Explore strategies for upping and extracting CH_4 at the lying area using a Cubicle Hood System (CHS). The hypothesis was that placing a CHS over the lying area would minimise air mixing, thereby increasing CH_4 concentrations under the hood for potential removal and utilisation in a treatment system.
3. Assess effects of the CHS on thermal climate and air quality at the lying cubicle area.
4. Evaluate factors influencing CH_4 concentrations at the lying cubicle.

2. Materials and methods

2.1. Preliminary survey of spatial CH_4 concentrations and a cubicle hood test

Two field surveys were undertaken prior to the investigation in Section 2.2. The aim of the first survey was to assess spatial variations in CH_4 concentrations in Norwegian cowsheds. Therefore, measurements were taken in four commercial cattle buildings during winter, spring, and autumn seasons, at feeding and lying areas. During the survey, CH_4 concentrations were also monitored at the concentrate feeder, but only in two farms. The aim of the second survey was to evaluate the effect of a hood without an air extraction system over the cubicles on reducing air mixing at the lying area in a naturally ventilated dairy barn.

The investigated buildings in both surveys were previously described in Tabase et al. (2023) including the measurement periods. Therefore, for consistency, same numerical references to buildings used in Tabase et al. (2023) will be used in this paper. Building I, which is located at Inderøy is the same mechanically ventilated building used in Section 2.2. Building II was a mechanically ventilated barn in Oslo. Buildings III and IV were both located in Mære. Building III was the naturally ventilated building used in the second survey, and building IV was mechanically ventilated. As previously stated, Tabase et al. (2023) provided detailed information on farm management, animals, diet, equipment, measuring protocols, gas sampling locations, sensors, and calculations used during the surveys.

The second survey in building III was conducted in four phases, from January 18 to February 11, 2022 (Table SM1). Twelve cubicles were chosen for the study, six each at the CON and treatment areas (Fig. SM2-4). During the survey, no hood was placed over the cubicles at the CON area. In phase I, neither the CON nor treatment cubicles had hoods, but in phases II and III, the base hood in the treatment area was put 1.6 m above the cubicle floor and then reduced to 1.2 m during phase IV. The difference between phases II and III was, in phase II, gas samples were collected in a single vertical line at the centre of the hood at the treatment area. In phase III, three gas samples were collected in a single horizontal line along the ridge of the hood, and a gas sampling point was located in the centre of two opposite cubicles at the treatment area. In phase IV, the gas sampling points were identical to phase III, except that the base of the hood was lowered to a height of 1.2 m above the cubicle floor. The hood at the treatment area was a triangular prism (Fig. SM5), constructed to cover 6 cubicles. The materials used to construct the hood were the same as those described in Section 2.2. The experimental design (Table SM1) and corresponding experimental settings are shown in (Fig. SM3 & SM4).

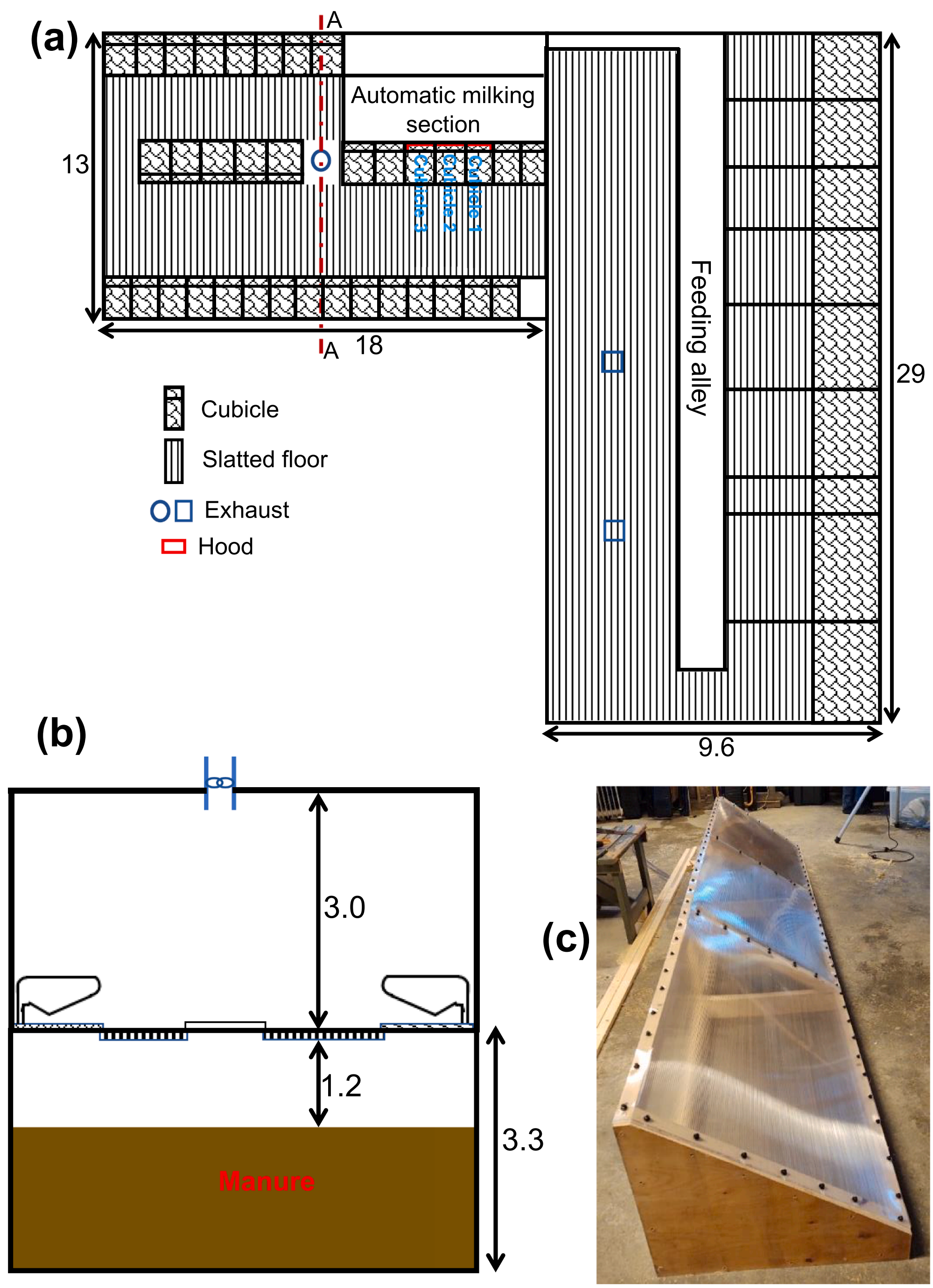

Fig.1. The mechanically ventilated dairy barn (a) plan view, (b) cross-sectional view and (c) photo of the cubical hood construction. Calves and heifers are on the right side of the feeding alley, and dairy cows are on the left.

In addition to assessing how the cubicle hood affected air mixing at different heights at building III, another objective of the experimental design was to see how cows reacted to the hood over the cubicles compared to the CON area. Therefore, cameras were installed to observed animal behaviour at both the treatment and CON cubicles. The camera specification is identical to that described in Section 2.2. Information on farm management, animals, diet, equipment, measuring protocols, sensors, and calculations used during the survey were mentioned in Tabase et al. (2023).

2.2. Cubicle hood system experiment

2.2.1. Barn and animals

The CHS experiment was taken in a loose-house, commercial dairy cattle barn (Fig. 1) located at Inderøy (63° 53′ 45.24" N and 11° 19′ 19.236″ E), Norway. The barn was mechanically ventilated with sidewall air inlet valves and two operational ceiling exhaust ducts. The building housed mature cows, heifers and calves in the same structure. The building had a total volume of 1212 m^3, slatted floor, resting and feeding areas of 291, 172 and 41 m^2, respectively. During measurements, set-point temperature at the climate controller was 10 °C. Tabase et al. (2023) previously gave a detailed description of the barn.

The cows were all Norwegian red breed—composed of 35 dairy cows, 25 of which were 22 to 195 days pregnant. The remaining ten cows were not pregnant (dry cows). All dairy cows (average weight, 640 kg) were lactating and had an average daily milk production of 25.8 kg cow^{-1}. The heifer and calve section had eight calves at an average weight of 137 kg, and 31 heifers at an average weight between 167 and 500 kg—15 of the 31 heifers were pregnant. Animal weight was estimated using Norwegian cattle production data. Roughage consumption by cows was not weighed during the investigation. However, concentrate given to cows via an automatic feeder at feeding alley, Automatic Milking System (AMS) and concentrate feeder at the dairy cow section were monitored. Daily average concentrate intake was 8.8 kg per dairy cow and between 1.5 kg and 2 kg per calves and heifers. Additional information on animal diet and feeding schedule are provided in Tabase et al. (2023).

2.2.2. Cubicle hood and experimental design

A triangular prism CHS (Fig. 1c) covering three cubicles at the lying area was constructed to evaluate effect of hood and air extraction strategy on CH_4 concentration at the AOZ and in the CHS exhaust duct. The CHS was placed above the petitions of three cubicles. The aim was to reduce air mixing at AOZ while enhancing buoyant transport of cow breath CH_4 and/or capture breath CH_4 near the cows before air mixing. The CHS's frame was made of 36 mm × 98 mm wooden boards and 36 mm x 48 mm solid wood. The CHS's sides and rear were covered with 15 mm plywood, and the roof was covered with a transparent channel polycarbonate sheet.

Dimensions of the CHS are shown in Fig. 2a, and Table 1a describes the experimental design. Fig.SM1 in the Supplementary Material (SM) shows more images of the experimental setup for each treatment. In addition to the control (CON), four other case studies (i.e., Treatments (T)) were performed. CON served as a background check, with no CHS over the cubicles. There was no exhaust duct or air extraction in T1 and T2, but the hood alone was installed on the neck rails of the cubicles (Fig. 2a). Gas samples were taken 1.5 m above the cubicle floor under the hood in T1; in T2, gas samples were taken 1.0 m above the cubicle floor. In T3, a meter long PVC pipe (4 mm thick and 110 mm external diameter) was installed in the hood (Fig. 2b). T4 involved installation of a 100 mm diameter suction fan, model 100 DFM (Flexit AS, Ørje,

Table. 1
Experimental design in building I.

Treatment	Measurement period	Description	*Gas sample height
CON	29 - 31/03/2023	No cubicle hood	1.0 m
T1	04 - 09/03/2022	Cubicle hood	1.5 m
T2	09 - 14/03/2023	Cubicle hood	1.0 m
T3	14 - 20/03/2023	Cubicle hood + exhaust duct without suction fan	1.0 m
T4	22 - 26/03/2023	Cubicle hood + perforated manifold + suction fan	1.0 m
T5	26 - 28/03/2023	Cubicle hood + exhaust duct + suction fan	1.0 m

* Gas sampling points were placed above the cubicle floor at the lying area.

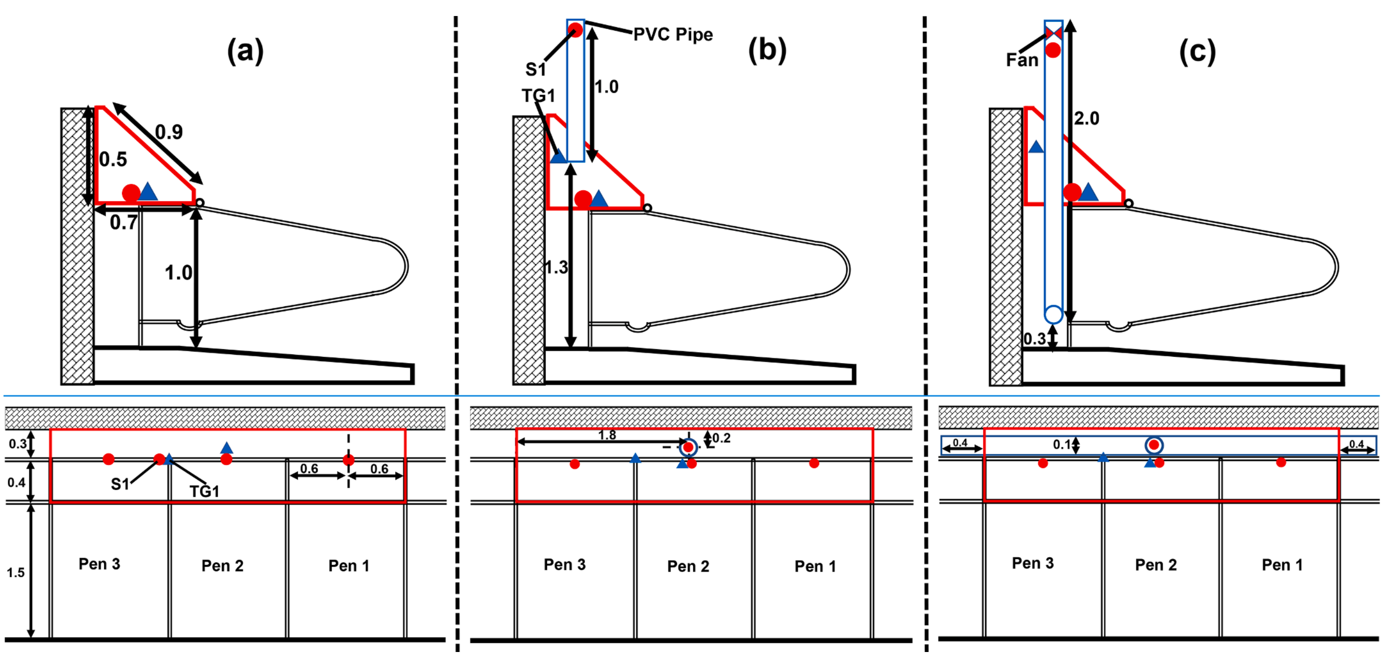

Fig. 2. Side (top) and plan (bottom) view at the investigated cubicles during (a) T2, (b) T3 and (c) T4. The symbols (● and ▲ and abbreviations S and TG) represent FTIR gas sampling point and Tinytag Humidity-Temperature sensor locations.

Norway) in the PVC pipe and a perforated tee PVC pipe connected to the system (Fig. 2c). Only the horizontal sections of the tee pipe, near the cows were perforated, and this was fasted to the cubicle metal partitioning. At the side of the pipe facing the cows, there were twelve evenly spaced (0.3 m) 7 mm diameter perforations. Each cubicle under the hood had two perforations and one perforation each in the adjacent cubicle outside the CHS. We measured an average fan speed of 3.8 m s^{-1} which corresponded to the factory specified max flow rate (107 m^3 h^{-1}). However, measured air velocities in the perforations ranged between 3.2 and 3.6 m s^{-1}, which was less than the calculated average velocity of 5.4 m s^{-1} per hole due to frictional pressure losses. Furthermore, the PVC pipe joints were not very airtight. T5 involved only the meter long PVC pipe as in T3 but with the suction fan. Slurry pit headspace gaseous concentrations were also monitored after the CON measurements.

2.2.3. Measurements

Measurement equipment used were the same as those used by Tabase et al. (2023). The sensors were: Four Tinytag data loggers (Gemini Data Loggers Ltd., Chichester, UK) for monitoring indoor temperature and Relative Humidity (RH). An Oregon scientific weather station for monitoring outside climate. Two Tinytag data loggers were placed around the investigated cubicles (Fig. 2), one in the barn's exhaust duct at the dairy cow section and another placed 2 m above the feeding alley (Fig. 1). Data loggers registered data at a sampling frequency of 5 minutes. A Fourier Transform Infrared Spectrometer (FTIR) gas analyser (GT5000 Terra, Gasmet Technology Oy, Helsinki, Finland) and a multi-point gas YAGA Stream Switcher system (YAGA AS, Ski, Norway) continuously monitored the gaseous concentrations (CO_2, NH_3, CH_4 and N_2O). Measurements were taken sequentially at 8 different sample points. Before measurements began, and at least every other second day, zero-point calibrations were performed using pure N_2 gas.

Four gas sampling locations were placed around the cubicles (Fig 2). The remaining sampling locations are as follows: (1) one in the barn's exhaust duct at the dairy cow area, (2) another, 2 m above the feeding alley (Fig. 1), and (3) the rest in two different air inlet valves. Gas samples were collected using polytetrafluoroethylene tubes (2 mm thickness and 4 mm internal diameter) for the FTIR gas analyser. Calcmet (Gasmet Technology Oy, Helsinki, Finland) and YAGA control software were set to consecutively flush and collect gas per sample location at a sample cycle period of 60 s for flushing and 120 s for gas sampling. As a result, every hour, 5 to 10 gas samples were collected from each location and analysed. The last gas samples analysed for each sampling episode (i.e., every 24 - 30 minutes) were selected and the average (i.e., 2 ≥ samples per hour) was computed as hourly gaseous concentrations at the sample location. The recorded air temperature and RH were computed on hourly basis. It should be noted that the length of the polytetrafluoroethylene tubing connecting the various gas sample locations and the FTIR analyser ranged from 8 to 20 metres. This means a flushing interval of 60 s was sufficient to flush the sampling tubes of previous sample residues 8–20 times before fresh measurements, depending on the tubing length.

2.2.4. Animal behaviour

This study did not require ethical approval because no animal procedures were done. Throughout the study, a video camera (Hikvision, Model: DS 2CD4D26FWD-IZ, Hangzhou, China) was mounted to continuously record cow activity at the CHS (Fig. SM1). After recording, the videos were transferred to an external hard drive and analysed every 10 minutes for cow absence or presence at the three cubicles. When there was a cow present, cow activity was further classified as either standing or lying. Individual cows were not marked and studied in this investigation, but the three cubicles beneath the hood were regarded the test area. Effect of cattle presence on CH_4 concentrations at the CHS was investigated in eight different scenarios: 000, 001, 010, 011, 100, 101, 110, and 111. The three numerical digits from left to right represent cubicle number under the hood, with 0 indicating an empty cubicle and 1 indicating an occupied cubicle.

Hourly occupancy under the CHS were computed on percentage basis by counting cattle presence (only lying) in each cubicle at 10-minute video frames. The occupancy under the CHS per hour was then calculated as the sum of number of counts there was a lying cow at the three cubicles, divided by 18 (Eq. 1). The denominator 18, implies maximum number of counts of lying cows at 10-minute video frame in an hour (6 * 3 cubicles).

$$Occupancy\ (\%) = \frac{\left(\sum_{i=0}^{n} Cubicle\ (i) + \sum_{j=0}^{n} Cubicle\ (j) + \sum_{k=0}^{n} Cubicle\ (k)\right)}{18} \times 100 \tag{1}$$

Where i, j and k represent cubicles 1, 2 and 3 respectively and $n = 6$.

2.2.5. Ventilation rate, air and thermal quality assessment indices

Metabolic gas (i.e., CO_2) produced by the cows was used to indirectly estimate ventilation rate on hourly basis. This approach is known as the CO_2 mass balance (Cigr 2002) method and is regarded a practical alternative to the fan-wheel anemometer method, particularly in naturally ventilated and mechanically ventilated barns which have multiple exhaust openings. Detailed description of equations and assumptions used to calculate ventilation rate were provided in Tabase et al. (2023). Computed ventilation rate was expressed on barn air exchange rate (ACH, h1) basis, which is the number of times the barn volume is refreshed with fresh air per hour. ACH was calculated as the quotient of the hourly volumetric flow rate (m^3 h-1) and the barn volume (m^3).

Three other indices were employed to analyse the influence of the CHS and extraction methods on cow breath CH_4 capture efficiency (η_c) and their effect on pollutant (i.e., CO_2 and NH_3), and heat removal effectiveness (μ_e) at the AOZ. The indicators implemented are commonly used to assess the performance of ventilation systems in domestic kitchens (Zhang et al., 2021). Methane capture efficiency (η_c) was computed as:

$$\eta_c = \frac{C_e - C_r}{C_e - C_o} \tag{2}$$

Where C_e is the CH_4 concentration (ppm) in the CHS exhaust duct in T3 - T5 or the sampling points at the neck rails in T1, T2 and CON (Fig. 2). C_r is the barn CH_4 concentration (ppm), which was chosen as CH_4 concentration in the barn's exhaust duct, and C_o is outdoor CH_4 concentration (ppm). Pollutant (ε_e) and heat (μ_e) removal effectiveness was calculated using Eqs 2 and 3, respectively.

$$\varepsilon_e = \frac{C_{ex} - C_o}{C_p - C_o} \tag{3}$$

$$\mu_e = \frac{T_{ex} - T_o}{T_p - T_o} \tag{4}$$

Where C_{ex} and T_{ex} are pollutant concentration (ppm) or air temperature (°C) in the barn's exhaust duct and C_p and T_p are pollutant concentration (ppm) or air temperature (°C) at point p chosen as around the investigated cubicles (Fig. 2). ε_{CO_2}, ε_{NH_3} and $\mu_e = 1$ implies uniform air mixing, ε_{CO_2}, ε_{NH_3} and $\mu_e < 1$ means short-circuiting of the incoming air and ε_{CO_2}, ε_{NH_3} and $\mu_e > 1$ stands for effective contaminant removal at the AOZ.

2.3. Data analysis

IBM SPSS Statistics 28.0 (IBM Corp. Armonk, NY, USA) was used for the statistical analysis. Scatter plots and simple linear regression analysis were performed using SigmaPlot 15.0 (Systat Software, San Jose, CA). Before deciding on which statistical method to use, the data was subjected to Kolmogorov-Smirnov and Shapiro-Wilk tests. Visual inspection of QQ-plots, frequency plots and the quotient of skewness and kurtosis values revealed that the data were not normally distributed ($p < 0.05$). Therefore, Kruskal-Wallis H-tests were run on the data at a significance level of 0.05. Kruskal-Wallis H-test is a nonparametric test that analyses two or more independent groups, similar to one-way ANOVA. It determines whether or not groups differ significantly in terms of the variable of interest's measure of central tendency (Plichta and Garzon, 2009). The treatments were the independent groups, and the data compared between groups were T_{out}, T_{in}, ΔT, ACH, RH, gaseous concentrations (i.e., CO_2, NH_3 and CH_4), animal occupancy, outdoor wind speed and direction, ε_{CO_2}, ε_{NH_3} and μ_e.

3. Results and discussion

3.1. Spatial and Temporal variations in CH_4 concentrations

Fig.3 illustrates spatial CH_4 concentrations at the selected cattle buildings during the first field survey (Section 2.1). The values shown are raw data from 4 of 8 sampling locations, where 5 continuous gas samples were analysed in 120 s per sampling location, every 30 minutes. For brevity, the results provided are restricted to only buildings I and II, and during the winter survey. In building I, CH_4 concentrations at the lying and feeding areas ranged from 27 to 307 ppm and 3 to 778 ppm, respectively. Corresponding coefficient of variation (CV) of CH_4 measured 1.2 m above floor at the lying area was 35 %, and 36 % at height 3.0 m. The CV of CH_4 at the feeding alley measured 0.6 m and 2.0 m above the floor were 87 % and 41 %, respectively. In building II, measured CH_4 concentrations at the lying area, feeding area, and concentrate feeder varied from 53 to 731 ppm, 46 to 282 ppm, and 49 to 3303 ppm, respectively. This resulted in CVs of 54 % at the lying area (0.6 m above floor), 31 % and 12 % in the feeding area (1.0 and 5.0 m above floor, respectively), and 106 % in the concentrate feeder. The mean ACH in building I was 17.8 h^{-1} compared to 4.1 h-1 in building II, which explains why minimum CH_4 concentration in building I was lower than building II.

As expected, even higher CH_4 concentrations with wider variations were observed at the concentrate feeder, which controlled how frequently specific cows were allowed in but was an enclosed space and measurements were closer to the nostrils of cows than at all other locations (Sorg et al., 2017, Place et al., 2011, Wu et al., 2012, van Engelen et al., 2018, Difford et al., 2016). The aforementioned results were the reason why the hood was chosen for the second field survey in building III and the subsequent test in building I and installed above the lying cubicle.

Fig.4 compares variations in CH_4, CO_2 and NH_3 concentrations between the AOZ (cubicle 2), feeding alley, slurry pit headspace, and barn exhaust duct during the CHS test in building I. Measurements were taken after the CON test when there was no hood above the cubicles. Due to equipment failure, only 4 h (11:00 - 15:00) of measurement data were collected when the pit headspace gas samples were taken. Nonetheless, Fig. 4 shows that CH_4 concentrations at the feeding alley and the AOZ varied more than at the pit headspace and the barn's exhaust duct, with the feeding alley (115 ppm) having slightly higher mean CH_4 concentrations than the AOZ (113 ppm). Fig. 4 shows comparable results for CO_2 concentrations as for CH_4 concentrations. For NH_3 concentrations, comparable mean concentrations were obtained at all sampling locations. Thus, the AOZ, feeding alley, pit headspace, and exhaust duct had mean NH_3 concentrations of 9.3, 9.0, 8.6, and 10.0 ppm, respectively. It should be noted that the pit headspace CH_4 concentrations in our investigation were comparable to the results in Schep et al. (2022), but our headspace CO_2 concentrations were higher than in Schep et al. (2022).

Fig.5 compares diurnal variations in T_{out}, barn temperature, ACH, and animal occupancy at the monitored cubicles during the CHS test. Corresponding diurnal variations in CH_4 concentration between CON and T2 are shown in Fig.6, while Figs. 7 and 8 compare CH_4 concentrations at the monitored cubicles, and in the CHS's exhaust duct between T3 – T5, respectively. The values shown (a data point) represent the overall average of each hourly data for the different measurement days in each treatment. That is, data from the same hour on different days of a treatment are binned and averaged as a single data point. Hourly fluctuations in CH_4 concentrations during the day show two peak and two dip periods in T2 - T5. Diurnal CH_4 trends in CON were similar to T2 – T5 but less pronounced in CON than in T2 – T5. The sharpest CH_4 drop in CON was noted between 17:00 and 19:00, with the peak occurring few h later around 21:00. Minimum CH_4 concentrations in CON were 83, 83, and 86 ppm during the dip period, while maximum CH_4 concentrations were 180, 182, and 170 ppm during the peak period, in cubicles 1, 2, and 3, respectively. The Kruskal-Wallis test indicated that CH_4 concentrations in the three CON cubicles did not differ (p = 0.31) which was further confirmed by the post hoc test (Table SM2).

For T2 - T5, the first and second peaks in CH_4 concentrations at the three cubicles occurred between 22:00 - 05:00, and 11:00 - 16:00, respectively. Dips in CH_4 concentrations, were observed between 08:00 - 10:00 a.m. and 17:00 - 19:00 p.m. Peak CH_4 concentrations ranged from 216 - 233 ppm, 178 - 215 ppm, 207 - 228 ppm, and 229 - 248 ppm in T2 - T5, respectively. Whereas the dip CH_4 concentrations in T2 - T5 varied from 110 - 115 ppm, 72 - 88 ppm, 63 - 67 ppm, and 67 - 85 ppm, respectively. Methane concentrations between cubicles in T2 and T3 differed ($p < 0.01$). Post-hoc test for T2 and T3 further revealed that except for cubicles 2 and 3, which did not differ, CH_4 concentrations differed for the other cubicle combinations. For T4 and T5, both Kruskal-Wallis hypothesis and post-hoc tests revealed that there were no spatial differences in CH_4 concentrations between the three cubicles. Furthermore, in T3 - T5, the CH_4 concentrations at the cubicles did not differ from the observed concentrations in the CHS exhaust duct, apart from an instance in T3 where the CH_4 concentrations in cubicle 3 and the CHS exhaust duct differed (p = 0.02).

A comparison of the diurnal trends in Fig. 5 with those in Figs. 6, 7, and 8, reveals that the observed CH_4 trends in T2 - T5 correspond more with animal occupancy than T_{out}, barn temperatures, and ACH. That is, whereas T_{out}, barn temperatures, and ACH had a single dip and a single peak during the day (sinusoidal trend), the two drop and two peak periods exhibited in Figs. 6, 7, and 8 for CH_4 concentrations were also seen

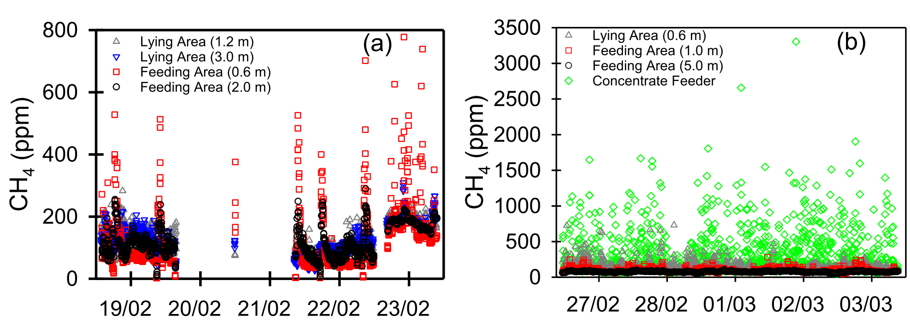

Fig.3. Spatial CH_4 concentrations in (a) building I and (b) building II.

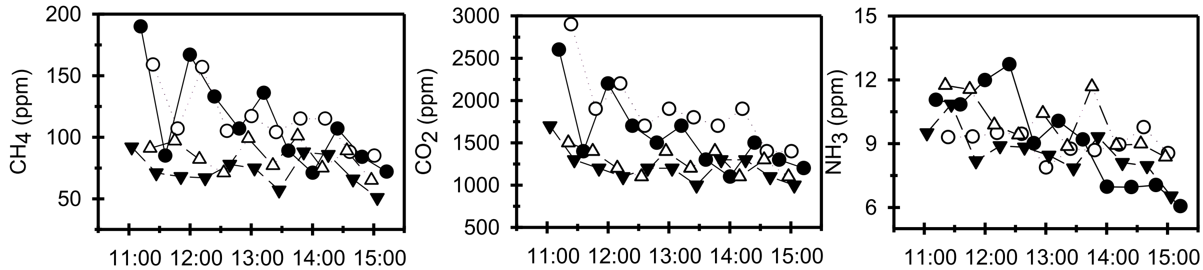

Fig. 4. Spatial variations of CH_4, CO_2 and NH_3 concentrations in the mechanically ventilated barn (Building 1) during the cubicle hood test at the AOZ (●), feeding alley (○), slurry pit headspace (▼) and exhaust duct (Δ).

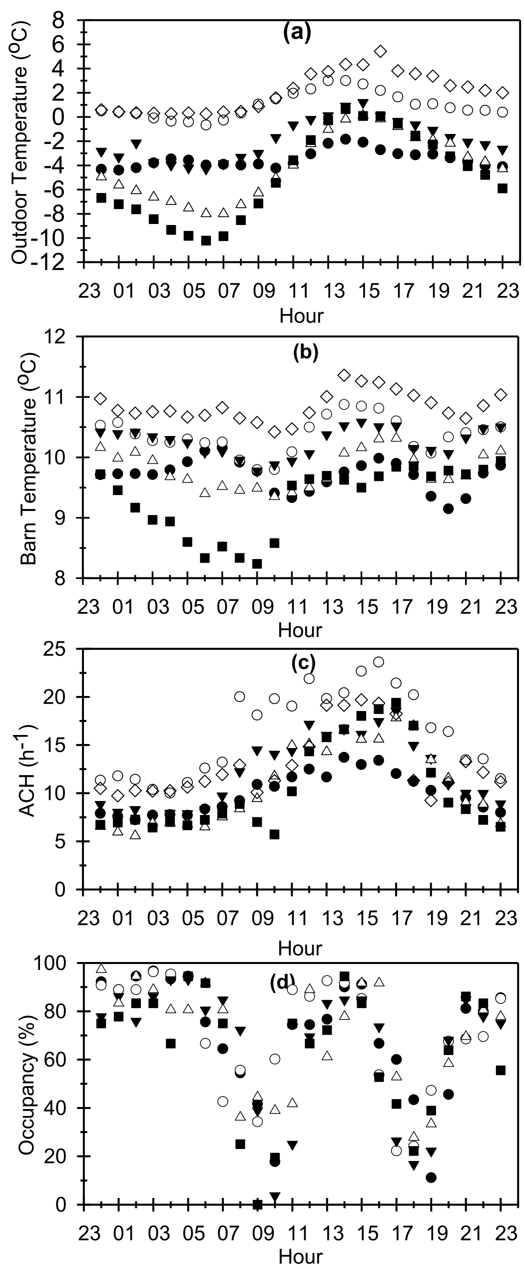

Fig. 5. Diurnal variation in (a) outdoor temperature (b) barn temperature (c) air change rate (ACH) and (d) animal occupancy in T1 (⋄), T2 (●), T3 (○), T4 (▼), T5 (Δ) and CON 5 (■).

for animal occupancy. Peak and the dip periods in CH_4 concentrations in Figs. 6, 7 and 8 occurred when animal occupancy in Fig. 5d were > 85 % and < 40 %, respectively. These trends coincide with the barn management, as the dip periods occurred when the cubicles were empty because cows were being fed and peak periods coincided with the cattle resting period. Indeed, there was a rise in CH_4 concentrations by 98 % at the feeding alley when the cubicles were empty compared to when they are fully occupied in T2 (Fig. 9).

3.2. *Effect of cubicle hood*

This section validates the hypothesis that placing a cubicle hood over the lying area minimizes air mixing, thereby increasing CH_4 concentrations. First, placing the hood over the cubicles in the treatment area had no effect on cow activity (Table SM3). This is because both the CON and treatment cubicles had identical daily mean animal activity (lying, standing, and vacant cubicle) at building III (Section 2.1). Therefore, it is expected that differences in CH_4 concentration between the CON and treatment area was due to the cubicle hood at the cubicles.

Table 2 compares the descriptive statistics of measured CH_4 concentrations between CON and treatment cubicles at the naturally ventilated building (III), as well as the ACH, T_{in}, T_{out}, wind speed and direction. Methane concentrations during phase I of the field test at the treatment area with no cubicle hood were similar to the values observed at the CON area.

Methane concentrations measured 1.6 m above the cubicle floor did not differ between the treatment and CON cubicles during phase II, when the hood was placed over the cubicles in the treatment area (Table 2). However, CH_4 concentrations measured 2.0 m above the cubicle floor in the treatment cubicles, were 25 % ($p < 0.05$) higher than in the CON cubicles. The reason was that the latter sampling point was positioned inside the hood at the ridge, which minimised air mixing. The former sampling point was located outside the hood and was susceptible to air mixing (Fig. SM3-4).

When the hood was lowered from 1.6 m to 1.2 m (phase IV), CH_4 concentrations in the treatment cubicles differed from the CON cubicles by 15 % ($p < 0.05$, Table 2). Despite a reduced percentage difference in CH_4 concentrations between CON and treatment cubicles in phase IV, the measured CH_4 concentrations in phase IV were 20 - 30 ppm higher than in phases II and III. This was because the mean T_{out} during phase IV was 2.7 – 3.6 °C lower than in phases II and III, resulting to 19 - 53 % lower ACH in phase IV than phases II and III.

Table 3 compares the descriptive statistics for the measured T_{out}, ACH and T_{exh} during the CHS test at the mechanically ventilated building (I). Table 3 also compares measured temperature, RH, gaseous concentrations and the dimensionless ε_{CO_2}, ε_{NH_3} and μ_e around cubicle 2. Similar to the test in building III, the hypothesis was that placing the hood over the cubicles (Fig. 1 & Fig. 2) in T1 – T5 would minimise air mixing at the AOZ, thereby increasing CH_4 concentrations for potential capture and use. Apart from T1 and T3, which had comparable CH_4 concentrations to the CON ($p > 0.05$, Table SM3), hourly mean CH_4 concentrations in T2, T4, and T5 were 20 %, 18 %, and 14 % higher than

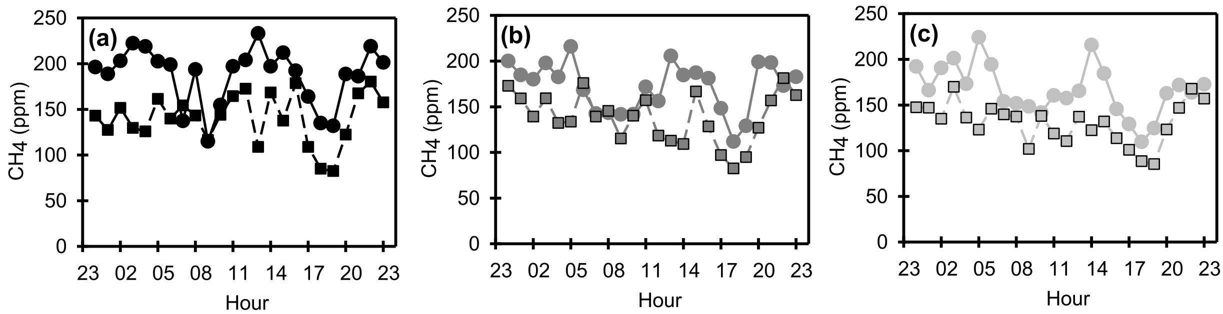

Fig. 6. Diurnal variation in CH_4 concentrations with (T2) (●) and without (CON) CHS (■) in (a) Cubicle 1 (b) Cubicle 2 and (c) Cubicle 3.

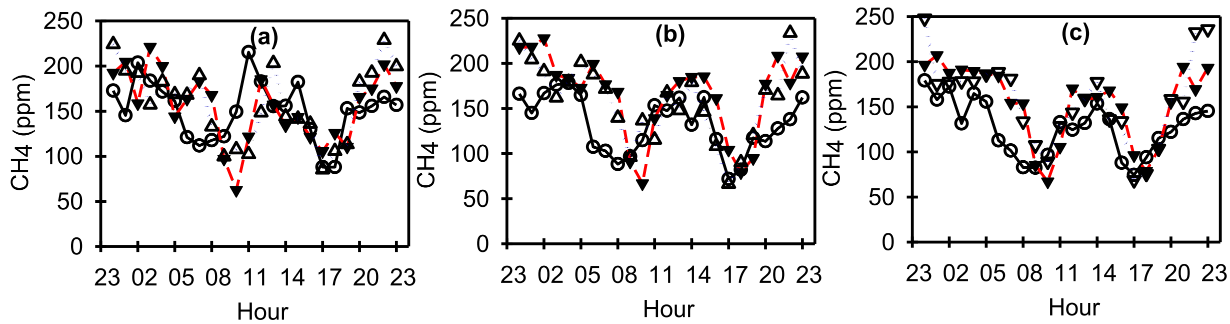

Fig. 7. Comparison of diurnal variations of CH_4 concentration between T3 (○) T4 (▾) and T5 (Δ) in (a) Cubicle 1 (b) Cubicle 2 and (c) Cubicle 3.

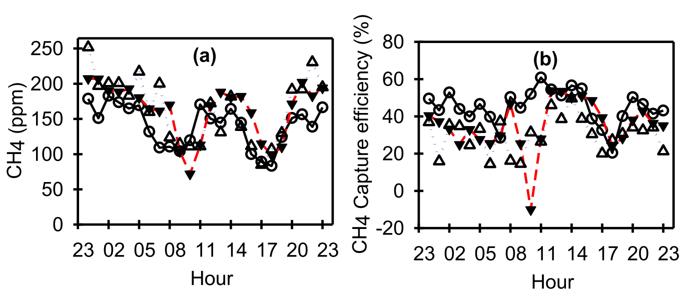

Fig. 8. Effect of CH_4 capture strategy on (a) CH_4 concentration and (b) CH_4 capture efficiency in the roof cover exhaust duct in (○) T4 (▾) and T5 (Δ).

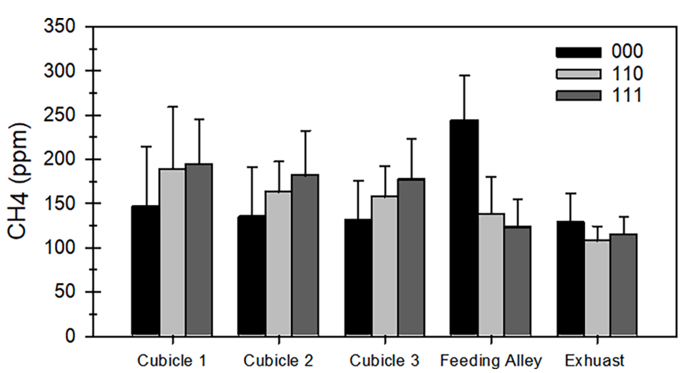

Fig. 9. Spatial variations in CH_4 concentrations during T2 at different animal occupancy (000, 110, 111). The three-digit numbers from left to right refer to cubicles 1 to 3. Number 0 indicate that a cubicle is empty, while number 1 indicate that a cubicle is occupied.

the CON ($p < 0.05$).

To confirm that the difference in CH_4 concentrations between CON and T2, T4, and T5 was indeed due to the hood over the cubicles and not because of key factors known to influence CH_4 concentrations at the AOZ (Wu et al., 2016), the Kruskal-Wallis hypothesis and post-hoc tests were performed for T_{out}, ACH, and animal occupancy. The results show that the comparable CH_4 concentrations between CON and T1, T3 were because of higher T_{out} in T1 and T3 than CON, which caused the ACH in T1 and T3 to be higher than CON (Table 3). Of course, even though there was a hood over the cubicles in T4, the higher ACH increased CH_4 gas dilution with fresh air and its transport from the AOZ. Differences in CH_4 concentration between CON and, T2 and T5 were certainly caused by the cubicle hood, as the measured T_{out}, ACH, and animal occupancy did not differ ($p > 0.05$) between the three treatments (Table SM4).

Furthermore, the difference in CH_4 concentrations between T4 and CON validate the above hypothesis, because while T_{out} in CON was lower than T4 ($p < 0.05$), and ACH in CON was lower than T4 ($p < 0.05$), CH_4 concentrations in T4 were still 18 % greater than CON.

Fig.6 shows that, in addition to cubicle 2, the hourly average CH_4 concentrations at the remaining cubicles in T2 were always greater the CON throughout the day. The hourly mean CH_4 concentrations at cubicles 1 - 3 in CON were 141 ± 33, 137 ± 32 and 130 ± 30 ppm, compared to 188 ± 52, 172 ±52 and 167 ± 46 ppm in T2, respectively. The Kruskal-Wallis hypothesis test indicate that CH_4 concentrations between cubicles in T2 differed ($p = 0.01$) but not for CON ($p = 0.31$). The post-hoc test for CON further verifies that there were no differences in CH_4 concentrations between the three cubicles (Table SM2), whereas in T2, except for cubicles 2 and 3, which did not differ in CH_4 concentrations, the CH_4 concentrations differed for the other cubicle combinations. These findings clearly demonstrate that the use of hood decreases air mixing around the cubicles, given that the hourly mean values ε_{CO_2} and ε_{NH_3} at cubicle 2 were 18 % and 9 % higher in T2 than CON, respectively (Tables 3 and SM4).

3.3. Effect of hood air extraction system

This section compares the influence of hood treatments with air extraction system on CH_4 concentrations around the cubicles. Because the sample points around the CHS in T1 differed from those in the CON, T2 - T5, the results presented here will not cover the former treatment.

Table. 2
Descriptive statistics of measured CH_4 concentrations and other parameters between control and treatments cubicles at building III.

Parameter		Phase I	Phase II	Phase III	Phase IV
$^{a}CH_4$ (ppm)	Mean (SD)	71 (36)	56 (32)	53 (23)	80 (45)*
	Min - Max	15 - 142	13 - 165	21 - 132	17 - 214
$^{aa}CH_4$ (ppm)	Mean (SD)	66 (32)	53 (28)*	55 (21)*	84 (45)
	Min - Max	22 - 135	13 - 154	21 - 123	14 - 199
$^{b}CH_4$ (ppm)	Mean (SD)	73 (32)	62 (28)		92 (46)**
	Min - Max	23 - 150	14 - 148		22- 225
$^{bb}CH_4$ (ppm)	Mean (SD)	69 (34)	66 (28) **	69 (21) **	
	Min - Max	21 - 140	20 - 167	29 - 142	
ACH (h^{-1})	Mean (SD)	5.6 (3.2)	7.2 (5.0)	5.6 (2.3)^{x}	4.7 (2.7)^{y}
	Min - Max	2.0 - 17.8	2.2 - 29.8	1.8 - 11.4	1.0 - 14.4
T_{in} (oC)	Mean (SD)	8.5 (1.4)	9.3 (0.7)	8.5 (0.9)	8.1 (1.5)
	Min - Max	5.1 - 10.3	7.6 - 13.3	6.5 - 10.5	2.1 - 9.8
T_{out} (°C)	Mean (SD)	-0.3 (3.7)	2.0 (3.3)	1.1 (0.9)^{x}	-1.6 (3.2)^{y}
	Min - Max	-5.8 - 6.4	-5.4 - 7.4	-0.6 - 2.3	-8.3 - 3.0
Wind speed (m s^{-1})	Mean (SD)	-	2.5 (1.6)	2.4 (1.7)	2.9 (2.1)
	Min - Max	-	0.1 - 6.3	0.2 - 7.1	0.1 - 8.9
Wind direction(°)	Mean (SD)	-	206 (49)	212 (83)^{x}	166 (83)^{y}
	Min - Max	-	21 -323	5 - 353	3 - 358

Superscripts a, aa indicates CH_4 sampling locations at the CON cubicle at heights 1.6 m and 2.0 m above cubicle floor, respectively.
Superscripts b, bb indicates CH_4 sampling locations at the treatment cubicle at heights 1.6 m and 2.0 m above cubicle floor, respectively.
Superscripts *, ** indicates significant difference ($P < 0.05$) between treatments within the same column.
Superscripts x, y indicates significant difference ($P < 0.05$) between treatments within the same row.

As indicated in Section 2.2, whereas T2 only had the hood, T4 and T5 were designed to assess the impact of different exhaust installations with a running fan on enhancing force transport of breath CH_4 from the cows before air mixing at the lying area. T3, on the other hand, was designed to assess the effect of the hood exhaust installation on enhancing buoyant transport of breath CH_4 when the fan was turned-off.

Overall, T2 had the highest CH_4 concentrations, with 22 %, 4 %, and 7 % higher mean concentrations around cubicle 2 than T3 - T5, respectively (Table 3). Although the Kruskal-Wallis hypothesis test show that CH_4 concentrations differed ($p < 0.001$) across these treatments, the post-hoc test show that CH_4 in T2 was only higher than T3 ($p < 0.05$, Table SM4) but not T4 and T5. The reason was that ACH in T2 was lower than T3 (Table 3), while ACH in T2 did not differ ($p = 0.25$) from T5 because the latter treatments had comparable mean T_{out} (Table 3). Conversely, while the observed ACH and T_{out} differed between T2 and T4 ($p < 0.05$), the recorded CH_4 near cubicle 2 remained comparable ($p = 0.44$).

Fig.7 compares diurnal variations in CH_4 concentrations at the three cubicles between T3 - T5. Methane concentrations at three cubicles in T4 and T5 did no differ ($p > 0.05$), however both T4 and T5 had higher ($p = 0.00$) CH_4 concentrations than T3, but only in cubicles 2 and 3 (Table SM5). The higher CH_4 concentrations in T4 and T5 than T3 were due to the influence T_{out} had on ACH and CH_4 concentrations at the AOZ rather than treatment effect. This is because the ACH and T_{out} between three treatments were significantly different ($p = 0.00$) (Table SM4). Therefore, there is insufficient evidence in this study to demonstrate that the hood exhaust systems impacted CH_4 concentrations near the AOZ, although it is evident that placing the hood over the cubicles increased CH_4 concentrations under the hood compared to the CON treatment (Section 3.2). Perhaps because the air extraction tubing was not very airtight and the fact that the extraction system was not designed to directly deliver the extracted air outside the barn (Section 2.2) resulted in CH_4 recirculation. Furthermore, the fan airspeed in T4 and T5 were fixed at maximum further promoting more air mixing at the AOZ.

Diurnal CH_4 concentrations in the hood exhaust duct in T4 and T5 exhibited comparable patterns to the concentrations at the three cubicles under the hood, apart from T3, where the diurnal trends in cubicle 3 differed from the hood's exhaust concentrations (Figs. 7 and 8a). Difference in CH_4 concentration between the hood's exhaust and cubicle 2 (3 - 8 ppm) was lower than cubicles 1 (5 - 11 ppm) and 3 (7 - 14 ppm). Similar to the results in cubicles 2 and 3, the Kruskal-Wallis hypothesis test revealed that the hood's exhaust CH_4 concentrations and capture efficiencies (η_c) across T2, T3, and T4 were significantly different ($p < 0.05$). The post-hoc test also revealed that the hood exhaust CH_4 concentrations and η_c in T3 differed from T4 and T5 ($p < 0.00$). However, the CH_4 concentrations in T4 and T5 did not ($p > 0.05$, Table 4).

Fig.8b compares the diurnal variations in η_c between T3, T4 and T5. Only T4 had a negative η_c among the treatments. This occurred at 10 a.m., when the cows were being fed and the cubicles were empty. To eliminate the effect of animal occupancy on η_c between treatments, a similar analysis as above was performed but using only data with 100 % animal occupancy under the hood. The new results (Table 4, Fig. 10) show that only the hood exhaust CH_4 concentrations in T3 and T4 differed significantly. The results for η_c were contradictory to the observed CH_4 concentrations.

3.4. Thermal climate and air quality under the cubicle hood

There is an increasing demand for developing strategies to mitigate CH_4 emissions in the cattle industry, however one of the important requirement is that new mitigation strategies do not impair animal health, welfare and have cross-pollutant effect (Giner Santonja et al.). We therefore examined the impact of the hood installations on thermal climate and air quality beneath the hood cubicles. For this exercise, air temperature, RH, CO_2, NH_3, as well as ε_{CO_2}, ε_{NH_3} and μ_e at cubicle 2 were used. ε_{CO_2}, ε_{NH_3} and μ_e were employed to normalise the impact of outdoor gaseous concentrations and temperate on the gaseous concentrations and temperature in cubicle 2 (Section 2.5).

Hourly mean CO_2 levels in T2 – T5 was never > 3000 ppm (Table 3), however an hourly examination of the data shows that the hourly average CO_2 concentrations exceeded the recommended limit of 3000 ppm in 6 % of the measurement periods in T2 and T4, and 4 % in T5. In T3, which had the exhaust duct without fan in the hood, the hourly average CO_2 did not exceed the recommended limit of 3000 ppm. This was because the ACH in T3 was greater than the other treatments. Ammonia concentrations in cubicle 2 appear to be inversely related to the barn ACH (Table 3), meaning that the cubicle hood treatments had negligible effect on NH_3 concentration levels at the AOZ. As a result, the hourly mean NH_3 concentrations in T2, T3, T4, and T5 were greater than the recommended limit of 10 ppm in 79 %, 23 %, 34 %, and 71 % during the measurement period, respectively, compared to 57 % in CON. The corresponding ACHs were 10.1, 16.5, 12.1, 11.1, and 10.6 h-1 in T2, T3, T4, T5 and CON, respectively. Since CON had no hood over the cubicles, the mean ε_{CO_2} and ε_{NH_3} around cubicle 2 (1.24 and 1.01, respectively) were closer to 1 than the values in T2 (1.52 and 1.11, respectively), T3 (1.80 and 1.23, respectively), T4 (1.76 and 1.15, respectively) and T5 (1.42 and 1.15, respectively), which all had the hood over the cubicles (Table 3). The results obtained in CON indicate perfect air mixing around the cubicle due to the lack of hood, whereas the higher ε_{CO_2} and

Table. 3
Descriptive statistics of measured parameters between treatments around cubicle 2 including outdoor temperature (T_{out}), barn air exchange rate (ACH) and hypothesis test.

Parameter		T1	T2	T3	T4	T5	CON	Kruskal–Wallis Test
	Mean (SD)	1.7 (3.1)	-3.4 (2.2)	1.0 (2.2)	-1.9 (3.0)	-3.9 (3.3)	-5.2 (3.6)	
T_{out} (°C)	Min	-5.0	-8.9	-4.7	-8.5	-10.7	-10.7	0.000
	Max	8.6	-0.1	5	1.8	0.3	0.5	
	Mean (SD)	10.8 (0.6)	9.7 (0.5)	10.4 (0.5)	10.3 (0.4)	9.8 (0.4)	9.3 (0.6)	
T_{in}	Min	9.0	8.5	9.2	9.2	9.1	7.8	0.000
	Max	11.9	10.8	11.8	10.9	10.4	10.1	
	Mean (SD)	9.1 (2.7)	14.6 (2.2)	10.4 (2.6)	13.3 (3.2)	14.8 (3.6)	15.1 (3.4)	
ΔT	Min	3.2	10.2	5.5	8.4	9.7	8.4	0.000
	Max	15.3	19.9	17.0	21.2	22.2	20.5	
	Mean (SD)	12.7 (4.3)	10.1 (3.0)	16.5 (6.6)	12.1 (4.3)	11.1 (4.4)	10.6 (4.7)	
ACH (h^{-1})	Min	6.1	5.3	6.7	5.5	5.3	5.7	0.000
	Max	25.6	18.1	43.4	22.1	19.4	21	
	Mean (SD)	11.1 (1.0)	11.1 (1.2)	11.4 (1.2)	11.4 (1.0)	10.9 (0.9)	10.3 (0.7)	
T (°C)	Min	7.8	8	8.4	9	8.4	8.9	< 0.001
	Max	13.1	13.4	14	12.9	11.9	11.8	
	Mean (SD)	77 (5)	78 (5)	74 (6)	80 (4)	74 (8)	68 (4)	
RH (%)	Min	54	68	60	67	55	59	0.000
	Max	87	91	87	89	88	77	
	Mean (SD)	124 (55)	171 (52)	133 (52)	165 (60)	159 (49)	136 (33)	
CH_4 (ppm)	Min	31	78	33	52	46	57	< 0.001
	Max	317	322	299	307	271	202	
	Mean (SD)	1671 (528)	2166 (482)	1735 (454)	2080 (577)	2034 (482)	1822 (309)	
CO_2 (ppm)	Min	800	1250	800	1000	1000	1000	< 0.001
	Max	3550	3533	2767	3300	3133	2500	
	Mean (SD)	7.9 (2.0)	12.5 (3.0)	8.6 (2.5)	9.9 (1.8)	11.6 (2.6)	13.0 (2.2)	
NH_3 (ppm)	Min	4.9	6.7	4	7.4	6.7	6.1	0.000
	Max	14.8	20.6	19	15.2	16.9	16.5	
	Mean (SD)	0.63 (0.22)	1.52 (0.41)	1.80 (0.62)	1.67 (0.56)	1.42 (0.32)	1.24 (0.34)	
ε_{CO_2}	Min	0.25	0.63	0.62	0.59	0.84	0.67	0.000
	Max	1.50	2.54	5.08	3.8	2.29	2.32	
	Mean (SD)	1.00 (0.21)	1.11 (0.18)	1.23 (0.18)	1.15 (0.13)	1.15 (0.14)	1.01 (0.15)	
ε_{NH_3}	Min	0.63	0.74	0.61	0.89	0.92	0.75	0.000
	Max	1.92	1.62	2.1	1.53	1.43	1.48	
	Mean (SD)	0.76 (0.10)	0.79 (0.07)	0.72 (0.08)	0.81 (0.08)	0.85 (0.06)	0.89 (0.07)	
μ_e	Min	0.38	0.66	0.55	0.64	0.75	0.72	0.000
	Max	1.07	1.04	1.02	1	1.03	0.98	
N		120	119	145	94	51	49	
Occupancy	Mean (SD)	NA	71 (30)	71 (31)	67 (31)	70 (27)	64 (31)	***0.265***

Table. 4
Effect of air extraction system on CH_4 concentration in the hood exhaust duct and CH_4 capture efficiency during entire measurement period and when cubicles were fully occupied.

Treatment (*i*)	Treatment (*j*)	Entire measurement period		100 % Occupancy	
		CH_4 conc.	η_c	CH_4 conc.	η_c
3	4	0.00	0.01	0.00	***0.06***
	5	0.01	0.00	***0.22***	0.00
4	5	***0.85***	***0.08***	***0.25***	***0.07***
Hypothesis test		0.00	0.00	0.01	0.00

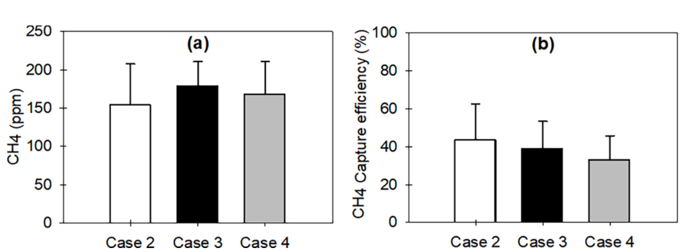

Fig. 10. Effect of CH_4 capture strategy on (a) CH_4 concentration and (b) CH_4 capture efficiency in the roof cover exhaust duct at 100 % animal occupancy.

ε_{NH_3} in T3, T4 and T5 than CON suggests that the use of the hood, in addition to the exhaust installations effectively promoted contaminant removal (Section 2.5).

Because ACH influences macro/microclimate in livestock buildings, and that the post-hoc test (Table SM4) showed the measured ACH among majority of the treatment combinations differed ($p < 0.05$), treatment effect on air temperature, RH, CO_2 and NH_3 concentrations as well as the dimensionless ε_{CO_2} and ε_{NH_3} are only presented for treatments when post-hoc test show no significant difference in ACH. For T4 vs T5, although T_{out} in T5 was lower than T4, the ACH between the treatments did not differ ($p = 0.10$), therefore ε_{CO_2} between the two treatments were similar but not ε_{NH_3}. The results obtained for the CO_2 and NH_3 concentrations were opposite. These findings are related to differences in CO_2 and NH_3 production sources as well as factors influencing their production (Tabase et al., 2023). That is, the higher NH_3 concentrations observed in T5 than in T4 appear to reflect that installing an exhaust fan in T5 without piping perforations either promoted NH_3 transport from the pen floors and/or slurry pit to the lying area or enhanced NH_3 production from the slatted floor by disturbing the manure boundary layer on the pen floor, stripping NH_3 from the pen floor/pit (Tabase et al., 2023).

The results for T2 vs T5 (Table SM4) show that the two treatments had comparable air quality (gaseous concentrations, $p > 0.005$), except for RH ($p < 0.005$). Post-hoc test (Table SM4) for CO_2 and CH_4 concentrations, as well as RH and the dimensionless ε_{CO_2} between CON and T2, show that using a hood without a fan resulted in pollutant accumulation under the hood. This is because overall, the CH_4, CO_2 and RH concentrations at cubicle 2 was higher in T2 than the CON, as well as the

ε_{CO_2} (Table 3). The results for NH_3 were the opposite of CO_2 and CH_4 concentrations, with no difference in NH_3 concentration between the CON and T2 (p = 0.09, Tables 3 and SM4). This could be attributed to differences in NH_3, CO_2 and CH_4 generation sources. Furthermore, the presence of the hood in the lying area of T2 may have acted as an obstacle, changing the local airflow pattern in the lying cubicles when compared to the situation without a hood. Indeed, preliminary computational fluid dynamics simulations of building I (not shown) showed that placing the cubicle hood at the lying cubicle, compared to not, disturbed the airflow vortex that circulated through the lying cubicle to the barn exhaust duct.

Overall, RH in cubicle 2 differed amongst treatments, even among treatments with comparable T_{out} and ACH (Table SM4). T4 had the highest overall mean RH (80 ± 4 %), whereas CON had the lowest (68 ± 4 %). The higher levels of RH in T2 (68 - 91 %) and T5 (55 - 88 %) than in CON (57 - 77 %) tend to validate what was previously reported for the gases (CO_2 and CH_4), that the use of the hood resulted in accumulation of moisture produced by the cows under the hood. The use of an exhaust fan in T5 resulted in lower RH at cubicle 2 compared to T2, which only had the hood over the cubicles, while the higher RH in T4 (67 - 89 %) than T5 (55 - 88 %) was due to moisture stripping from the moist slatted floor to the cubicles in T4.

Measured temperature at cubicle 2 in all treatments was ~ 1 °C higher than the exhaust temperature in building I (Table 3), however T_{exh} was comparable to the control set-point temperature (10 °C, Section 2.1). The higher temperatures in cubicle 2 than in T_{exh} were of course, because measurement was taken near the cows. Among the treatments with comparable T_{out} and/or ACH, the observed temperature in T5 was comparable to T2 but not T4, and the hood in T2 and T5 resulted in higher temperature at cubicles 2 than CON (Tables 3 & SM4). Air exchange at the investigated cubicles was not effective as the mean μ_e was < 1 in all treatment. The overall mean μ_e around cubicle 2 in CON (0.89) and T5 (0.85) were comparable (p = 0.09) and closer to 1 than the values in T2 (0.79), T2 (0.72) and T4 (0.81) (Table 3). The results appear to show that T5 is a better option than T4 for extracting heat from cows at the AOZ.

3.5. Factors influencing CH_4 concentrations

This section aims to identify key factors influencing CH_4 concentrations at the AOZ and to address whether the identified factors can be optimised to increase CH_4 concentrations for the capture and potential air treatment without compromising animal health and welfare and/or increase other pollutant generation. Fig.11 presents the linear correlations between the CH_4 concentrations in the CHS's exhaust duct and air temperature, RH, ACH, ΔT, animal occupancy and η_c in the mechanically ventilated building (I). The data presented are only for measurements in treatments with an exhaust duct in the cubicle hood (i.e., T3, T4, and T5, Table 1). In Fig. 12 is the relation between CH_4 concentrations and air temperature, ΔT, RH, ACH, external wind speed and direction at the naturally ventilated cattle building (III). Fig.SM6 shows bird's-eye view and wind rose during measurements at farm III.

Animal occupancy exhibited the strongest positive association with CH_4 concentrations among the factors studied in building I, with coefficient of determinations (R^2) of 0.32, 0.56, and 0.23 in T3, T4, and T5, respectively (Fig. 11). After animal occupancy, the second strongest factor was ACH. In contrast to animal occupancy, there was a negative ACH dependence on CH_4 concentrations with R^2 equals to 0.19, 0.21, and 0.39 in T3, T4, and T5, respectively. In building III (Fig. 12), negative associations were also observed between CH_4 concentrations and ACH for both the treatment and CON cubicles, with the second highest R^2 after ΔT. External wind speed and wind direction, which are related to ACH in naturally ventilated cattle buildings (Tabase et al., 2023, Wu et al., 2012), had a negative correlation with CH_4 concentrations (Fig. 12). Indeed, these results collaborate with the findings of Wu et al. (2016) between CH_4 concentrations and external wind speed measured at the lying cubicles in a naturally ventilated barn ventilation.

In both building I and III, there was no evidence that RH affected CH_4 concentrations at the lying cubicles (Figs. 11 & 12), the overall association between ΔT and CH_4 concentrations in building I for T3 (R^2 = 0.19), T4 (R^2 = 0.15) and T5 (R^2 = 0.10) were weaker than that of animal occupancy and ACH but stronger than air temperature and RH (R^2 = 0.05, 0.14 and 0.09 for T3, T4 and T5, respectively). Nonetheless, the positive association between CH_4 and RH in T3 - T5 at building I agrees with the findings of Wu et al. (2016).

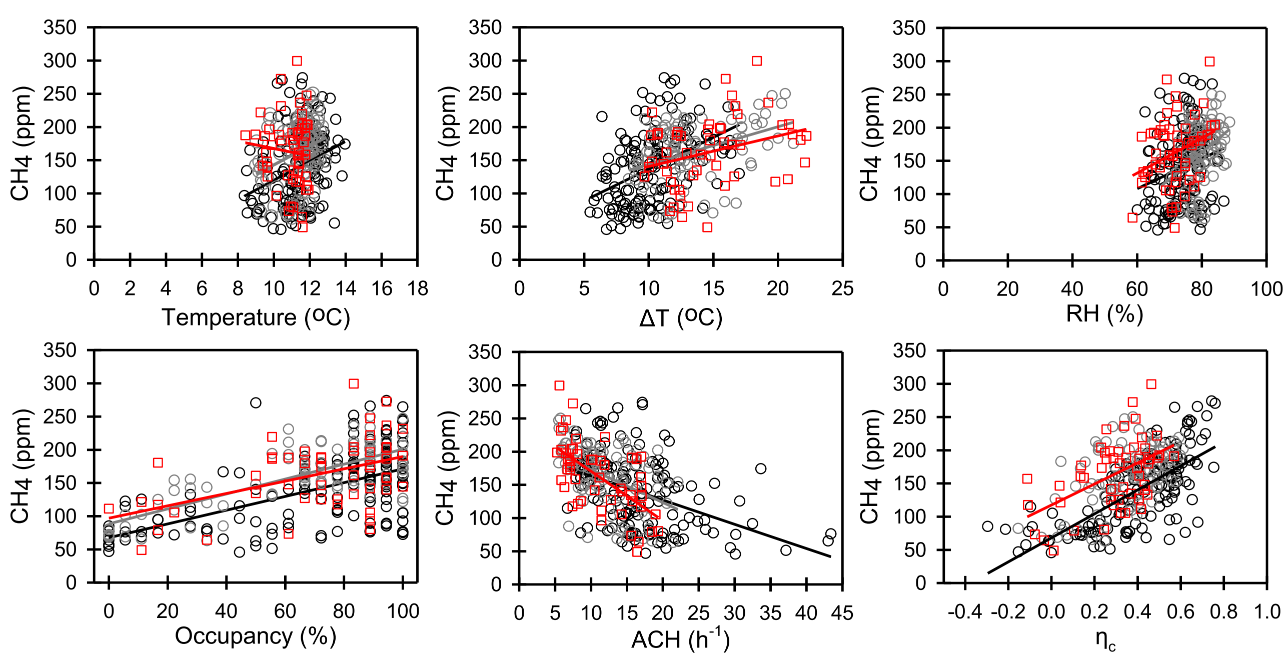

Fig. 11. Relation between CH_4 concentration and temperature, ΔT, RH, cubicle occupancy, ACH and η_c in building I during T3 (black circle), T4 (dark grey circle) and T5 (red square). The symbols represent the hourly mean CH_4 concentration in the CHS's exhaust duct and temperature and RH are recorded at cubicle 2. ΔT was the temperature difference at cubicle 2 and the outside air temperature.

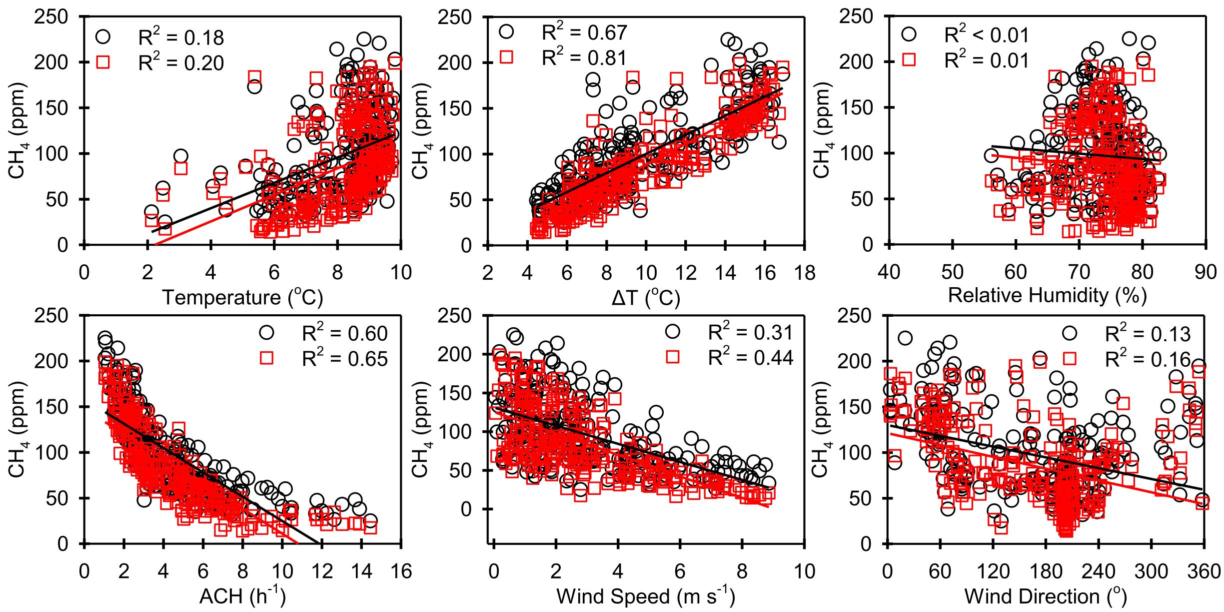

Fig. 12. Relation between CH_4 concentration and temperature, ΔT, RH, ACH, outdoor wind speed and direction in the naturally ventilated building (III) when the cubicle hood was placed 1.2 m above the cubicle floor (○) treatment cubicles and (�) control cubicles. The symbols represent the hourly mean value. CH_4 concentration, temperature and RH were measured 1.6 m above the cubicle floor.

Temperature dependence on CH_4 concentrations was only negative in T5, which had the weakest R^2 (0.01) (Fig. 11). In T3 and T4, R^2 was 0.10 and 0.09, respectively. The positive temperature dependence on CH_4 concentrations in T3 and T4 agreed with the findings of Wu et al. (2016) and the results in the naturally ventilated building in Fig. 12. According to Wu et al. (2016), positive temperature dependence on CH_4 concentrations is related to animal activity because at high barn temperatures, cow activity is reduced, giving cattle more time to rest and ruminate. Furthermore, slurry CH_4 production increases with increasing temperature. The negative temperature dependence on CH_4 concentrations seen for T5 was due to a lack of adequate data points when compared to T3 and T4 (Table 3), given that the time that the cows spent lying in T5 was similar to T3 and even greater than T4 (Table SM6).

3.6. Limitations, recommendations and implications for practical application

In this study an experimental design similar to the Case-Control approach recommended by the VERA protocol (VERA, 2018) was applied to assess the effect of a hood at the lying cubicle on CH_4 concentrations at the AOZ. However, the main weakness was that only one mechanical and one naturally ventilated barn were used in cubicle hood trials, despite the VERA protocol's recommendation of at least two of each ventilation system. Furthermore, the cubicle hood trails were only performed during winter and did not include the other seasons of the year. Nonetheless, the strength of this paper is that although two different ventilation types were used, both barns indicated that the use of cubicle hood upped CH_4 concentrations at the lying cubicles.

In Norway, cows are required to graze during the summer months, so it would have been interesting to conduct similar tests at least during the spring and autumn. However, the purpose of this work was to highlight the potential of the CHS to increase CH_4 concentrations around the lying area for capture and utilisation, particularly during the winter, when indoor air quality is less than other seasons due to lower ventilation rates. When concentrated pollutants are captured by such a system, the secondary benefit is that air quality at the animal-occupied zone is improved. At building I, the air extraction tubes in the CHS were not very airtight. Although the exhaust fan in the CHS extracted air from the lying cubicles, the extracted air recirculated in the barn since the tubing from the CHS was not designed to directly deliver the extracted air outside the barn. Therefore, it was difficulted to determine how the CHS influence the thermal, air quality and CH_4 capture efficiency at the lying cubicles. Furthermore, the fan airspeed in the CHS during T4 and T5 were fixed at the maximum. In future test, it will be useful to assess the effect of different fan airspeeds on CH_4 capture efficiencies. This can be easily evaluated for different scenarios using computational fluid dynamics (CFD). Finally, the use of cubicle hood in T2 and T5 resulted in moisture and CO_2 accumulation at the AOZ (Tables 3 & SM4), for practical purposes (animal welfare), it important that these results are given further attention.

4. Conclusion

There is a scarcity of data on CH_4 concentration levels and other gas compositions around animals in commercial cattle barns, especially for developing technology for gaseous CH_4 treatment. First, spatial CH_4 concentrations were measured at four commercial cattle buildings during the winter, spring, and autumn seasons at the feeding and lying areas, and in the concentrate feeder. The second measurement assessed the effect of a hood without an air extraction system above the cubicles on minimising air mixing and upping CH_4 concentrations at the lying cubicles in a naturally ventilated dairy barn. The third measurement was performed in a mechanically ventilated dairy barn to further validate the hypothesis that placing a cubicle hood over the lying area minimizes air mixing. Thereby increasing CH_4 concentrations and to assess the effect of different air extraction systems in the cubicle hood on CH_4 capture efficiency, thermal and air quality at the AOZ. The study's findings include the following: Higher CH_4 concentrations were measured closer to the animals, regardless of the sampling location. However, the measured CH_4 concentrations were more variable closer to the animals than farther away. CH_4 concentrations at the feeding, lying, and concentrate feeder during the first field survey ranged from 3 - 778 ppm, 53 - 731 ppm and 49 - 3303 ppm, respectively. Periods of CH_4 peaks and dips at the three locations coincided with animal presence, however, because cows spend more time lying than doing other activities the CH_4 concentrations measured at the lying cubicles varied less compared to the other locations. Thus, developing a CH_4 capture systems at the lying cubicles is more practical. Placing only the hood over the cubicles at the lying area increased the hourly average CH_4 concentrations at the lying cubicle by 14 - 25 % depending on the height of the cubicle hood from the floor and the effect of outdoor temperature on barn air exchange rate.

CRediT authorship contribution statement

Raphael Kubeba Tabase: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Geir Næss:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Yngve Larring:** Writing – review & editing, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

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Supplementary materials

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